Stratigraphic framework of upper Paleozoic rocks, southeastern Sangre de Cristo Mountains, New Mexico, with a section on speculations and implications for regional interpretation of Ancestral Rocky Mountains paleotectonics

by Elmer H. Baltz and Donald A. Myers

MEMOIR 48 New Mexico Bureau of Mines & Mineral Resources 1999

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

COVER–View of southeastern foothills of Sangre de Cristo Mountains north from Hermit Peak. Light band is Quaternary sediments lying on Precambrian rocks in Sapello Valley (left) and Quebraditas Valley (right). Most of the wooded areas are underlain by Pennsylvanian rocks. (Photograph by J. Michael O'Neill.)

Memoir 48

New Mexico Bureau of Mines & Mineral Resources

A DIVISIO OF
EW MEXICO INSTITUTE OF MI ING & TECHNOLOGY

Stratigraphic framework of upper Paleozoic rocks, southeastern Sangre de Cristo Mountains, New Mexico with a section on speculations and implications for regional interpretation of Ancestral Rocky Mountains paleotectonics

Elmer H. Baltz and Donald A. Myers
U.S. Geological Survey, retired, Lakewood, CO 80226

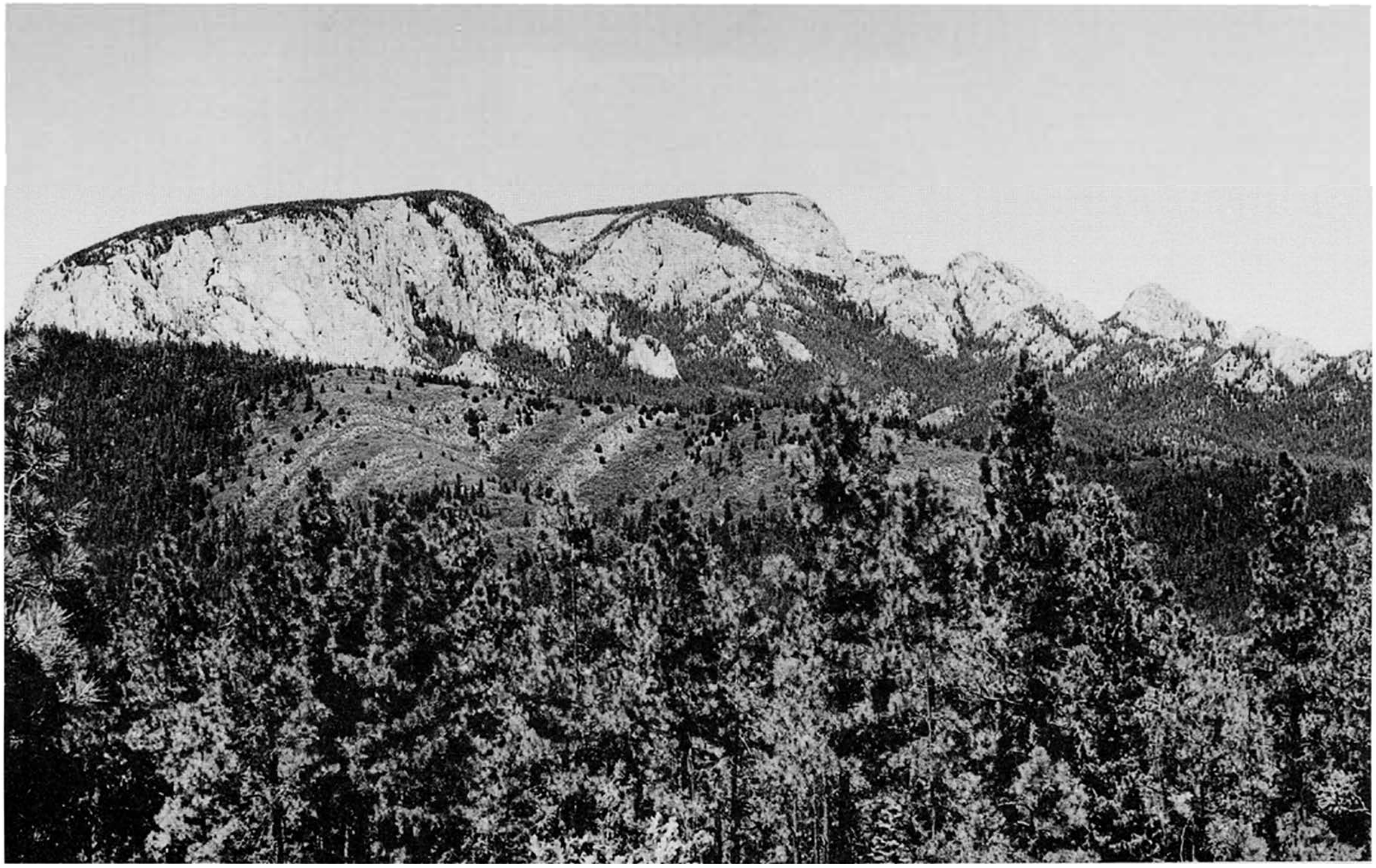
I COOPERATION WITH
THE UNITED STATES GEOLOGICAL SURVEY
SOCORRO 1999

Original Printing

Published by Authority of State of New Mexico, NMSA 1953 Sec. 63–1–4
Printed by Lithexcel, Albuquerque, New Mexico, 87106, April 1999
Plates 1–5 printed by Williams & Heintz Map Corporation, Washington Heights, Maryland, 20743, April 1999

ISSN pending
ISBN 1-883905-03-6

Available from New Mexico Bureau of Mines & Mineral Resources, 801 Leroy Place, Socorro, NM 87801; phone (505) 835-5410



FRONTISPIECE—Hermit Peak, a famous landmark of the southeastern Sangre de Cristo Mountains. View to the north from NW¼SW¼ sec. 24 T17N R14E south of Gallinas Creek. Altitude of the highest (central) part of the peak is about 10,250 ft (3,125 m). The southwest (extreme left) side is bounded by the narrow, 2,000 ft (600 m) deep, canyon of Porvenir Creek. Most of the peak is granite, schist, and quartzofeldspathic gneiss of Late Proterozoic age. Highest part is capped by a veneer of west-dipping Mississippian and Lower Pennsylvanian sedimentary rocks. Banded outcrops in the middle foreground are steeply southeast-dipping limestone and shale of the Middle Pennsylvanian Porvenir Formation on the ridge between Canovas Canyon (left) and Gallinas Creek.

Hermit Peak is said to resemble the face of a reclining man; forehead at the left and chin at the lowest peak at the right. This resemblance may account for the names of Porvenir Creek and of the village of El Porvenir southeast of the peak. The Spanish words *El Porvenir* can be translated as "The Future", or "He of the Future", perhaps an allusion to the Biblically prophesied future return of Christ.

The peak has had a strong religious significance to Hispanic residents of the region. A trail along the top of the highest central part is marked by large, hand-hewn wooden crosses, erected by the *Sociedad del Ermitaño* (Society of the Hermit), that represent the Christian Stations of the Cross. The last station, at the eastern brink, is marked by three crosses.

The name of Hermit Peak is derived from the brief but well-remembered residence there of a singular man. Giovani Maria de Augustino (or Agostini) was born in Novara, Italy, about 1800. He wandered through Europe, South and Central America, Mexico, Cuba, and Canada. In 1863 he travelled west with a wagon train along the Santa Fe Trail from Council Grove, Kansas, to Las Vegas, New Mexico, walking all the way. From 1865 or 1866 to 1867, he lived a solitary life in a small cave at the western side of the highest part of Hermit Peak (just below the "bridge" of the "nose"). He became venerated as a holy man, and legend says that, by striking the ground with his oak staff, he caused the spring to appear that still exists near his cave. He is said also to have healed the sick during his visits to nearby villages. Later, he wandered into southern New Mexico where in April 1869 he was murdered by unknown assailants at his last abode, a cave in the Organ Mountains. Accounts of the hermit are given by Callon (1962, p. 317–321) and Campa (1963, p. 161–196).

CONTENTS

ILLUSTRATIONS

Figures

Appendix II: Descriptions of stratigraphic sections

Plates

ABSTRACT—The Sangre de Cristo Mountains of south-central Colorado and north-central New Mexico are the physiographic expression of a southerly trending Cenozoic structural uplift that plunges gently south to die out in the Great Plains south of Santa Fe and Las Vegas, New Mexico. The uplift is bounded on the west by Neogene downfaulted and downwarped basins of the Rio Grande depression and, on the east, mainly by broad Laramide (latest Cretaceous through Eocene) basins that have sharply folded western limbs. In Colorado, where the uplift is narrow, Precambrian and strongly folded Paleozoic rocks are sliced by easterly yielding Laramide thrust faults, and the uplift is shortened at least 5 mi (8 km). In New Mexico, where the uplift is widest, it consists of as many as four northerly trending zones of broad, west-tilted, basement-cored anticlinal blocks that are bounded by eastward-yielding Laramide reverse and thrust faults. The eastern-frontal faults caused 0.5–3.5 mi (0.75–5.5 km) of shortening and overthrusting across parts of the west limbs of the Laramide Raton and Las Vegas Basins. The uplift was modified in Neogene time by local igneous-intrusive doming and normal faulting related to the Rio Grande rift.

The Sangre de Cristo uplift incorporates marine and nonmarine sedimentary rocks of parts of two major late Paleozoic basins and Precambrian rocks of parts of several late Paleozoic uplifts. In Colorado, Pennsylvanian and Lower Permian rocks as much as 13,000 ft (4,000 m) thick, were deposited in the Central Colorado Basin whose eastern part is in the subsurface of the Laramide Huerfano Park–Raton Basin of Colorado and northern New Mexico. Precambrian rocks in some Laramide thrust plates in the western part of the uplift probably are parts of the late Paleozoic Uncompahgre uplift that bounded the west side of the Central Colorado Basin.

From the New Mexico State line south to near Eagle Nest, Paleozoic rocks are mainly absent from the Sangre de Cristo uplift. Near Eagle Nest, thin nonmarine Lower Permian and Triassic rocks lie on Precambrian rocks of the northwesterly trending, late Paleozoic Cimarron arch that formed a southern boundary of the Central Colorado Basin. Farther south in New Mexico Mississippian rocks are present and Pennsylvanian and Lower Permian rocks are widely exposed in the uplift. The Pennsylvanian and Permian rocks of the uplift were deposited in the Taos trough and in the Rainsville trough whose eastern part is in the subsurface of the Laramide Las Vegas Basin. The rocks are about 10,000 ft (3,050 m) thick at outcrops but thin eastward in the subsurface, and locally are absent entirely from the late Paleozoic Sierra Grande uplift. The rocks thin southward, also, onto the Pecos shelf and locally are only 300–1,000 ft (100–300 m) thick on intrabasinal uplifts. In the western part of the Sangre de Cristo uplift south of Taos, a large Cenozoic-uplifted block of Precambrian rocks was part of the late Paleozoic Brazos and Cañoncito uplifts at the western margin of the Pecos shelf.

Southeastern Sangre de Cristo Mountains—An area in New Mexico extending from near Bernal at the south to near Mora at the north was mapped for this report. Precambrian (Early Proterozoic) basement rocks of the northern part of the mapped area are quartzite, quartzofeldspathic gneiss, mica schist, and amphibolite that occur in large, Proterozoic folds intruded by synkinematic gabbro and tonalite and by scattered bodies of younger Proterozoic granite and thick pegmatites. Farther south, granite stocks occur, and the metamorphic rocks generally are folded more tightly and welded by the intrusives. The Proterozoic rocks were eroded to a regionally nearly flat surface that was formed mainly in late Precambrian and was modified only slightly in early Paleozoic time prior to deposition of Mississippian rocks. In Pennsylvanian and Early Permian the northern Proterozoic terrane became mainly the deep parts of the Taos and Rainsville troughs; however, the southern welded terrane became a shallow, tectonically unstable shelf. Metamorphic and igneous rocks of both terranes locally were sources of Pennsylvanian and Permian clastics.

Mississippian rocks of the map area and the subsurface of parts of the Cenozoic Las Vegas Basin are the Espiritu Santo Formation and the overlying Tererro Formation, which constitute the Arroyo Peñasco Group. The group is as much as 110 ft (34 m) thick, but it is absent locally because of unconformity with overlying rocks and, probably, nondeposition in the northwest part of the area. The Osagean Espiritu Santo Formation is 0–33 ft (0–10 m) thick. It consists of the basal Del Padre Sandstone Member, 0–15 ft (0-4.5 m) thick, and an overlying carbonate member that were deposited during and after transgression of a shallow sea. The Espiritu Santo is unconformable with the overlying Tererro Formation. The Tererro Formation has three members. The Macho Member, at the base, is a late Osagean or early Meramecian age limestone breccia, 0–30 ft (0–9 m) thick, that formed as karst during subaerial weathering of the Espiritu Santo. The unconformably overlying Manuelitas Member is Meramecian limestone pebble-and-cobble conglomerate, calcarenite, and sandy and silty limestone deposited in a transgressing shallow sea. The Manuelitas erosionally overlaps the Macho Member and the Espiritu Santo Formation to lie on Precambrian rocks at places to the south and northwest. The Manuelitas is 3–50 ft (1–15 m) thick; variations result mainly from filling of sinkholes in the Macho Member but partly from an erosional upper contact. The Cowles Member, the early Chesterian upper part of the Tererro, is crossbedded sandy calcarenite, siltstone, limestone, and marly shale deposited in a transgressing shallow sea. The Cowles is 0–40 ft (0–12 m) thick. Locally, it is absent because of erosional unconformity with overlying rocks. During the widespread deposition of Mississippian rocks in north-central New Mexico the repeated shallow submergences and emergences mainly were responses to epeirogeny or eustatic sea-level changes with only small local tectonic influence.

The Sandia Formation of Pennsylvanian (Morrowan through late Atokan) age lies unconformably on the Arroyo Peñasco Group and locally on Precambrian rocks. The Sandia is a heterogeneous assemblage of gray shale, black carbonaceous shale, fine- to coarse-grained sandstone and conglomerate, and subordinate generally thin fossiliferous limestone and some thin coal. It is present throughout most of the southern Sangre de Cristo Mountains and in the subsurface of most of the Las Vegas Basin, but it wedges out southward depositionally on the Paleozoic Tecolote intrabasinal uplift of the Pecos shelf and on the Paleozoic Sierra Grande uplift. The Sandia Formation thickens northwestward, reflecting the depression of the newly forming Taos and Rainsville troughs. To the south the Sandia is only 10–33 ft (3–10 m) thick; whereas, in the central part of the map area, it is about 1,000 ft (300 m) thick on the Paleozoic Manuelitas saddle of the Pecos shelf. The thickening is intraformational, but it is not uniform because the northerly trending Bernal, Hermit Peak, and Tecolote intrabasinal uplifts and the complementary San Geronimo Basin were forming on the Pecos shelf. In the northeastern part of the map area near Mora, the northerly trending El Oro–Rincon intrabasinal uplift began to rise in

latest Morrowan or Atokan time, probably on east-yielding reverse faults, to partly separate the subsiding deep basin into the eastern Rainsville trough and the western Rociada Basin and the Taos trough. The Sandia is more than 5,000 ft (1,525 m) thick in the Rainsville trough and 1,400–3,300 ft (425–1,000 m) thick in the Rociada Basin.

The Sandia Formation in the southern half of the area is coastal-plain deposits of sandstone and shale that contain thin estuarine marine limestone and shale. The late Atokan upper part is mainly marine shale and thin limestones. As the Sandia thickens northward into the Rociada Basin and the Manuelitas saddle it contains progressively more gray marine shale that contains medium to very coarse grained pebbly sandstones and some bioclastic and shaly limestones. The clastics were derived from mainly metamorphic Precambrian terranes on the Sierra Grande uplift and possibly the Brazos and Pedernal uplifts. The intrabasinal Tecolote and Bernal uplifts were local sources of clastics.

In the Rainsville trough the lower half of the Sandia Formation is dominantly gray shale that contains limestones, some sandstone, and some thin coal beds. The upper part contains shale, limestones, thin coal beds, and thick units of micaceous fine-grained to very coarse grained pebbly sandstone, much of which is feldspathic to arkosic. These sandstone units probably were eastward-prograding fans derived from Precambrian rocks of the El Oro–Rincon uplift and deposited in the rapidly subsiding Rainsville trough where they interfinger with sediments derived from the Sierra Grande uplift.

In the Rociada Basin west of the El Oro–Rincon uplift, the northward-thickening Sandia is dominantly shale, although it contains thick, pebbly sandstones scattered throughout. Farther north, in the eastern part of the Taos trough, the upper half of the Sandia is mostly dark-gray shale that contains some limestone and is an eastern distal marine facies of sediments derived primarily from the Brazos uplift.

The Porvenir Formation of Pennsylvanian (early through late Desmoinesian) age lies generally conformably on the Sandia Formation, but locally on the Espiritu Santo Formation and Precambrian rocks on the southern part of the Tecolote uplift. The Porvenir consists of three laterally intergrading facies. These are (1) a shallow-marine carbonate facies in the southern half of the area and the subsurface of the adjacent part of the Las Vegas Basin; (2) a shallow-marine sandstone-shale-limestone facies on the Manuelitas saddle and in the Rainsville trough; and (3) a dominantly shaly facies of deeper water origin in the Rociada Basin. Hemicyclic sequences in the carbonate facies suggest tectonic control of sedimentation. Hemicyclic sequences in the sandstone-shale-limestone facies suggest episodic rapid subsidence and progradation of coarse clastics derived from Precambrian rocks of the El Oro–Rincon uplift.

The carbonate facies of the Porvenir Formation is only 100–600 ft (30–180 m) thick on the northern part of the Tecolote uplift and is absent from its southern part and from the Sierra Grande uplift because of unconformity with overlying rocks. Adjacent to the Bernal uplift, the carbonate facies is locally only 500 ft (150 m) thick because of angular unconformity with the overlying Sangre de Cristo Formation, but the facies thickens northward intraformationally in the San Geronimo Basin and grades into the shaly facies that is about 1,600 ft (485 m) thick in the southern part of the Rociada Basin. The shaly facies grades northeastward into the sandstone-shale-limestone facies that is only 550–680 ft (165–207 m) thick in the Rainsville trough where the upper part is missing locally because of unconformity with the overlying Alamitos Formation.

The San Geronimo and Rociada Basins, the Manuelitas shelf, and the Rainsville trough subsided throughout most of Desmoinesian time although local unconformities in the Porvenir indicate episodic shoaling and slight erosion. The Bernal, Tecolote, and Hermit Peak intrabasinal uplifts were submerged during early and middle Desmoinesian, but all were mainly emergent in late Desmoinesian, as was the Sierra Grande uplift. The El Oro–Rincon uplift was active episodically throughout Desmoinesian.

The Alamitos Formation of Pennsylvanian and earliest Permian age lies mainly on the Porvenir Formation, but on the Precambrian of southern parts of the Tecolote uplift. The Alamitos consists of greenish-gray, gray, and red shale and interbedded fossiliferous limestone, feldspathic to arkosic sandstone, and pebble conglomerate that were deposited in and near fluctuating shallow seas during accelerated local tectonic activity. To the south, the Alamitos is late Desmoinesian through early Wolfcampian age. To the north, the formation is late Desmoinesian, Missourian, and possibly Virgilian age. In the subsurface of the Las Vegas Basin the Alamitos Formation is overlapped southward by the overlying Sangre de Cristo Formation on the margin of the Sierra Grande uplift. The Alamitos is absent from most of the Tecolote and Bernal uplifts because of depositional thinning, intraformational unconformities, and angular unconformity with the Sangre de Cristo Formation. In the intervening San Geronimo Basin the Alamitos thickens northward intraformationally from a wedge edge to about 600 ft (180 m). The Alamitos is about 1,800 ft (550 m) thick in the Rociada Basin but thins northeastward onto the Manuelitas saddle where it is at least 1,075 ft (328 m) thick. Farther north the Alamitos is locally only 100–200 ft (30–60 m) thick where the Desmoinesian part is overlain unconformably by the Sangre de Cristo Formation on a Paleozoic anticline. North of the anticline the Desmoinesian and Missourian parts of the Alamitos are about 1,050 ft (320 m) thick in the Rainsville trough at Mora River, but only about 630 ft (192 m) thick in the subsurface to the northeast.

The Alamitos Formation is heterogeneous laterally. Precambrian rocks of the northern part of the Bernal uplift probably were sources of some feldspathic sediments of the mainly shaly Alamitos in the San Jose Basin to the west and in parts of the San Geronimo Basin to the east. Locally derived feldspathic limy sandstone and feldspar-pebble and limestone-pebble conglomerate beds occur in the Alamitos on the Tecolote uplift and its western flank. The Sierra Grande uplift was the source of shale, feldspathic sandstone, and conglomerate of the Alamitos in subsurface areas to the east.

In the Rociada Basin much of the Alamitos is thick, mainly nonmarine, pebbly arkoses and unfossiliferous red shales that are fans probably derived from Precambrian granite of the Hermit Peak uplift. Sparse limestones in the upper half are coarsely bioclastic and sandy, indicating nearshore deposition. To the east, on the Manuelitas saddle, feldspathic conglomerates are present, but much of the shale is gray and marine, and the limestones are thicker and finer grained.

At Mora River about half of the Alamitos Formation is greenish-gray marine shale containing limestone nodules and thin fossiliferous limestones. Interbedded feldspathic to arkosic, micaceous, conglomeratic sandstones and red shale are mainly nonmarine fan and fan-delta deposits, derived from Precambrian rocks of the El Oro–Rincon uplift, and spread eastward into the Rainsville trough and southward onto the Manuelitas saddle. Near Los Cisneros, north of the map area, the Alamitos contains thin marine limestones but is dominantly alluvial-fan deposits of quartzose, feldspathic, and arkosic conglomeratic sandstone and some interbedded red shale derived from the El Oro–Rincon uplift. To the east, in the subsurface, the Alamitos contains finer grained sandstones, limestones, shale, and traces of gypsum and anhydrite that are not seen at the outcrops. North and south of Mora River the Alamitos is overlain by nonmarine alluvial-fan deposits, locally as much as 700 ft (215 m) thick, that are assigned to the lower part of the Sangre de Cristo Formation. However, they contain probable Late Pennsylvanian palynomorphs and probably are age equivalent to the mainly marine, Virgilian upper part of the Alamitos farther south.

The Sangre de Cristo Formation, of Late Pennsylvanian and Early Permian age, lies on the Alamitos Formation except to the south where it lies on older Pennsylvanian and Precambrian rocks on the Tecolote uplift, Precambrian rocks on the Sierra Grande uplift, and the Porvenir Formation at places on the Bernal uplift. The Sangre de Cristo consists of red, purple, and some greenish-gray shale and sandy shale and interbeds of thin to thick, feldspathic to arkosic sandstone, pebbly arkosic conglomerate, and some unfossiliferous, bedded limestones and limestone nodules. The formation is nonmarine except for a bed of fossiliferous sandstone near the base west of Sapello. To the south, the Sangre de Cristo is Early Permian (Wolfcampian) age. To the north, near Mora River, most of the formation is Wolfcampian, but the lower part is probably Late Pennsylvanian (Virgilian) age. North of the map area, the lower part contains a probable Wolfcampian megaflora. The Sangre de Cristo is overlain by the marine Yeso Formation that also is Early Permian (Leonardian) age. The Sangre de Cristo Formation is as little as 180 ft (55 m) thick on the Sierra Grande uplift and about 300 ft (90 m) thick on the southern parts of the Tecolote and Bernal uplifts. To the southwest it is 900–1,000 ft (275–300 m) thick in the San Jose Basin, and it is 690–960 ft (210–290 m) thick in the southern part of the San Geronimo Basin. To the north it is at least 1,500 ft (457 m) thick on the Manuelitas saddle and 2,500–3,000 ft (760–915 m) thick in the Rainsville trough. The variations are intraformational, reflecting continuing local tectonic activity during deposition of the Sangre de Cristo.

Throughout the map area the Sangre de Cristo Formation contains lower and upper zones of feldspathic to arkosic sandstone, conglomerate, and shale interbeds. Both zones interfinger irregularly with a medial shaly part that constitutes most of the formation and contains feldspathic sandstones and some limestone. A greater proportion of the Sangre de Cristo is shale to the south and southwest than to the north. In the northern half of the area, the uppermost part contains many lenses of well-rounded pebbles to cobbles of varicolored quartz, quartzite, and some chert. In the Rainsville trough north and northeast of the map area the lower third of the Sangre de Cristo contains many beds of limestone and limestone nodules and, in the subsurface, some gypsum.

The Sangre de Cristo Formation was deposited in alluvial-fan, stream, floodplain, and local shallow lacustrine environments. Sediments of the lower sandstone and conglomerate zone were derived mainly from Precambrian rocks of the Sierra Grande uplift but partly from the Bernal, Tecolote, Hermit Peak, and El Oro–Rincon uplifts. Although these intrabasinal uplifts and the local basins continued to be tectonically active, they were buried by the medial and upper parts of the Sangre de Cristo during regional deep depression of the Pecos shelf and the Taos and Rainsville troughs and the pronounced rise of the major basin-margin uplifts. Sediments of the medial and upper parts in the southern part of the area probably were derived mostly from Precambrian rocks of the adjacent Sierra Grande uplift during recurrent elevation and pedimentation of that area, although some sediments may have been derived also from the Brazos and Pedernal uplifts. The medial and upper parts in the Rainsville trough were derived from sources of sediments that included the San Luis(?) uplift and Cimarron arch to the north and the Sierra Grande and Brazos uplifts. The relative importance of these uplifts as sediment contributors is not known. By the end of Wolfcampian time the tectonic cycle that began in Early Pennsylvanian (Morrowan) was completed, the basins were filled, and sediments lapped back onto basin-marginal uplifts. Later Permian (Leonardian) marine sedimentation was influenced mainly by regionally more uniform epeirogenic movements or eustatic sea-level changes.

The late Paleozoic intrabasinal uplifts of the southeastern part of the Sangre de Cristo Mountains were mainly northwest- and north-northwest-trending, easterly verging, asymmetric, basement-cored anticlines, some of which probably were bounded on the east by west-dipping reverse faults. These uplifts and the complementary, asymmetric, local structural and depositional basins correspond generally, but not in all details, with larger Cenozoic faulted anticlines and synclines. The asymmetry of the Paleozoic structures and their right-stepping echelon patterns suggest they were produced by northeasterly oriented compressional and transpressional forces similar in orientation to the regional compressional forces that produced the Cenozoic structures.

Regional implications and speculations—The northerly trending Precambrian and Cenozoic Deer Creek and Pecos–Picuris faults of the southwestern Sangre de Cristo Mountains were also, at times, the western boundary between the Paleozoic Pecos shelf and Taos trough and the Paleozoic Cañoncito and Brazos uplifts. The Pecos–Picuris fault is postulated in the literature to have extended northward and to have been the eastern boundary of the Uncompahgre uplift in Colorado. However, isopachs, facies distribution, and gravity data suggest that the northwest-trending Taos trough did not terminate at this fault but, instead, extended into the area that is now the downfaulted Neogene San Luis Basin near Taos. The northwestern part of the trough may have separated at least the southeastern part of the Brazos uplift from the San Luis(?) and Uncompahgre uplifts of the areas farther north in New Mexico and Colorado.

Facies changes and sediment-transport directions in Morrowan through Desmoinesian rocks of the Taos trough suggest a sediment-shedding late Paleozoic intrabasinal uplift, similar to the El Oro–Rincon uplift, in the area northeast of Taos and west of Eagle Nest where probable Upper Pennsylvanian bouldery conglomerate lies unconformably on Precambrian rocks. Thick Pennsylvanian rocks west of Eagle Nest were deposited in a local basin between this uplift and the major, northwest-trending, late Paleozoic San Luis(?) uplift, part of which was situated farther north in the Sangre de Cristo Mountains in New Mexico where Paleozoic rocks are absent. The southern margin of the San Luis(?) uplift northwest of Eagle Nest is the northwest-trending Cenozoic Comanche Creek fault that probably was active in Late Pennsylvanian and Early Permian time. The San Luis(?) uplift probably connected to the northwest with the Uncompahgre uplift of Colorado prior to Neogene disruption by the Rio Grande rift system.

To the southeast, the San Luis(?) uplift probably was connected with the northwest-trending late Paleozoic Cimarron arch north of the Rainsville trough. On this arch thin sections of the Sangre de Cristo Formation and Upper Triassic rocks lie with sedimentary contact on the Precambrian. During Pennsylvanian and Early Permian time parts or most of the San Luis(?) uplift and Cimarron arch structurally separated the Taos trough and Rainsville trough from the Central Colorado Basin.

The fault-bounded block of Precambrian rocks, now the southern part of the Cimarron Mountains south of Eagle Nest, may have deformed partly independent of the main Cimarron arch. In Early and Middle Pennsylvanian the block was on the northern limb of the Rainsville trough, but it became a source of sediments of the northern part of the trough in Late Pennsylvanian and Early Permian time. The southern Cimarron Mountains block is bounded on the south by the Cenozoic northwest-trending Saladon Creek fault and, on the east, by the Cenozoic northerly trending Fowler Pass fault. These faults probably were active also in Late Pennsylvanian, Permian, and possibly Triassic times. Just west of the Moreno Valley southwest of Eagle Nest, the Precambrian is overlain locally by the Sangre de Cristo Formation and locally by Triassic and Jurassic rocks, indicating that the southern Cimarron Mountains block extended northwestward that far and was bounded at the south by a probable northwest extension of the Saladon Creek fault.

Gravity data and scanty well data suggest that the Cimarron arch extends southeastward in the subsurface to merge with the Sierra Grande uplift, which underlies most of the northeast part of New Mexico. Southeast-trending structural culminations, marked by gravity anomalies and partly by overlap of Permian (Leonardian) rocks onto the Precambrian, extend across the Sierra Grande uplift through the Bravo dome, and into the late Paleozoic Amarillo uplift of the Texas Panhandle. Facies relationships on the margins of the Sierra Grande uplift indicate that it was a sediment-shedding positive feature at times throughout Pennsylvanian and into Early Permian (Wolfcampian).

The Cenozoic Sangre de Cristo Mountains lie within the chain of northwesterly trending late Paleozoic Ancestral Rockies uplifts and basins that extended from southeastern Oklahoma across north-central New Mexico and Colorado to die out in eastern Utah and southern Wyoming. The paleostructural styles of the uplifts and basins are not known well, but large segments of the margins of asymmetric uplifts and basins were faulted. On the southeast, the late Paleozoic Wichita uplift of Oklahoma was thrust possibly 6–12 mi (15–22 km) northward across the southern limb of the Anadarko Basin. To the northwest, the asymmetric late Paleozoic Uncompahgre uplift in Utah and western Colorado was thrust southwestward almost 3 mi (4.8 km) across the northeast limb of the Paradox Basin. Other large faults at the southwest margins of the Frontrange and Wet Mountains uplifts in Colorado may have been buttressing high-angle upthrusts. The overall regional pattern suggests orogenic welts and furrows produced by northerly and northeasterly oriented compressional forces.

The late Paleozoic west–northwest structural grain of Oklahoma and Texas changes to northwest and north–northwest in New Mexico and Colorado. This change suggests that the crust west of about 105° longitude shifted northeastward. This western crustal segment included areas that are now the Sangre de Cristo uplift, the Rio Grande rift, and the eastern Colorado Plateau. The shift might have been caused by compressional forces applied to the crust from the southwest. On the other hand, the shift might have resulted from intraplate movements in the mantle that dragged the crust and created intracrustal northeast-oriented compression.

Introduction

Purpose and scope

Pennsylvanian and Lower Permian rocks of the Sangre de Cristo Mountains and adjacent areas in north-central New Mexico (Fig. 1) are heterogeneous marine and nonmarine deposits that accumulated in and on the flanks of structurally deep late Paleozoic basins that subsided between large uplifts of the Ancestral Rocky Mountains. The facies and thicknesses of rock-stratigraphic units change rapidly laterally, reflecting their deposition in active tectonic environments near sources of terrigenous clastic sediments. The distribution of some major facies and the northward thickening of parts of the rocks have been known generally since regional-stratigraphic studies by Read et al. (1944), Read and Wood (1947), and Brill (1952). Biostratigraphic studies by Sutherland (1963) and Sutherland and Harlow (1973) extended a general knowledge of parts of the rocks northward in the central and western part of the mountains to the vicinity of Taos, New Mexico.

In the topographically and structurally high central parts of the mountains only parts of the Pennsylvanian rocks are preserved from Cenozoic erosion, and Pennsylvanian and Lower Permian rocks have been subdivided and mapped only in the southern and southeastern margins of the mountains. Therefore, many aspects of stratigraphic variations, depositional history, and paleotectonics are poorly known.

A main objective of the present work was to determine, document, and paleontologically date the highly complex variations in thickness and lithofacies that occur in Lower Pennsylvanian through Lower Permian formations between the southern, Pecos shelf and the deep northern Taos trough and Rainsville trough. In the southeastern part of the Sangre de Cristo Mountains between Bernal and Mora, New Mexico (Fig. 1; Plate 1) entire stratigraphic sections of Mississippian, Pennsylvanian, and Lower Permian rocks are preserved, and exposures are mainly continuous between the Pecos shelf and the Rainsville trough. The thin, Paleozoic rock-stratigraphic units, established at the south by Northrop et al. (1946), were mapped northward and westward, concurrently with biostratigraphic study, through several facies changes into the thick, lithologically more complex rocks and the more complex Cenozoic structure near Mora. More than 160 collections of fusulinids were studied as part of the work.

Plate 1 is a synthesis of previously published mapping and the detailed (1:24,000 scale) and reconnaissance mapping done for this report. The mapping and biostratigraphic studies for this report established a more complete regional Paleozoic stratigraphic framework than existed previously. This framework is useful for interpreting general depositional environments, sources of clastic sediments, paleotectonics, and Cenozoic structure. The framework should be useful also for future detailed analyses of highly complex local late Paleozoic depositional environments that are considered only briefly in this report.

The present study also included reconnaissance of other parts of the Sangre de Cristo Mountains, study of logs and some samples from wells in the Las Vegas Basin east of the mountains, and examination of geophysical data. Regional implications of the findings, and some new hypotheses about regional stratigraphy and paleotectonics, are discussed in a final section of the report.

All the upper Paleozoic rocks are vertically and laterally heterogeneous, and at places pronounced lithologic changes occur in relatively small distances. Therefore, this report presents much documentation and discussion of many units that cannot be portrayed adequately by generalized descriptions. Also, parts of the report contain more discussion and documentation of Cenozoic structure than might be expected in a report concerned primarily with Paleozoic rocks. However, there are many places where these rocks cannot be interpreted reasonably without at least a general understanding of the present structure, and vice versa.

Fieldwork and literature research for this report were completed by 1988, and the authors have not attempted to update the report to take into account the later literature. It is appropriate, nevertheless, to reference the 1990 guidebook of the New Mexico Geological Society on the southern Sangre de Cristo Mountains (Bauer, Lucas, Mawer, and McIntosh, 1990, eds.) which contains information relevant to this report.

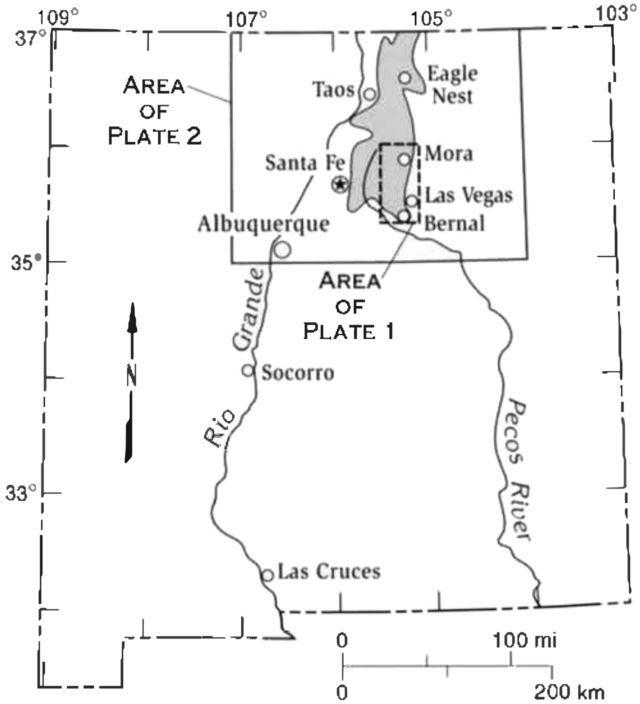


FIGURE 1—Index map of New Mexico showing location of Sangre de Cristo Mountains (stippled) and areas of Plates 1 and 2.

Acknowledgments

The writers thank members of the Branch of Paleontology and Stratigraphy of the U.S. Geological Survey for their assistance. Preliminary identification of Pennsylvanian and Early Permian fusulinids by Lloyd G. Henbest and Raymond C. Douglass in 1965 helped in establishing and correlating rock-stratigraphic divisions of the Sandia Formation and the Madera Group. In 1971 Richard E. Grant, in consultation with E. L. Yochelson and Mackenzie Gordon, Jr., identified collections of brachiopods and gastropods that validated correlations of some Pennsylvanian rock-stratigraphic units mapped in the Gallinas Creek area (Baltz, 1972).

During mapping of the Mora River and Sapello River areas (Baltz and O'Neill, 1984, 1986) and other parts of the region, J. T. Dutro, Jr., E. L. Yochelson, and John Pojeta, Jr., provided timely identifications of Mississippian and Pennsylvanian megafossils that helped greatly in correlations and in determining some structural and paleotectonic relations. Robert M. Kosanke examined many samples for palynomorphs and provided data to confirm a major Upper Pennsylvanian facies change. Identification of probable Early Permian fossil plants by Sergius M. Mamay also were useful in this connection.

Earle R. Cressman and Gordon W. Weir of the Branch of Central Regional Geology made thorough technical and editorial reviews that improved the manuscript substantially.

We thank Robert A. Bieberman for permitting the study of well samples from the New Mexico Library of Subsurface Data of the New Mexico Bureau of Mines and Mineral Resources. Thanks are expressed also to Ben Donegan, Consulting Geologist, who provided data from some wells and spirited discussions of Cenozoic structure and paleogeography of various areas. Thanks are owed to New Mexico Bureau of Mines and Mineral Resources, Nancy Gilson for editorial assistance and Rebecca Titus for drafting, in preparing the manuscript for publication.

Previous work

Stevenson (1881) published the first geologic map and summary of the Sangre de Cristo Mountains and the Raton and Las Vegas Basins in Colorado and New Mexico. His text on the southeastern part of the mountains describes Paleozoic stratigraphic sections, lists Paleozoic fossils, and gives extensive descriptions of structure. This classic report of the Wheeler Survey deserves special mention because of Stevenson's overall acuity of observation and his generally correct portrayal of much previously unexplored geology.

The modern Paleozoic and Mesozoic stratigraphic nomenclature of the southern part of the Sangre de Cristo Mountains and Las Vegas Basin stems mainly from the reconnaissance mapping and stratigraphic studies of north-central New Mexico by Read et al. (1944) whose work extended into the southwestern part of the mapped area (Plate 1) of the present report, and also from the detailed mapping and stratigraphic studies by Northrop et al. (1946) in the southeastern part of the area and the adjacent Las Vegas Basin. More recent mapping is referenced on the index map of Plate 1 and is cited at appropriate places in this report.

The general geology of the southeastern part of the mountains was discussed (Baltz and Bachman, 1956; Lessard and Bejnar, 1976) in guidebooks of the New Mexico Geological Society. Road logs of the area (Baltz and Read, 1956; Lessard, 1976; Budding, 1979; and Baltz and O'Neill, 1990) also are in guidebooks of this society. Paleozoic rocks of the Sangre de Cristo Mountains are mentioned briefly in studies of the subsurface of adjacent parts of the Great Plains by Foster et al. (1972) and Roberts et al. (1976).

A historical summary of the nomenclature and age assignments of Paleozoic rocks, from principal reports on the New Mexico portion of the Sangre de Cristo Mountains, is shown in Figure 2.

Cenozoic regional structural setting

The Sangre de Cristo Mountains of south-central Colorado and north-central New Mexico are the physiographic expression of a southerly trending Cenozoic structural uplift that is slightly sinuous but is generally accurate and slightly concave to the west (Fig. 3). This is the southernmost uplift of the Southern Rocky Mountains; south of Santa Fe and Las Vegas, New Mexico, it plunges gently southward and southeastward to die out in the Great Plains. Throughout its length the uplift is bounded at the west by downfaulted and downwarped basins of the Rio Grande depression, which are the principal structural and physiographic expressions of the Neogene Rio Grande rift system. On the east the uplift is bounded, mainly, by broad Laramide structural basins that are asymmetric, having steeply dipping western limbs and axes that lie in their western parts.

In Colorado, where the uplift is narrow, much of the Laramide (latest Cretaceous through Eocene) deformation was accomplished by uplift and folding of Paleozoic sedimentary rocks that were faulted and crowded eastward against the sharply folded Mesozoic and lower Tertiary rocks of the west limbs of the Laramide Huerfano Park and Raton Basins (Johnson, 1969; Tweto, 1979a). The Paleozoic rocks and the Precambrian rocks within the western part of the uplift are sliced by lengthy, northwest-trending, easterly yielding thrust faults. Lindsey et al. (1983, p. 225–226) calculated that folding and thrusting within the sedimentary rocks indicates a minimum shortening of about 5 mi (8 km) in the northern part of the mountains in Colorado, and possibly 9 mi (14 km) a little farther south.

Plate 2 shows the principal Cenozoic structural features and gravity anomalies of north-central New Mexico, some of which are discussed in various sections of the report. The block diagrams of Plate 2 generally portray the accumulated deformation of the Precambrian basement that has occurred since a widespread veneer of Mississippian marine rocks was deposited on an erosion surface cut on the Precambrian rocks. Although much of the deformation was Cenozoic, a substantial part was Pennsylvanian and Early Permian, and some was Mesozoic.

In northern New Mexico the Sangre de Cristo uplift northeast of Taos consists of fault blocks of Precambrian rocks that are overlain by remnants of thin lower Tertiary sedimentary rocks and by eroded but extensive remnants of middle Tertiary volcanic rocks. The Precambrian rocks have been crowded against, and probably have overridden, the west limb of the Raton Basin, mainly along a frontal zone of Laramide eastward-yielding reverse and thrust faults (Clark and Read, 1972; Dane and Bachman, 1965). The Laramide shortening may have been 3.5–5 mi (5.5–8 km). The Precambrian rocks are intruded at places by middle Tertiary granitic plutons and much of the uplift is shattered by Neogene normal faults of the Rio Grande rift system and by the Questa caldera (Lipman and Reed, 1984; Reed et al., 1983). The west side of the uplift in Colorado and as far south as the Picuris Mountains in New Mexico is a complex zone of Neogene faults that have mainly down-to-the-west displacements totaling many thousands of feet. The Neogene San Luis Basin is tilted eastward and its eastern margin is dropped along these faults. The northeast-trending Embudo fault (Plate 2) south of Taos, New Mexico, is a hinge fault, probably having some left-lateral strike-slip, that accommodated the tilting of the San Luis Basin relative to the block of Precambrian rocks of the Picuris Mountains (Baltz, 1978).

The eastern front of the Sangre de Cristo uplift is stepped southeastward in the Cimarron Mountains southeast of Eagle Nest, New Mexico, by a large northwest-plunging anticline whose core of Precambrian rocks is a fault-bounded, Laramide-upthrust block (Wanek et al., 1964; Goodknight, 1973). The Precambrian rocks are overlain locally by thin Permian rocks and by remnants of thin Upper Triassic rocks, indicating late Paleozoic, and probably, early Mesozoic uplift (Baltz, 1965). The block is truncated at the south by a northwest-trending fault that mainly is concealed by upper Tertiary volcanic rocks. This fault throws the Precambrian rocks against thick Permian rocks of the Las Vegas Basin on the south and probably has a history of repeated displacement from Late Pennsylvanian to Neogene time. The exposed part of the fault south of Eagle Nest was named the Saladon Creek fault by Smith and Colpitts (1980).

The Saladon Creek fault, or other unmapped faults having generally the same trend, may extend northwestward across the main part of the Sangre de Cristo uplift, causing downwarping and down-to-the-south dropping of the Precambrian basement. For many miles south of this zone the surface rocks of the uplift are mostly of Pennsylvanian age. These rocks, eroded remnants of which are as much as 6,000 ft (1,800 m) thick, were deposited in a deep part of the late Paleozoic Taos trough, and the area southeast of Taos is the uplifted relic of part of that basin.

South of the Cimarron Mountains, the lengthy but relatively low Ocate anticline (Bachman, 1953) lies in the northwestern part of the Laramide Las Vegas Basin. This anticline is east-verging and its east limb is broken in places at the surface by normal faults that have displacements of a few hundred feet down to the east and to the west, also. Well data (Plate 3) indicate that the anticline is basement cored and at least part of it is broken by an eastward-yielding reverse fault that may die out upward in folded sedimentary rocks. The surface rocks are mainly Permian, but they are overlain and concealed at many places by upper Tertiary and Quaternary basaltic rocks (O'Neill and Mehnert, 1988). A thick Pennsylvanian section is present in the subsurface.

The main part of the Sangre de Cristo uplift from the latitude of Taos southward to the vicinity of Mora has not been mapped in detail. Reconnaissance examinations indicate that the east front in the Rincon Range (Plate 2) is a large, asymmetric, east-verging, basement-cored anticline whose eastern limb is broken by west-dipping reverse or thrust faults. From Mora south to about Las Vegas, in the mapped area of this report (Plate 1), the east front is a series of east-verging, basement-cored, asymmetric anticlines whose steep eastern limbs are broken by west-dipping listric reverse and thrust faults (Baltz and O'Neill, 1984, 1986; Baltz, 1972). Two other similar, but structurally higher, zones of basement blocks bounded by eastward-yielding thrusts and reverse faults occur in the interior part of the uplift west and southwest of Mora. The present understanding indicates only modest amounts of shortening on any of these faults. Near Mora the shortening in the frontal zone may be a little more than 2 mi (3.5 km) (Plate 1, secs. *A–A'* and *B–B'*). To the south the shortening probably is several thousand feet on any fault zone (Plate 1, secs. *F–F'* and *G–G'*) and a little more than 2 mi (3.5 km) in total across interior and frontal zones.

From Las Vegas south, the Creston anticline at the eastern front is east-verging, basement-cored, asymmetric, and plunges gently southeast (Northrop et al., 1946). This anticline was an area of Pennsylvanian and Early Permian uplift. West of Las Vegas the interior zone passes into a southwest-tilted basement block bounded by reverse-faults; the block plunges southeast and passes into the northeast-verging Serafina monocline near Bernal. This block also was an area of Pennsylvanian and Early Permian uplift.

East of Santa Fe, where the Sangre de Cristo uplift reaches its maximum width, (Plate 2), the central part is an asymmetric syncline that plunges south and has a sharply folded west limb. The surface rocks of the syncline are Pennsylvanian and, at the south, Permian. The western part of the uplift that constitutes the Santa Fe Range is a south-plunging block of Precambrian rocks that probably was anticlinal originally. A thin section of Mississippian, Pennsylvanian, and Lower Permian rocks occurs on its southern margin northwest of Lamy (Booth, 1976, 1977) and a faulted sliver of Pennsylvanian rocks occurs within the block a little farther north (Budding, 1972). Remnants of eroded, west-dipping Mississippian and Pennsylvanian rocks occur at places along the western foothills of the block from the vicinity of Santa Fe (Spiegel and Baldwin, 1963) northward to the latitude of Nambe (Sutherland and Harlow, 1973). At least parts of this block were areas of Pennsylvanian and Early Permian uplift. The west side of the block merges, through west-facing warps and faulted anticlinal bends, into the eastern limb of the Neogene Española Basin (Baltz, 1978).

The Precambrian rocks of the Santa Fe Range are bounded at the east by northerly trending major high-angle faults. The Deer Creek fault (Plate 2) at the south may be a reverse fault that dips west (Budding, 1972), although at places where it is exposed it is nearly vertical. On the south it passes into a very complex system of folds and faults, and its trend extends southward near Lamy into down-to-the-west faults that mark the faulted-monoclinal boundary between the Galisteo Basin and the Glorieta slope (Stearns, 1953). The Laramide Galisteo Basin is underlain by a late Paleozoic basin; whereas, much of the Glorieta slope is underlain by the Paleozoic Pedernal uplift (Kottlowski, 1961). Booth (1976) found that Precambrian, Pennsylvanian, and Permian, as well as Cenozoic, deformation occurred in the faulted area east of Lamy.

To the north the Deer Creek fault has been traced, as a zone with many splays, into the Pecos–Picuris fault (Plate 2) mapped by Miller et al. (1963, plate 1) and Moench and Robertson (1980). In places this fault zone forms the boundary between Precambrian and Pennsylvanian rocks, but at other places is entirely within Precambrian rocks. At the north end of the Santa Fe Range, the fault lies within Pennsylvanian rocks, and its trace is concealed for a few miles by Cenozoic deposits. It has been correlated northward with a major north-trending fault in Precambrian rocks in the eastern part of the Picuris Mountains (Montgomery, 1963). The Pecos–Picuris fault apparently is a Precambrian high-angle fault, or fault zone, with a complex subsequent history. Montgomery (1963) reasoned that 23 mi (37 km) of right-lateral, strike-slip displacement occurred on the fault in Precambrian time. Sutherland (1963) postulated that the fault marked the eastern margin of the Paleozoic Uncompahgre uplift and that vertical movements occurred on the fault in Mississippian and Pennsylvanian time. He suggested that post-Pennsylvanian, presumably Laramide, down-to-the-east vertical movements of thousands of feet occurred, also.

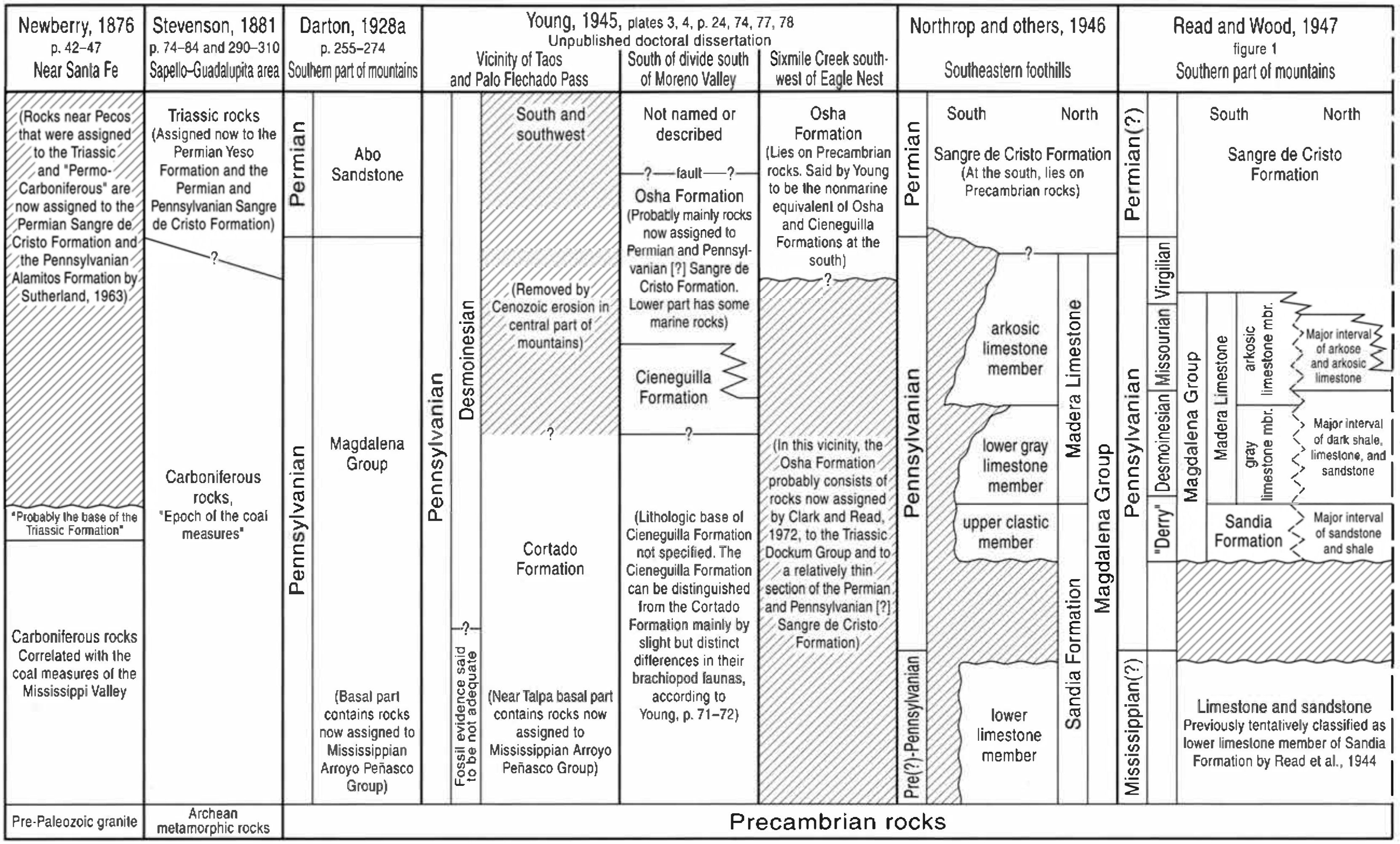
Lisenbee et al. (1979) wrote that the Deer Creek fault and other structures mapped by Booth (1976) near Lamy were parts of a northeast-trending fault system that connects with the Tijeras fault east of Albuquerque (Plate 2), and Chapin and Cather (1981, 1983) suggested the possibility of very large Laramide right-lateral, strike-slip displacement on this system and on the Pecos–Picuris fault. However, no direct evidence of Laramide strike-slip motion on the Deer Creek fault or the faults farther south along the edge of the Glorieta slope has been reported. The only place where such movement might have occurred would be along a hypothetical segment of the "Tijeras–Cañoncito system" of Lisenbee et al. (1979) that is concealed by alluvium in the broad valley of Galisteo Creek near Lamy. However, Booth (1976) has shown that, in at least one place, steeply dipping beds of Triassic and Jurassic rocks exposed on terrace margins on opposite sides of the Galisteo Creek valley project into each other along strike. Therefore, it is unlikely that a fault with a major Cenozoic strike-slip component exists beneath the valley of Galisteo Creek. Furthermore, the Tijeras fault on the northwest side of the Tijeras Basin east of Albuquerque has an apparent horizontal, left-lateral separation on the Dakota Sandstone of only about 3,000 ft (Ferguson et al., 1996). This seems to preclude large amounts of Cenozoic stripe-slip displacement even if the Tijeras fault connects with faults at Cañoncito, which the present writer (Baltz) believes is unlikely. Instead, it seems more likely that the Tijeras fault connects northward (beneath the Tertiary Tuerto gravels) with the north-trending Rosario fault (Plate 2), representing a Neogene reversal of vertical throw (down to the west) on the northern segment.

Much of the compressional deformation that produced the Sangre de Cristo uplift is contemporaneous with the Laramide orogeny as shown by the stratigraphic relations and facies of uppermost Cretaceous and lower Tertiary rocks in the east-flanking Raton Basin (Johnson and Wood, 1956), the Galisteo Basin southwest of Santa Fe (Stearns, 1953), and the San Juan Basin (Baltz, 1967) to the west in the Colorado Plateau. This compressional phase produced a large geanticline, or an anticlinorium, that included the present Brazos uplift (Plate 2) and areas now parts of the San Luis Basin (Baltz, 1965, 1967) as well as the present Sangre de Cristo uplift in New Mexico and Colorado. Part of the geanticline foundered in Neogene time to become the San Luis Basin (Baltz, 1965, 1978) in Colorado and New Mexico.

The remaining Sangre de Cristo uplift was modified in Miocene time by doming, sagging, and some faulting; in at least the area northeast of Taos this deformation was coeval with intrusions of intermediate to granitic magmas. In late Miocene, Pliocene, and Pleistocene time the present Sangre de Cristo uplift was modified at places throughout its length by normal faulting, and its western margin was outlined by the attendant development of the Rio Grande depression during a general, epeirogenic uplift of the western Great Plains, the Southern Rockies, and the Colorado Plateau (Baltz, 1978). At the eastern margin of the uplift near Eagle Nest, New Mexico, northerly trending, down-to-the-west Neogene faults delineate the Moreno Valley and the western part of the Cimarron Mountains (Clark and Read, 1972). Farther south, in the area of this report (Plate 1), down-to-the-west late Tertiary(?) and Quaternary faults, partly superposed on Laramide thrusts, occur north and south of Mora and in the Quebraditas fault zone as far south as the Sapello River (Baltz and O'Neill, 1984, 1986, 1990).

Pre-Mississippian erosion surface of north-central New Mexico and south-central Colorado

At most places in the Sangre de Cristo Mountains in New Mexico, the erosion surface at the base of Mississippian rocks is remarkably flat and locally smooth, regardless of the lithology of the Precambrian rocks on which it is cut. The local relief generally is no more than a few inches, and seldom more than a foot. The surface mainly is underlain by firm, unweathered, Precambrian rocks, but at places the


Newberry, 1876
p. 42–47
Near Santa Fe
Stevenson, 1881
p. 74–84 and 290–310
Sapello–Guadalupita area
Darton, 1928a
p. 255–274
Southern part of mountains
Young, 1945, plates 3, 4, p. 24, 74, 77, 78
Unpublished doctoral dissertation
Vicinity of Taos and Palo Flechado Pass
South of divide south of Moreno Valley
Sixmile Creek southwest of Eagle Nest
Northrop and others, 1946
Southeastern foothills
Read and Wood, 1947
figure 1
Southern part of mountains
(Rocks near Pecos that were assigned to the Triassic and "Permo-Carboniferous" are now assigned to the Permian Sangre de Cristo Formation and the Pennsylvanian Alamitos Formation by Sutherland, 1963)
"Probably the base of the Triassic Formation"
Carboniferous rocks Correlated with the coal measures of the Mississippi Valley
Pre-Paleozoic granite
Triassic rocks (Assigned now to the Permian Yeso Formation and the Permian and Pennsylvanian Sangre de Cristo Formation)
?
Carboniferous rocks, "Epoch of the coal measures"
Archean metamorphic rocks
Permian
Abo Sandstone
Pennsylvanian
Magdalena Group
(Basal part contains rocks now assigned to Mississippian Arroyo Peñasco Group)
Pennsylvanian
Desmoinesian
?
Fossil evidence said to be not adequate
South and southwest
(Removed by Cenozoic erosion in central part of mountains)
?
Cortado Formation
(Near Talpa basal part contains rocks now assigned to Mississippian Arroyo Peñasco Group)
Not named or described
?—fault—?
Osha Formation
(Probably mainly rocks now assigned to Permian and Pennsylvanian [?] Sangre de Cristo Formation. Lower part has some marine rocks)
Cieneguilla Formation
?
(Lithologic base of Cieneguilla Formation not specified. The Cieneguilla Formation can be distinguished from the Cortado Formation mainly by slight but distinct differences in their brachiopod faunas, according to Young, p. 71–72)
Osha Formation
(Lies on Precambrian rocks. Said by Young to be the nonmarine equivalent of Osha and Cieneguilla Formations at the south)
?
(In this vicinity, the Osha Formation probably consists of rocks now assigned by Clark and Read, 1972, to the Triassic Dockum Group and to a relatively thin section of the Permian and Pennsylvanian [?] Sangre de Cristo Formation)
Permian
Pennsylvanian
Pre(?)-Pennsylvanian
South
North
Sangre de Cristo Formation
(At the south, lies on Precambrian rocks)
?
arkosic limestone member
lower gray limestone member
upper clastic member
lower limestone member
Madera Limestone
Sandia Formation
Magdalena Group
Permian(?)
Pennsylvanian
Virgilian
Missourian
Desmoinesian
"Derry"
Mississippian(?)
South
North
Sangre de Cristo Formation
Magdalena Group
Madera Limestone
arkosic limestone mbr.
gray limestone mbr.
Major interval of arkose and arkosic limestone
Major interval of dark shale, limestone, and sandstone
Sandia Formation
Major interval of sandstone and shale
Limestone and sandstone
Previously tentatively classified as lower limestone member of Sandia Formation by Read et al., 1944
Precambrian rocks
MATCH LINE

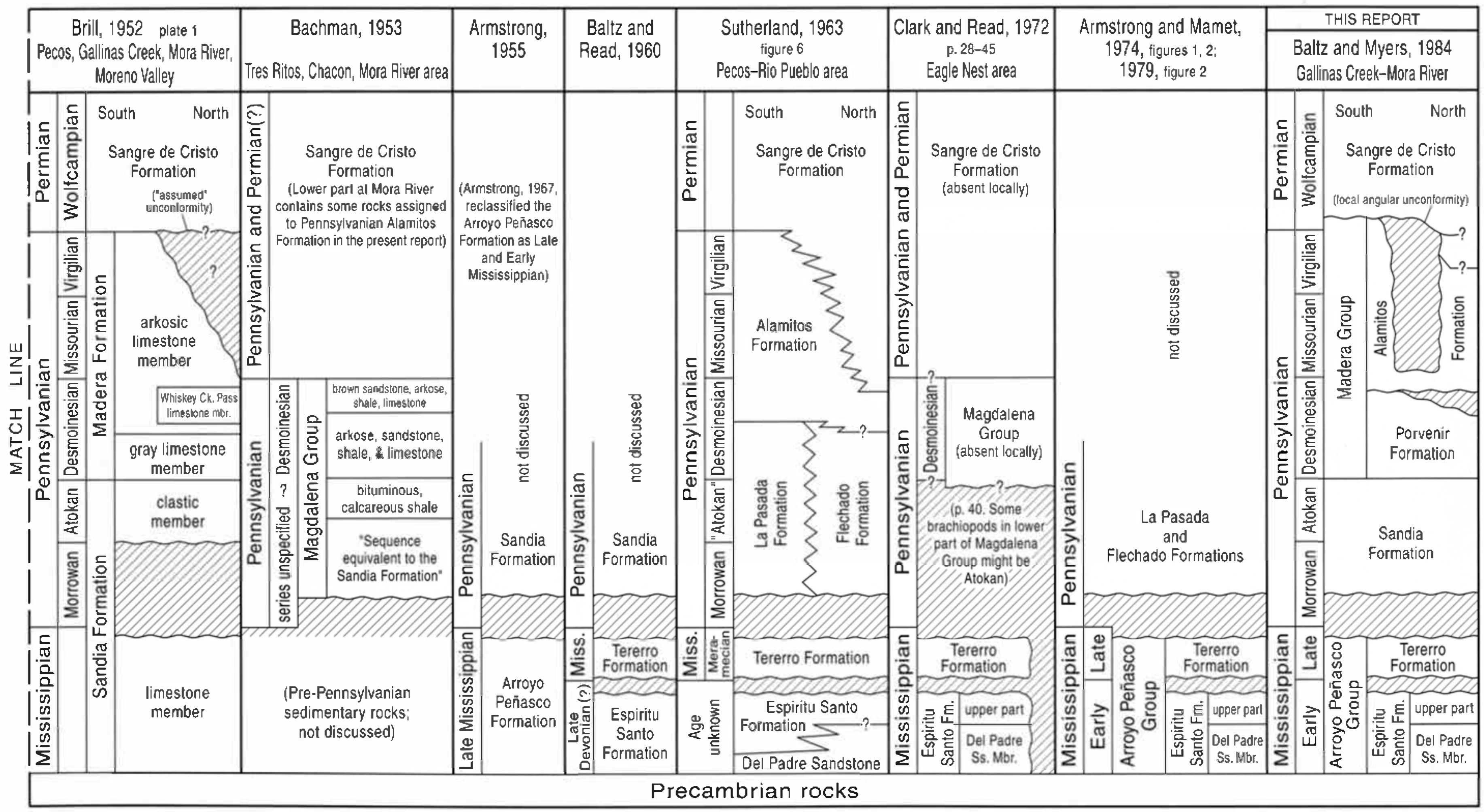


FIGURE 2—Summary of history of nomenclature and age assignments of Mississippian, Pennsylvanian, and Lower Permian rocks of parts of the Sangre de Cristo Mountains, New Mexico. Statements in parentheses are present writers' annotations.

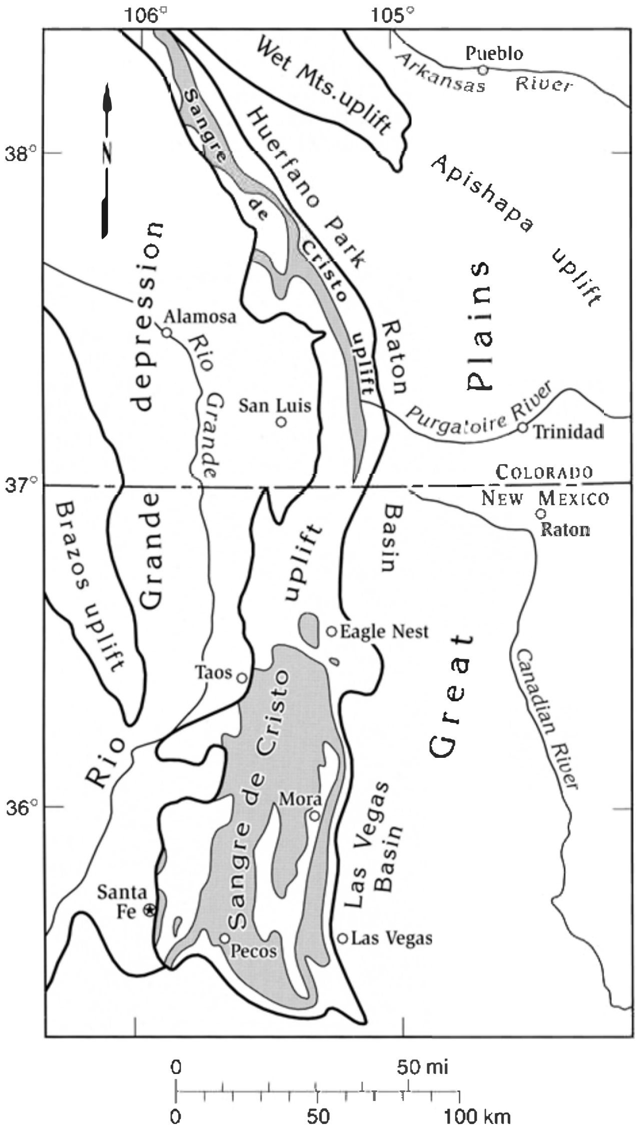


FIGURE 3—Index map of south-central Colorado and north-central New Mexico showing Sangre de Cristo uplift and generalized areas of outcrop (shaded) of Pennsylvanian rocks older than the Sangre de Cristo Formation.

rocks are strongly weathered for several inches or several feet below the surface. At places the surface is underlain by patches of deeply weathered, greenish, nonlaminated, nonsorted, sandy, silty clay that may be remnants of a fossil regolith. Such regolith is thickest in the upper Pecos River area (Baltz and Read, 1960; Sutherland, 1963, p. 24).

In the Rincon Range northwest of Mora, where the surface is cut on Precambrian quartzite, local relief is as much as 60 ft (18 m), as shown by thickening and thinning of the basal sandstone of the Mississippian (Baltz, 1969, fig. 3). Sutherland (1963, p. 24–25) reported that, in the western part of the mountains, the thickness of the basal Mississippian sandstone (the Del Padre Sandstone of his terminology) varies from 0–754 ft (0–230 m) where it lies on the predominantly quartzite rocks of the Early Proterozoic Ortega Quartzite of Montgomery (1963). However, Armstrong (1967, p. 9) suggested that sandstone assigned to the Del Padre by Sutherland (1963, p. 25) at the Rio Chiquito locality of maximum thickness (754 ft) may be partly or wholly of Pennsylvanian age. At Rio Pueblo west of Tres Ritos, part of the 64 ft (20 m) of rocks assigned to the Del Padre by Sutherland (1963, p. 25) are below a well-exposed channeled unconformity (Baltz and Read, 1960, fig. 8, p. 1758) and are quartzite and schist of Precambrian age. However, there is no question that pre-Mississippian relief of a few tens to possibly 100 ft (30 m) existed at other places on low hills and shallow valleys in the Precambrian quartzite terranes, as Sutherland (1963) reported. Nevertheless, in regional perspective, the pre-Mississippian erosion surface seems to have been remarkably flat, not only in the Sangre de Cristo Mountains, but also in the Nacimiento, Sandia, and Manzano Mountains of north-central New Mexico. This surface bevels a wide variety of Precambrian rock types and large structural features. (See Armstrong et al., 1979, figs. 3–4.)

The pre-Mississippian erosion surface may be primarily an exhumed late Precambrian feature, or it may be a compound surface that was modified in early Paleozoic time. Baltz and Read (1960, p. 1768) and Craig and Varnes (1979, p. 375) suggested that the area of part of north-central and northeastern New Mexico was part of the southwest-trending Transcontinental arch (the "continental backbone" described by King, 1951, p. 30). This arch might have been uplifted in Late Devonian time and older sedimentary rocks, if present, were removed by erosion from axial regions. In the subsurface of northeasternmost New Mexico and southeastern Colorado thick Ordovician carbonate rocks and the overlying Mississippian carbonate rocks all thin northeastward toward the late Paleozoic Sierra Grande and Apishapa uplifts in a manner suggesting they have a pre-Pennsylvanian history as a slightly positive area (Maher and Collins, 1949; Foster et al., 1972; Roberts et al., 1976; Mapel et al., 1979). In the northern part of the Sangre de Cristo Mountains in Colorado, carbonate and some thin clastic rocks of Ordovician age lap southward across Cambrian rocks, and the younger part of the Ordovician laps farther south than the older part (Ross and Tweto, 1980, p. 54). These rocks and overlying Devonian and Mississippian carbonates and thin clastics all wedge out southward beneath a pre-Pennsylvanian unconformity. In the San Juan Mountains in Colorado and in the subsurface of the San Juan Basin in northwestern New Mexico, carbonate and some thin clastic rocks of Cambrian(?) and Devonian ages underlie the Mississippian but wedge out southeastward onto the positive area (Loleit, 1963; Parker and Roberts, 1963).

In the mountain ranges of southern New Mexico and in the subsurface of the southeastern part of the State, sedimentary rocks of Cambrian, Ordovician, Silurian, and Devonian ages wedge out gently northward beneath Mississippian rocks. However, the wedgeout is not a simple offlap relation because (1) all the formations thin northward depositionally; (2) there are inter- and intraformational unconformities; and (3) the Devonian erosionally overlaps all older rocks (Kottlowski, 1963a, 1975, fig. 2) and, in turn is overlapped regionally northward by the Mississippian. These relations also suggest that the central and northern New Mexico region had a long history as a positive area but it probably was not a major source of terrigenous clastics because the Mississippian and older Paleozoic rocks in southern New Mexico are predominantly carbonates.

The cutting of the pre-Mississippian surface of north-central New Mexico and south-central Colorado required the erosional destruction of entire mountain ranges of highly deformed Precambrian rocks. If a major part of this erosion occurred in early and middle Paleozoic time the debris would likely be preserved in Paleozoic sedimentary rocks on the flanks of the positive area. Such debris is not known to exist, although some thin units of Paleozoic sandstone and shale might have been derived from this area or from multiple sources. Therefore, it seems probable that the pre-Mississippian erosional surface was formed mainly in late Precambrian time and that the surface was modified, but not extensively, by episodes of weathering and slight erosion of the broad positive area in Paleozoic time before the Mississippian rocks were deposited.

Late Paleozoic basins and uplifts

In Colorado the Pennsylvanian and Lower Permian rocks of the Sangre de Cristo Mountains were deposited in a narrow zeugogeosyncline (Brill, 1952) that was part of the late Paleozoic Central Colorado Basin (Mallory, 1975, fig. 62). This basin occupied the area of the present Sangre de Cristo uplift and the western parts of the Laramide Huerfano Park and Raton Basins of Colorado and northern New Mexico (Fig. 3). The Pennsylvanian rocks of the uplift are reported to be more than 5,500 ft (1,675 m) thick by Bolyard (1959, p. 1904) and are locally of Morrowan, Atokan, and Desmoinesian age. The Upper Pennsylvanian and Lower Permian Sangre de Cristo Formation is about 5,700 ft (1,740 m) thick in Colorado at its principal reference section described by Lindsey and Schafer (1984). The total upper Paleozoic section in the northern part of the mountains in Colorado may be locally as much as 13,000 ft (4,000 m) thick (Lindsey et al., 1986, p. 542). The Central Colorado Basin was bounded at the west by the late Paleozoic (and early Mesozoic) Uncompahgre uplift of Colorado. The eastern part of this uplift foundered and is buried in the Neogene San Luis Basin of the Rio Grande depression (Baltz, 1965, 1978; Tweto, 1975, 1979b); therefore, the Paleozoic eastern margins of the uplift are uncertain. Lindsey et al. (1986) presented evidence that some Precambrian rocks in the western part of the northern Sangre de Cristo Mountains are easternmost parts of the Uncompahgre uplift that were transported eastward tectonically in Laramide thrust plates. At the east, the Central Colorado Basin was bounded by the ancestral Wet Mountains–Apishapa uplift (Bolyard, 1959; Johnson, 1959).

In New Mexico, the Pennsylvanian and Lower Permian rocks were deposited in a broader basin (Fig. 4) which was separated from the Central Colorado Basin by the northwest-trending Cimarron arch (Baltz, 1965, p. 2049). On this arch thin sequences of the Upper Pennsylvanian and Lower Permian Sangre de Cristo Formation and, locally, Upper Triassic rocks lie on the Precambrian in the southern Cimarron Mountains south and southeast of Eagle Nest (Wanek et al., 1964; Clark and Read, 1972; Goodknight, 1976).

About 5 mi (8 km) northwest of Eagle Nest, the Sangre de Cristo Formation lies on Precambrian rocks at small outcrops (Wanek and Read, 1956, p. 93), as it does at several places southwest of Eagle Nest (Clark and Read, 1972, plate 1), suggesting a northwesterly trending extension of the Cimarron arch. Farther northwest, in the main part of the Sangre de Cristo uplift in New Mexico, Paleozoic and Mesozoic rocks are absent except for a few small patches of the Sangre de Cristo Formation (McKinlay, 1956), and the Precambrian rocks of this area probably are a Laramide-deformed part of the Paleozoic San Luis(?) uplift, which may have continued northwest into the Uncompahgre uplift of Colorado. Evidence for, and speculations about, the postulated paleogeographic conditions are presented in the last section of this report.

South of these uplifts the western part of the basin, the Taos trough of Sutherland (1963, fig. 17), occupied the area of most of the Sangre de Cristo Mountains. The eastern part of the basin, the Rainsville trough of this report, is in the subsurface and is generally coincident with the Laramide Las Vegas Basin. At the east, in the subsurface, the basin is bounded by the ancestral Sierra Grande uplift. Data from widely spaced wells indicate that Pennsylvanian rocks are absent generally from this uplift and that the Sangre de Cristo Formation, locally only a little more than 100 ft (30 m) thick, rests on the Precambrian and is absent from some areas (Foster et al., 1972; Roberts et al., 1976). However, the wells are so widely spaced that they do not preclude that Pennsylvanian rocks are present in downwarped or downfaulted blocks at places on the uplift.

At the west the Taos trough was bounded mainly by the northwest-trending ancestral Brazos uplift whose southeastern part included Cenozoic-uplifted Precambrian rocks of the western part of the Sangre de Cristo uplift south of Taos. In the literature these rocks usually are considered to be a south-trending prong of the Uncompahgre uplift of Colorado. However, gravity and other data, discussed in the last section of this report, suggest that the Taos trough extended northwest into the area of the Neogene San Luis Basin near Taos and may have separated at least the southeastern part of the Brazos uplift from Paleozoic uplifts farther north. To the southwest the Pecos shelf was bounded by the structurally lower Cañoncito uplift southeast of Santa Fe where Pennsylvanian rocks are only about 300 ft (90 m) thick and the Sangre de Cristo Formation also is about 300 ft thick (Read and Wood, 1947; Booth, 1976). The northerly trending Cenozoic Deer Creek and Pecos–Picuris faults probably were active in the late Paleozoic and, at times, were the eastern boundaries of the Cañoncito and Brazos uplifts.

Pennsylvanian rocks of the Taos trough now are bounded partly by Cenozoic-uplifted Precambrian rocks in the El Oro Mountains and Rincon Range at the east side of the Sangre de Cristo uplift near Mora (Plate 2). As will be discussed later, the ancestor of the El Oro–Rincon uplift (Fig. 4) of this report probably was also a northerly plunging, late Paleozoic, sediment-shedding uplift. The deep part of the Paleozoic basin in the subsurface east of this uplift is here called the Rainsville trough. Pennsylvanian (Morrowan through Missourian) rocks of the western part of the Rainsville trough are as much as 7,300 ft (2,225 m) thick, and the Upper Pennsylvanian and Lower Permian Sangre de Cristo Formation is as much as 3,000 ft (915 m) thick (Plate 3). Morrowan through Desmoinesian rocks (Sutherland, 1963) of the Taos trough are as much as 6,000 ft (1,800 m) thick. Younger Paleozoic rocks are not present in the Taos trough, presumably because of Cenozoic erosion.

In the south-central part of the Sangre de Cristo Mountains Lower and Middle Pennsylvanian rocks thin rapidly south from the Taos trough onto the Pecos shelf (Sutherland, 1963). On the southern part of the shelf south of Pecos, Morrowan through Virgilian rocks are about 2,200 ft (670 m) thick and the Sangre de Cristo Formation is 500 to locally 3,000 ft (150–915 m) thick. The Pecos shelf merges southward into the late Paleozoic San Jose Basin between the late Paleozoic Pedernal and Sierra Grande uplifts. The San Jose Basin forms a structural saddle between the shelf and the deep late Paleozoic Cuervo–Tucumcari Basin at the southeast.

In the southeastern part of the Sangre de Cristo Mountains, Pennsylvanian and Lower Permian rocks thin rapidly southward from the Taos trough onto the eastern part of the Pecos shelf that is marked by northwesterly trending late Paleozoic intrabasinal uplifts and complementary structural and depositional basins of the mapped (Plate 1) area of this report.

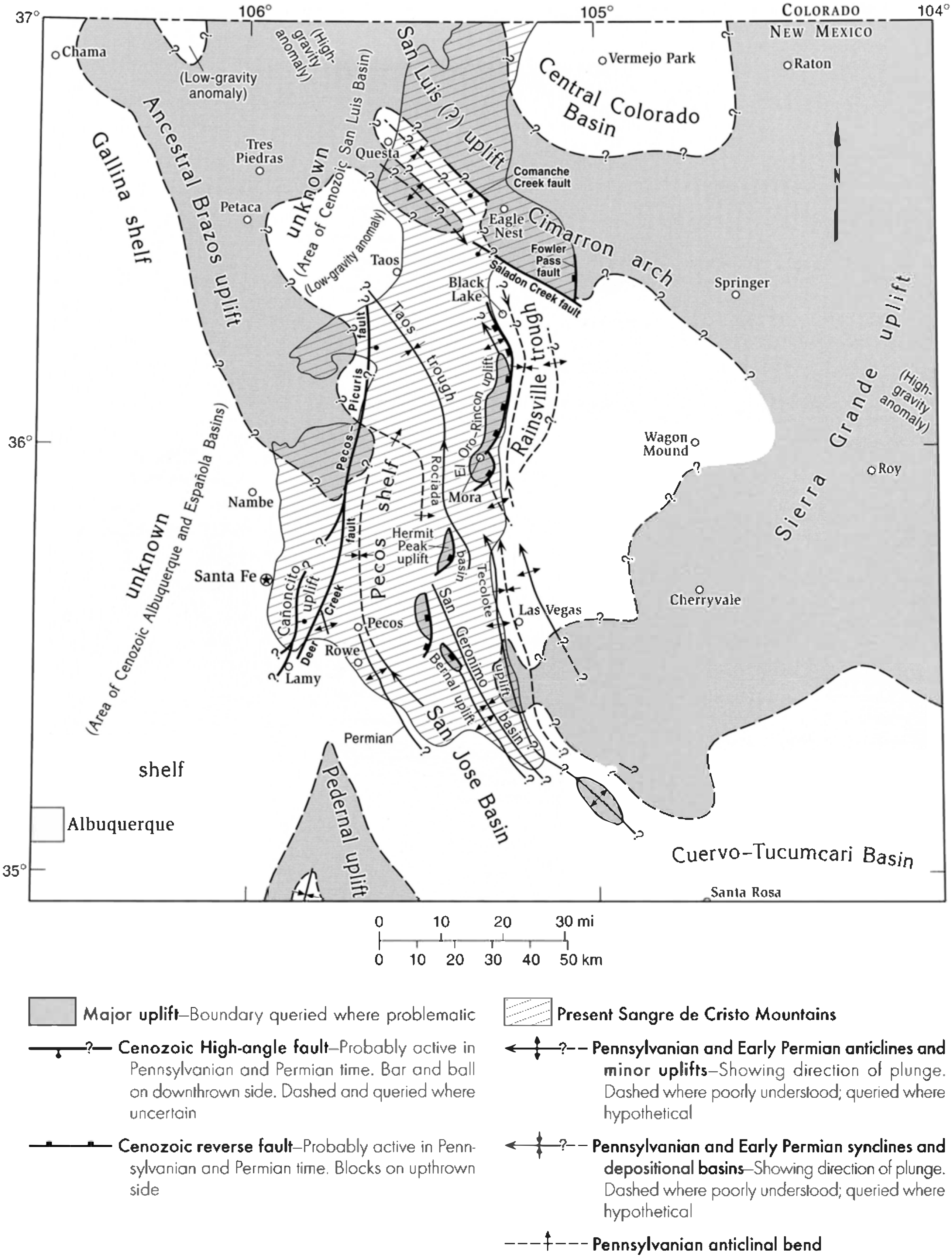


FIGURE 4—Generalized uplifts and sedimentary basins of Pennsylvanian and Early Permian time in north-central New Mexico.

Summary of Precambrian basement rocks in the southeastern Sangre de Cristo Mountains

Precambrian basement rocks are exposed widely in the southeastern part of the mountains but, in this region, they have been lithologically differentiated and mapped only in the northwest part of the area of Plate 1. Figure 5 is a generalized map of these rocks. A brief discussion of the Precambrian rocks is appropriate because of later discussions of some of these rocks as probable local sources of late Paleozoic clastic sediments.

Montgomery (1963) did the first regional reconnaissance mapping and description of Precambrian rocks of much of the southern part of the Sangre de Cristo Mountains, including the area west of 105°30' of Figure 5. He assigned predominantly metasedimentary rocks, including very thick quartzites, to his Ortega Formation, and he assigned mixed metavolcanic-metasedimentary rocks to the Vadito Formation, which he believed to overlie the Ortega. In the area of Figure 5, north of the latitude of Gascon, Montgomery (1963, plate 1) assigned metasedimentary rocks to the lower quartzite member and Rinconada Schist Member of the Ortega Formation; he assigned mixed metavolcanic-metasedimentary rocks farther south to the conglomerate and schist members of the Vadito Formation. According to Montgomery (1963, p. 9), the composite thickness of the metamorphic rocks exposed in the western part of the Sangre de Cristo Mountains may have been originally about 20,800 ft (6,340 m). The metamorphic rocks were folded sharply and were intruded by synkinematic and postkinematic igneous rocks ranging from ultramafic to granitic. Plutonic granite, granodiorite, and quartz-monzonite rocks of the region were called, collectively, the Embudo Granite by Montgomery (1953, 1963).

Parts of Montgomery's (1963) map area were remapped by Moench and Robertson (1980) in a reconnaissance of the Pecos Wilderness and some adjacent areas in the Sangre de Cristo Mountains. They did not adopt a stratigraphic terminology for Precambrian rocks, but classified them by lithologic types. Generally, the Vadito Formation of Montgomery was included in the Pecos greenstone belt of Robertson and Moench (1979) and Moench and Robertson (1980). They included Montgomery's Ortega Formation in their quartzite terrane that lies north of the Pecos greenstone belt.

Grambling and Codding (1982) mapped details of the Precambrian rocks of the upper Pecos River–Rio Valdez–Rio Mora area in the northwest corner of the area of Figure 5. They used Montgomery's terminology, slightly revised, but cast doubt on some structural and stratigraphic interpretations of Montgomery (1963) and Moench and Robertson (1980), concluding that the Ortega is younger than the Vadito. The Precambrian rocks from about Mora southeast to near Rociada (Fig. 5) were mapped as generalized lithologic units without stratigraphic terminology by Budding and Cepeda (1979) who discussed their metamorphic petrology and their structure in the El Oro anticline, which they called the El Oro gneiss dome.

The absolute ages of the Precambrian metamorphic rocks of the southern Sangre de Cristo Mountains are not well known because of the paucity of radiometric dates. According to Robertson and Moench (1979, p. 172), rocks included by them in the Pecos greenstone belt are probably 1,700–1,800 m.y. old, and, therefore, Early Proterozoic. Rubidium–strontium dates of quartz-monzonite plutons in the western part of the mountains range from 1,673±41 m.y to about 1,400 m.y. (Long, 1974), with some pegmatites dated as young as about 1,300 m.y. The Embudo Granite of Montgomery in the Picuris Mountains is dated as 1,673±41 m.y (Fullager and Shiver, 1973) by rubidium–strontium. Register and Brookins (1979) concluded that the Embudo Granite on the western margin of the Santa Fe Range to the south has a rubidium–strontium age of 1,465±50 m.y.

Precambrian rocks east of the Cenozoic Harvey thrust fault and Gascon fault (Fig. 5), from Hermit Peak to north of Mora, were mapped in detail and described mainly by J. M. O'Neill (Baltz and O'Neill, 1984, 1986). Because these rocks mainly are separated by Paleozoic rocks from the Precambrian outcrops along the western margin of the area, and because of poorly understood Precambrian structural and stratigraphic relations along and west of the Gascon and Harvey faults, an informal, local stratigraphic classification was used by Baltz and O'Neill. The lithologies, stratigraphy, possible regional correlations, and structure of the Precambrian rocks are discussed in considerable detail by O'Neill (1990).

The quartzofeldspathic gneiss of El Oro Mountains (Baltz and O'Neill, 1984), the oldest rocks in the Hermit Peak–Mora area, are exposed in the core of the Precambrian El Oro anticline. These rocks are layered, but strongly sheared and deformed, units of orange-tan, brown, and gray quartz-feldspar-mica gneiss, migmatitic gneiss, and thin to thick interlayers of gray micaceous quartzite.

The gneisses are overlain (in probable upright position) by the mica schist and amphibolite of Las Quebraditas (Baltz and O'Neill, 1984), which consist, generally, of upper, middle, and lower quartz-muscovite schist units separated by two units of amphibolite and hornblende gneiss. The upper schist contains interlayers of fine-grained metasedimentary quartzite, and the upper amphibolite contains interlayers of semi-translucent, gray to purple, magnetite-bearing quartzite. The mica schist and amphibolite of Las Quebraditas thin northward, and are absent a short distance northwest of Mora.

The stratigraphically uppermost unit, the quartzofeldspathic gneiss of Rociada (Baltz and O'Neill, 1984), is complexly interlayered metasedimentary and metavolcanic rocks. The lower part, north and east of Upper Rociada, consists of micaceous quartzite and quartz-plagioclase gneiss, and local amphibolite, calcsilicate rock, and marble. The upper part, southward to the vicinity of Hermit Peak, and also east and southeast of Mora, is complexly interlayered pinkish-tan and orangish quartzofeldspathic gneiss, felsite, and amphibolite.

From Rociada south to Rito Colorado and the lower parts of Beaver and Hollinger Creeks, the upper part of the quartzofeldspathic gneiss of Rociada is intruded intricately by the metagneous rocks of Sapello River (Baltz and O'Neill, 1986). Gabbro is common as concordant and discordant bodies ranging from thin sills and narrow dikes to bodies as much as 2,500 ft (760 m) wide. At places, just north and south of Sapello River, ultramafic rocks occur as small plugs and as cores of large gabbro bodies. In the same area, the quartzofeldspathic gneisses are intruded also by dikes, sills, and large bodies of tonalite. In places the tonalite grades into gabbro, but in other places appears to be younger than the gabbro. Both the gabbro and tonalite are mainly synkinematic with respect to the major folding of the metamorphic rocks but parts are postkinematic. Gabbro also occurs as small dikes and sills in the older metamorphic rocks north of Sapello.

From Rito Colorado south (Fig. 5), nonfoliated granite, thick granitic pegmatites, and migmatite of granite and quartzofeldspathic rocks of Rociada form much of Hermit Peak. These igneous rocks are postkinematic. Small bodies of similar granite are exposed intruding gabbro and quartzofeldspathic gneiss of Rociada west of Cebolla Pass 1–2 mi (1.6–3.2 km) southwest of Mora. Other small exposures of

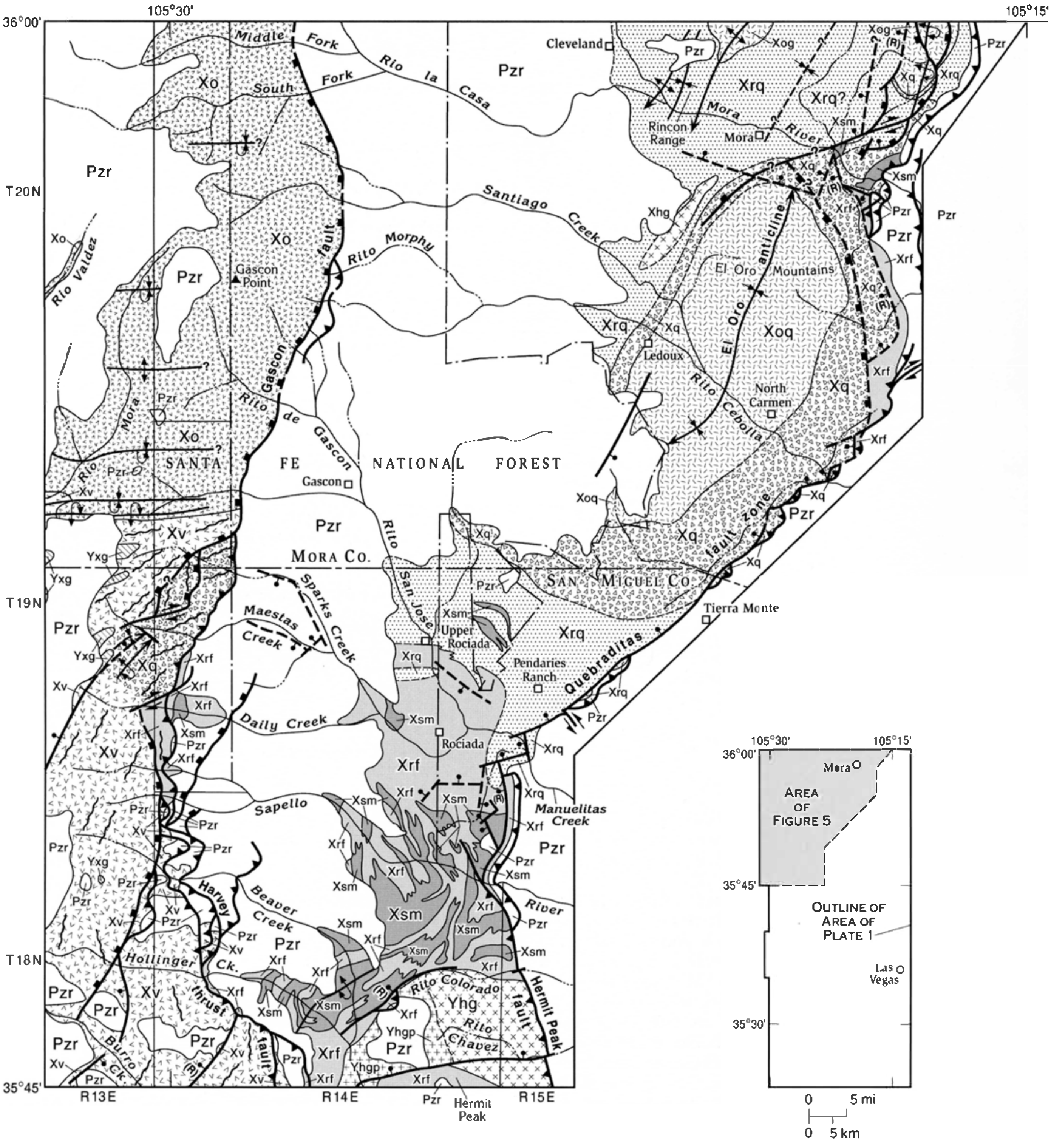


FIGURE 5—Bedrock map of Precambrian rocks in the Hollinger Creek–Rio la Casa–Mora area. Data from Montgomery (1963), Budding and Cepeda (1979), Moench and Robertson (1980), Grambling and Codding (1982), Baltz and O'Neill (1984, 1986), and O'Neill (1990).

DESCRIPTION OF UNITS

Pzr — Upper Paleozoic sedimentary rocks

WEST OF GASCON AND HARVEY FAULTS (Proterozoic)

- Yxg — Embudo Granite of Montgomery (1963)
- Xv — Vadito Formation of Montomery (1963) and included intrusive igneous rocks
- Xo — Ortega Formation of Montomery (1963)

HERMIT PEAK-MORA AREA

Middle and Early Proterozoic

- Yhg — Granite of Hermit Peak
- Yhgp — Pegmatitic granite and migmatite of Hermit Peak

Early Proterozoic

- Xsm — Meta-igneous rocks of Sapello River
- Quartzofeldspathic gneiss of Rociada
  - Xrf—gneiss, felsite, and amphibolite
  - Xrq—gneiss, quartzite, and minor amphibolite
- Xq — Mica schist and amphibolite of Las Quebraditas
- Xog — Quartzofeldspathic gneiss of El Oro Mountains

MAP SYMBOLS

Contacts, faults, anticlines, and synclines are shown by solid lines where accurately located, dashed lines where concealed by Quaternary deposits, and are queried where probable

Proterozoic structures

- **Trend of layering and foliation**—Southwest part of area only
- **Contact**
- **Anticline**—Showing direction of plunge
- **Anticline with overturned limb**
- **Syncline**
- **Syncline with overturned limb**

Cenozoic structures

- **Normal fault**—Bar and ball on downthrown side
- **Normal fault inferred to be superposed on older reverse fault**—Bar and ball on downthrown side of normal fault; (R) on upthrown side of reverse fault
- **High-angle strike-slip fault**—Arrows indicate horizontal movement
- **Reverse fault**—Blocks on upthrown side
- **Thrust fault**—Triangles on upthrown side

granite (the Embudo Granite of Montgomery, 1963) occur in the westernmost part of the area (Montgomery, 1963; Moench and Robertson, 1980) and the upper part of Gallinas Creek (Baltz, 1972).

Pegmatite dikes (partly mapped by Baltz and O'Neill, 1984, 1986) are common and locally abundant in much of the area. Postkinematic pink alaskite is probably related to the granites, although some synkinematic light-gray to light-tan pegmatites, particularly just east of Mora, probably are related to gabbros and, at some places, to tonalites. Very thick and lengthy alaskite pegmatites are commonly associated with the mica schist and amphibolite of Las Quebraditas, especially on the east flank of the El Oro anticline from Mora south almost to the San Miguel County line (Baltz and O'Neill, 1984). Thick, pink, alaskite pegmatites are common also in the quartzofeldspathic gneiss of El Oro Mountains.

The stratigraphic relations of the rocks mapped by Baltz and O'Neill to those mapped by Montgomery (1963) are not well known. The mica schist and amphibolite of Las Quebraditas in the upper parts of Maestas and Sparks Creeks, are parts of the rocks mapped as the Vadito Formation by Montgomery. Probably, the southern terrane of the quartzofeldspathic gneiss of Rociada also is equivalent to rocks mapped in the Vadito by Montgomery (1963) and in the Pecos greenstone belt by Robertson and Moench (1979).

North of Mora, at the east side of the Rincon Range (Plate 2) outside the area of Figure 5, quartzofeldspathic gneisses and thick, highly micaceous quartzites occur as northerly oriented east-verging Precambrian anticlines. Pegmatites, and some amphibolite, also are present there. We do not know the relationship of these rocks to those of areas at the south, except at the south end of the Rincon Range at Mora (Fig. 5).

Practically nothing has been published about the Precambrian rocks south of the area of Figure 5, and we have only general observations of these rocks. In the western part of the area from Gallinas Creek south (Plate 1), interlayered amphibolite, quartzofeldspathic gneiss, felsite, and some quartzite are strongly deformed and commonly have been migmatized by mainly granitic pegmatites. Small granite stocks occur. In the eastern part of the mountains, from Montezuma north to Cañon Bonito, similar migmatized rocks and granite gneisses are exposed on what is possibly a Precambrian dome. West and southwest of Aqua Zarca, similar amphibolite and gneiss are exposed, and include thick brown quartzite. These rocks are intruded by pink pegmatitic granite. At the small inlier on the Ojitos Frios anticline south of Ojitos Frios, brown quartzite is exposed.

In a general way, the structure of Precambrian rocks seems to have influenced subsequent structural development of the southeastern part of the mountains. From about

Sapello River south the exposed Precambrian metamorphic rocks generally have been welded into strong, structural units by tight folding, migmatization, and the intrusion of plutons that are mainly granitic, but also are gabbros and tonalite. North of Sapello River the Precambrian metamorphic rocks are in large, more open folds and, at least at the present depth of exposure, they contain only scattered, relatively small bodies of plutonic rocks. The Cenozoic structural relief increases generally northward, and the major Cenozoic structural trends change, more or less in the vicinity of the area of change in Precambrian structure. (See Plate 1.)

In Pennsylvanian and Early Permian time, the southern terrane of "welded" Precambrian rocks was the site of relatively shallow shelf deposition and intrabasinal uplifts and intervening local basins, whereas the northern terrane of more open Precambrian folds was the site of deeper basins and different facies of Pennsylvanian rocks. The large Cenozoic-uplifted block of migmatites and granite in the southwestern part of the area (Plate 1) was also a Pennsylvanian–Early Permian uplift as was the general area of the Cenozoic Creston anticline and La Sierrita dome in the southeastern part of the area. The area of coarse-grained granite of the eastern part of Hermit Peak was probably a Late Pennsylvanian–Early Permian uplift. The eastern parts of the Precambrian El Oro anticline and the northerly trending folds of Precambrian gneiss and quartzite in the Rincon Range probably were the sites of a Middle and Late Pennsylvanian and Early Permian uplift as well as being a major Cenozoic-uplifted block. Evidence of these paleotectonic relations is presented in later sections of the report.

Mississippian rocks

Arroyo Peñasco Group

The term Arroyo Peñasco Formation was applied by Armstrong (1955) to rocks in the Sangre de Cristo Mountains that had been called the lower limestone member of the Sandia Formation by Read et al. (1944) and Northrop et al. (1946). The name Arroyo Peñasco was derived from the type locality in the Jemez Mountains region of northwestern New Mexico (Armstrong, 1955; Fitzsimmons, Armstrong, and Gordon, 1956).

Baltz and Read (1960) subdivided Armstrong's (1955) Arroyo Peñasco Formation of the Sangre de Cristo Mountains into two new formations, the Espiritu Santo Formation and the overlying Tererro Formation. Sutherland (1963) recognized the Espiritu Santo and Tererro Formations in the western part of the mountains, but he separated the basal sandstone from the Espiritu Santo and named it the Del Padre Sandstone.

Armstrong and Mamet (1974) accepted the Espiritu Santo and Tererro Formations, raised the term Arroyo Peñasco to group status to include both formations, and redefined the Del Padre Sandstone of Sutherland (1963) as the Del Padre Sandstone Member of the Espiritu Santo Formation. The overlying carbonate rocks of the Espiritu Santo are not named. This revised terminology now is applied to the Mississippian rocks of the southeastern Sangre de Cristo Mountains (Baltz and Myers, 1984). A graphic summary of the nomenclature changes is shown in Figure 2 of the present report.

Outcrops of the undivided Arroyo Peñasco Group in the southeastern part of the mountains are shown on Plate 1. Localities of measurement, thicknesses, and the lines of correlated sections of the Espiritu Santo and Tererro Formations are shown in Figure 6. The graphic sections are shown in Figures 7 and 8, and an explanation of lithologic symbols used in the sections is shown in Figure 9. Several sections are described at the end of the report.

The Espiritu Santo and Tererro Formations both are recognizable in cuttings from wells in the Las Vegas Basin east and northeast of Las Vegas (Fig. 18), and the Arroyo Peñasco Group, probably including both formations, is present at the Amoco Production Co. no. 1 Salman Ranch "A" and "B" wells (Plate 3) east and northeast of Mora. The Arroyo Peñasco probably is present farther north at the Continental no. 1 Mares–Duran well (sec. 14 T23N R17E). In the northwestern part of the Las Vegas Basin the Arroyo Peñasco Group is present at the True Oil Company no. 34 Arguello well (sec. 24 T23N R17E), but the group probably is absent at the True Oil Company no. 21–25 Medina well (sec. 25 T24N R16E). (See Fig. 72, page 150, for location of wells.)

Espiritu Santo Formation

Definition

The name Espiritu Santo Formation was applied by Baltz and Read (1960, p. 1752) to the sandstone, sandy limestone, calcarenite, and dolomitic limestone that overlie Precambrian rocks near the confluence of Holy Ghost Creek (formerly called Espiritu Santo Creek) and Pecos River at Tererro Post Office in the west-central part of the Sangre de Cristo Mountains north of Pecos. At its type locality the Espiritu Santo is about 30 ft (9 m) thick and is overlain unconformably by limestone breccia assigned to the Macho Member of the Tererro Formation.

At the type locality the basal part of the Espiritu Santo Formation, the Del Padre Sandstone Member, is fine- to coarse-grained sandstone about 11 ft (3.4 m) thick. The Del Padre Member is overlain by medium- to dark-gray limestone and ferruginous, dolomitic limestone that contain minor amounts of sandstone and sandy limestone. The carbonate beds contain some thin layers of black chert and scattered nodules of concentrically banded chert. The highest part of the formation at the type locality is a calcarenite that contains limestone pebbles and cobbles, quartz sand, and chert fragments. Parts of all the carbonate rocks are conspicuously recrystallized. The entire carbonate part of the Espiritu Santo Formation is about 19 ft (5.8 m) thick at the type locality. The Espiritu Santo Formation in the southeastern part of the mountains is lithologically similar to, but generally slightly thinner than, the formation along the Pecos River.

Distribution and thickness

In the southeastern part of the Sangre de Cristo Mountains, the Espiritu Santo Formation is distributed widely, but is absent locally because of (1) erosion prior to or during deposition of the Tererro Formation; (2) erosion of the entire Arroyo Peñasco Group in Late Mississippian and Early Pennsylvanian time; and (3) erosion of the Arroyo Peñasco and Pennsylvanian rocks in Late Pennsylvanian and Early Permian time (Fig. 6).

In the southern part of the area, near the eastern front of the mountains about 1.6 mi (2.6 km) northeast of Tecolote Peak (Plate 1), Pennsylvanian rocks overlap the entire Arroyo Peñasco to lie on Precambrian rocks. On the Ojitos Frios anticline south of Ojitos Frios, the Espiritu Santo is

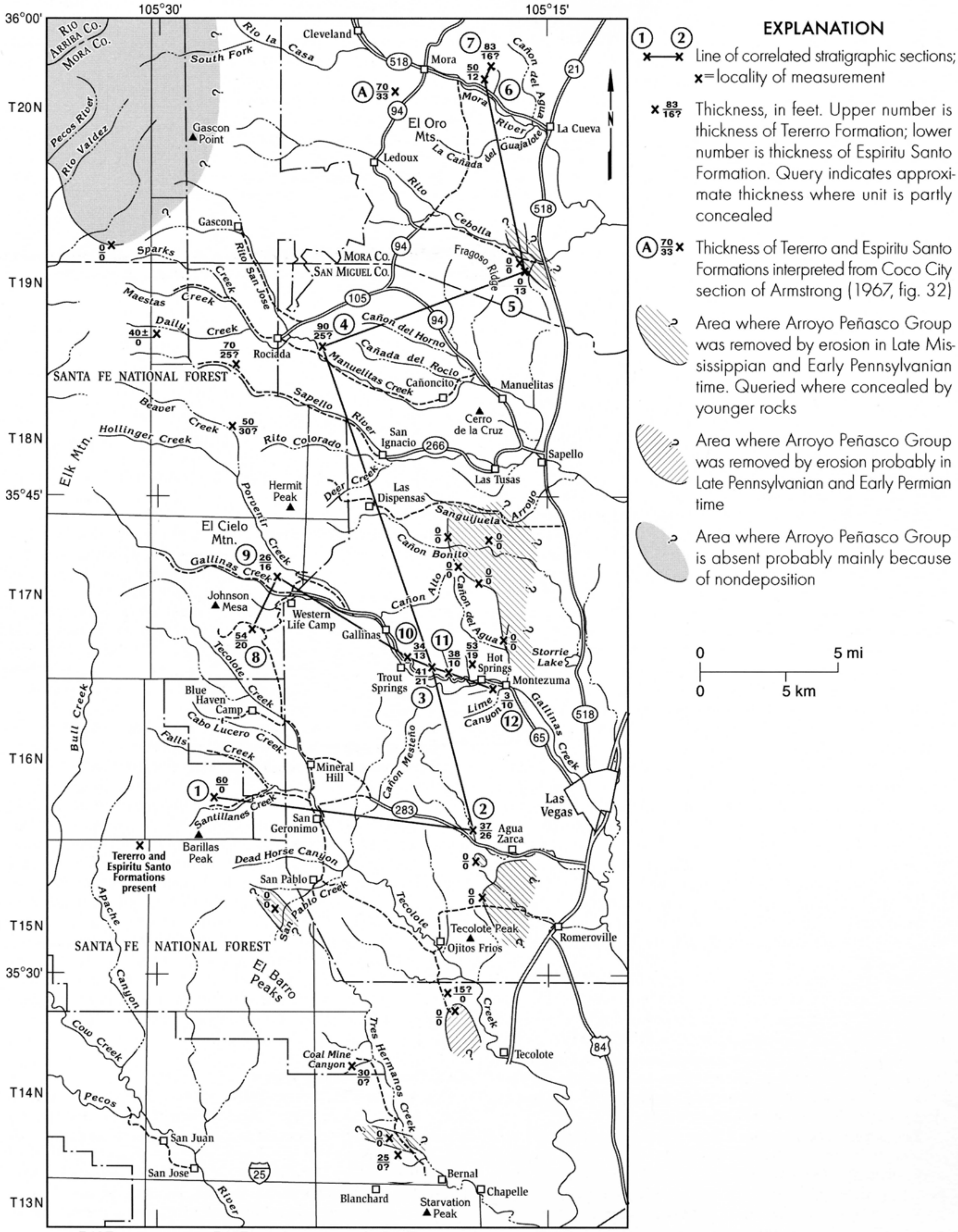


FIGURE 6—Index map of southeastern Sangre de Cristo Mountains showing localities of stratigraphic sections and local thicknesses of the Arroyo Peñasco Group. Area extends slightly west of area of Plate 1.

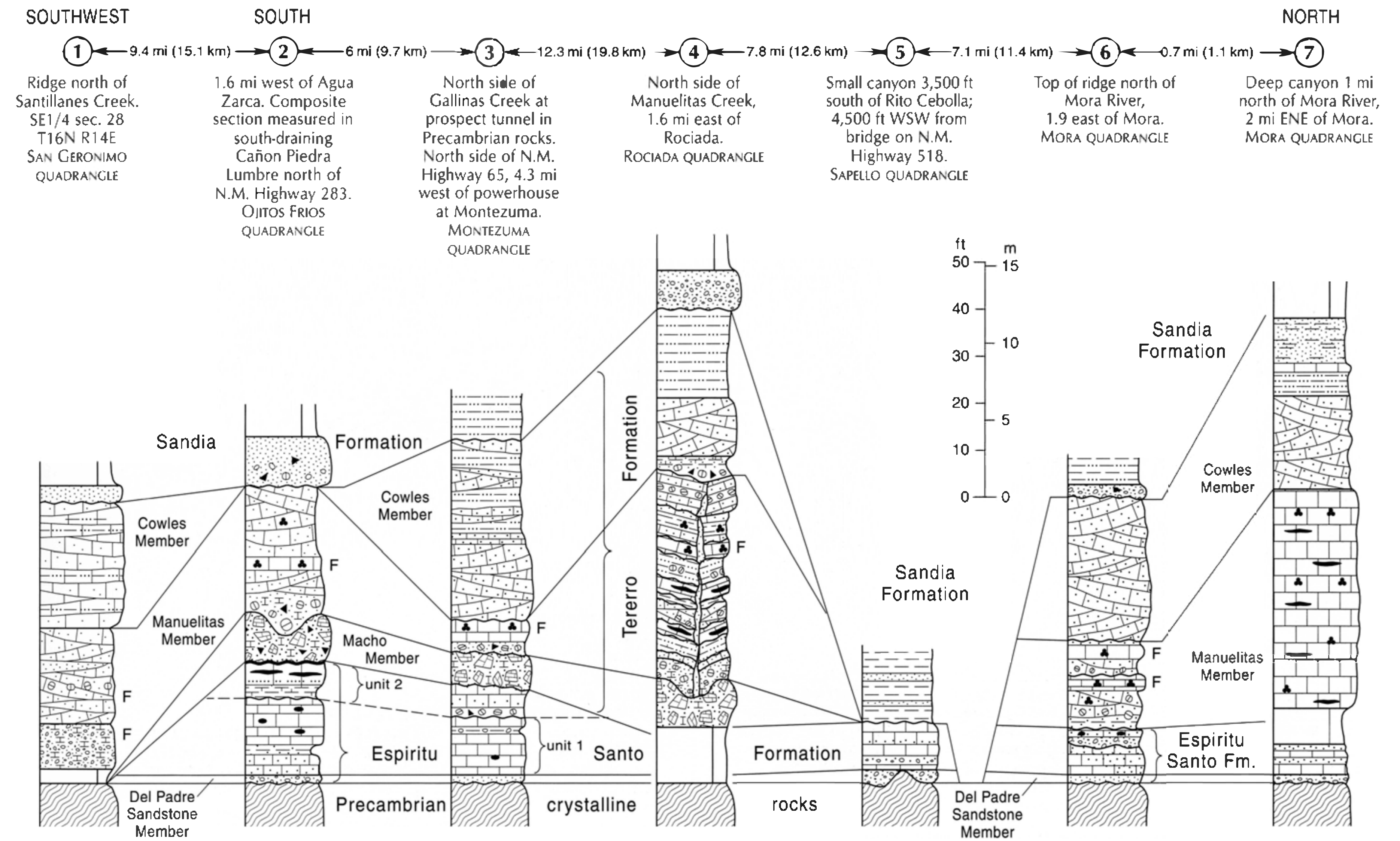


FIGURE 7—Stratigraphic sections of the Tererro and Espiritu Santo Formations of the Arroyo Peñasco Group, Santillanes Creek to Mora River. Localities and line of correlated sections are shown in Figure 6. Lithologic symbols are explained in Figure 9. Locations of USGS topographic quadrangles shown on Plate 1.

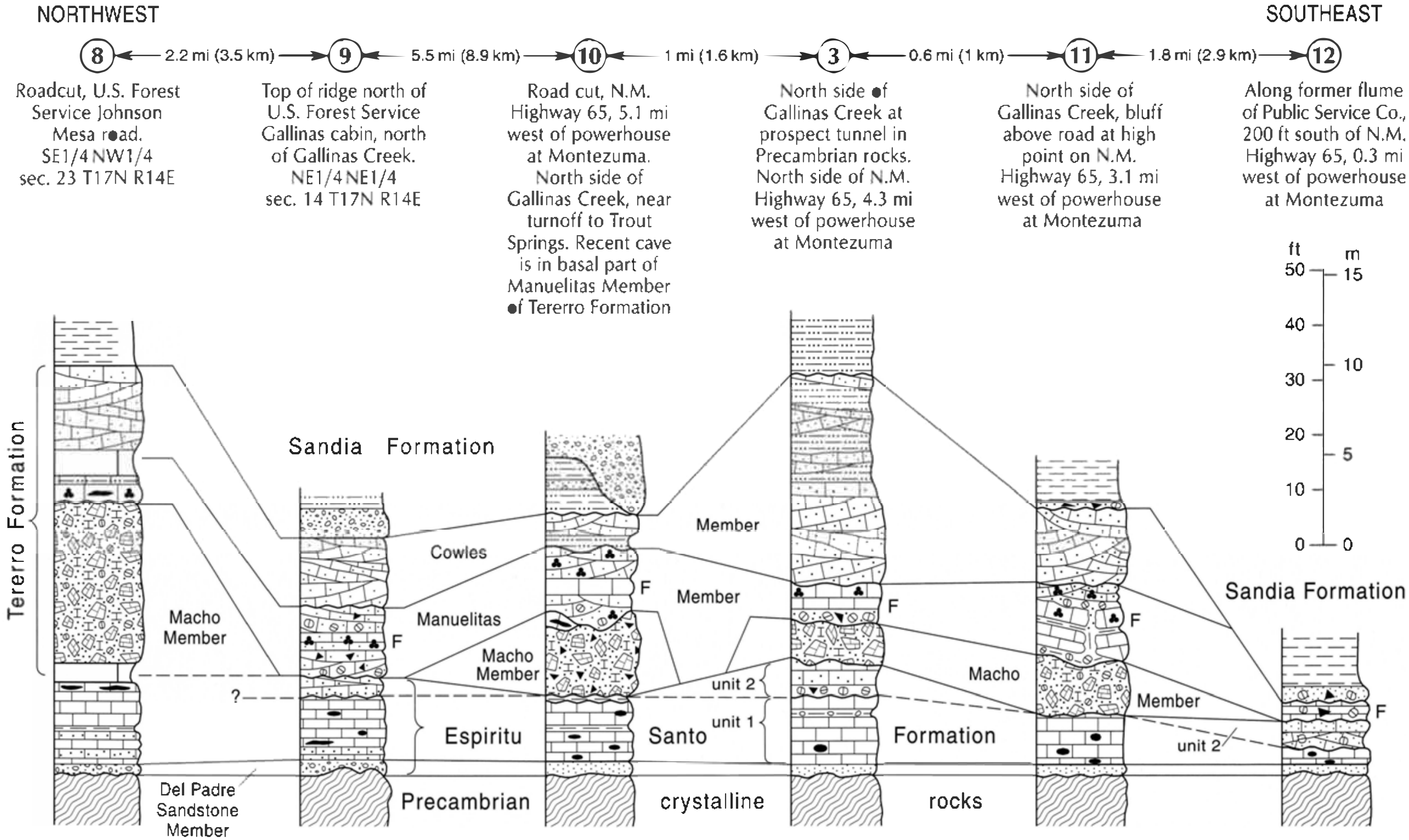


FIGURE 8—Stratigraphic sections of the Tererro and Espiritu Santo Formations of the Arroyo Peñasco Group, Gallinas Creek area. Localities and line of sections are shown on Figure 6. Lithologic symbols are explained in Figure 9. Localities 8 and 9 are in El Porvenir quadrangle; localities 10–12 are in Montezuma quadrangle. Locations of USGS topographic quadrangles are shown on Plate 1.

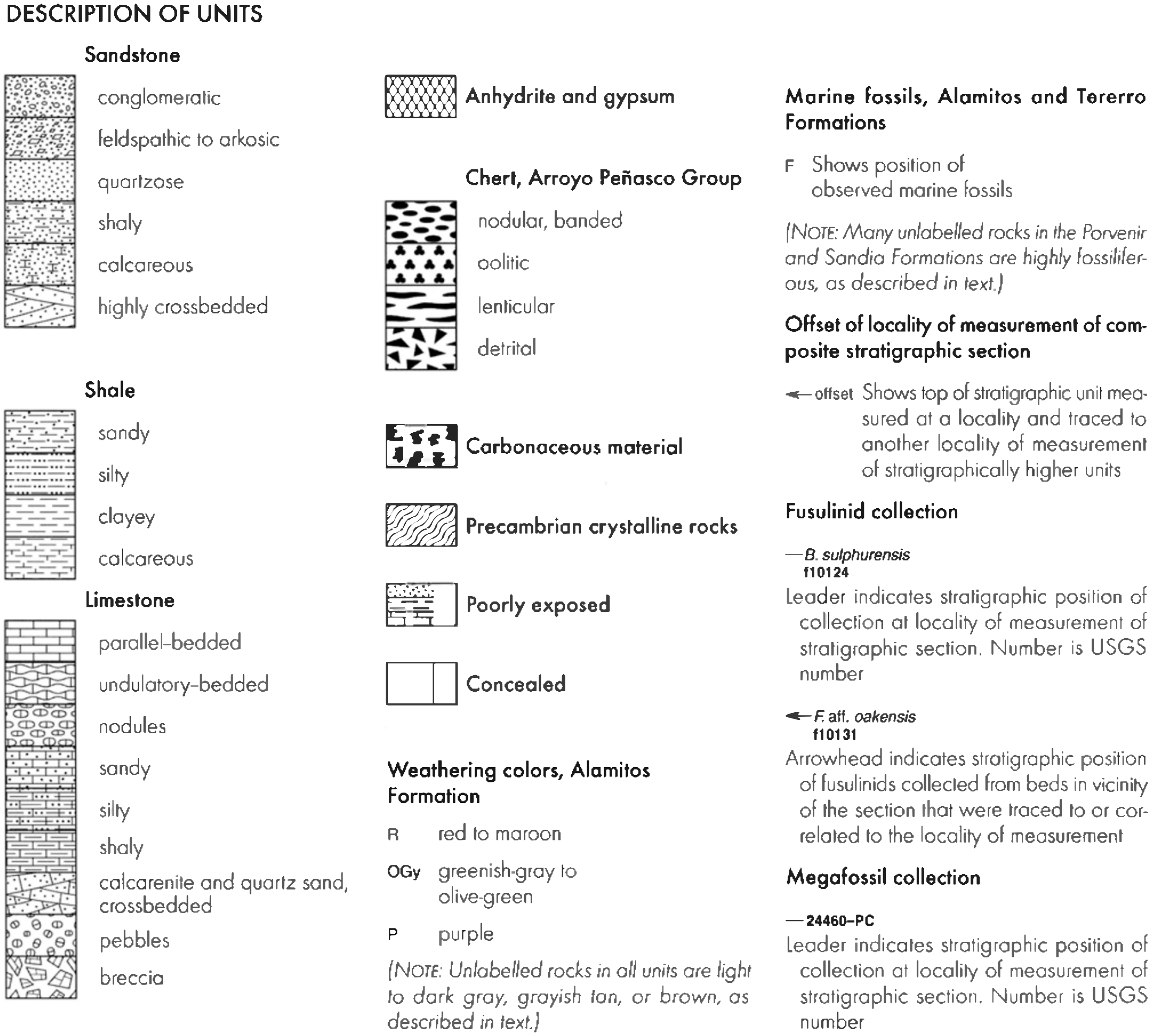


FIGURE 9—Explanation of lithologic symbols used in graphic sections of Mississippian, Pennsylvanian, and Permian rocks.

absent and the Tererro Formation lies unconformably on the Precambrian. West of Tres Hermanos Creek, along the east side of the Bernal fault, the Espiritu Santo is absent, or is so thin as not to be recognized, and the Tererro probably lies on the Precambrian where this part of the section was observed. (See Fig. 20, locs. 1, A, and 2, later in the report.) To the north, at outcrops east of El Barro fault, the entire Arroyo Peñasco Group is absent at San Pablo Creek and Pennsylvanian rocks lie on the Precambrian. At Santillanes Creek (loc. 1, Fig. 7) the Espiritu Santo is absent, and the Tererro lies unconformably on the Precambrian.

We have no data on the distribution of Mississippian rocks in most of the southwestern part of the area southwest of El Barro Peaks between Sebadilla Creek and Tres Hermanos Creek. The contact of Precambrian and Paleozoic rocks in this area, as shown on Plate 1, was adapted mainly from mapping by Read et al. (1944) who showed the Lower and Middle Pennsylvanian Sandia Formation (undivided) overlying the Precambrian. Inasmuch as those workers classified Mississippian rocks as the lower member of the Sandia, rocks of Mississippian age may be present at places. On a peak about 2 mi (3.2 km) northwest of Bernal, the Tererro Formation is present, although poorly exposed (loc. 1, Fig. 20), but the Espiritu Santo seems to be absent. West of Barillas Peak outside the area of this report, along the U.S. Forest Service road about 2 mi (3.2 km) east of Apache Canyon (NE¼ sec. 1 T15N R13E, USGS Lower Colonias quadrangle), both the Espiritu Santo and the Tererro are present, but their thicknesses were not determined. (USGS topographic quadrangles mentioned in this report are located on an index map on Plate 1.)

In the northwest part of the area, on upper Sapello River, Johns Creek, and Daily Creek, Mississippian rocks are slightly metamorphosed in fault slices and poorly exposed. The Espiritu Santo is mainly absent and the Tererro Formation lies on Precambrian rocks. In the northwestern corner of the area, north of the Mora County line and west of the Gascon fault, rocks equivalent to the Sandia Formation are reported by Sutherland (1963, plate 1) to lap northward across the Tererro and carbonate rocks of the Espiritu Santo and rest on the Del Padre Sandstone Member. Moench and Robertson (1980) show the wedgeout of the

Mississippian occurring farther south, and their contacts are shown on Plate 1 of this report. We have not observed these rocks and have no additional data. Sutherland (1963, p. 39–40) suggested that, in the northwestern part of the area underlain by the Early Proterozoic Ortega Quartzite (Fig. 5), Mississippian rocks may never have been deposited.

In most of the eastern part of the mountains, from Agua Zarca north, the Espiritu Santo Formation is present at outcrops and ranges from about 10 ft (3 m) thick at Montezuma (loc. 12, Fig. 8) to about 33 ft (10 m) thick about 2.7 mi (4.3 km) southwest of Mora (Armstrong, 1967, fig. 32). Throughout this area, the Del Padre Sandstone Member is present generally, but commonly it is only 2–3 ft (0.6–1 m) thick; at a few places it laps out against small knobs of Precambrian rocks. Southwest of Mora, the Del Padre is 10–15 ft (3–4.5 m) thick and forms a well-defined ledge beneath the poorly exposed carbonate part that is only 10–15 ft (3–4.5 m) thick.

At the eastern front of the mountains north of Gallinas Creek both formations of the Arroyo Peñasco Group were removed by Late Mississippian and Early Pennsylvanian erosion in two areas where the Lower and Middle Pennsylvanian Sandia Formation laps eastward onto Precambrian rocks (Plate 1). One of these areas, north of Montezuma, extends from about the mouth of Cañon del Agua to north of Cañon Bonito (Baltz, 1972). The other area is known from two small outcrops (just north of loc. 5, Fig. 7) south of Rito Cebolla (Baltz and O'Neill, 1986).

Lithology

Baltz and Read (1960, p. 1756) recognized four informal lithologic units within the Espiritu Santo Formation. Their basal sandstone is now the Del Padre Sandstone Member. The overlying carbonate part includes, in ascending order: (1) sandy limestone and dolomitic limestone that commonly contains concentrically banded chert nodules; (2) limestone that contains lenses of horizontally banded chert; and (3) upper silty, sandy limestone. All these units are known to be present together only in the region northwest of the area of this report where the Espiritu Santo is relatively thick. They are shown in Figure 10 where probable correlations are shown by dashed lines.

In the southeastern part of the mountains, the Del Padre Sandstone Member (Fig. 11) is buff, grayish-olive, and tan, fine- to very coarse grained sandstone that contains granules and, commonly, small pebbles. The sandstone is well cemented by silica and calcite and at places is an orthoquartzite. Bedding is parallel to gently inclined and locally slightly undulatory; beds are parallel laminated, inclined laminated, and cross laminated. Beds are 6–12 inches (15–30 cm) thick. The sand is dominantly quartz, but at some places a minor amount of feldspar is present, as are flakes of mica and fragments of amphibolite, and other metamorphic rocks.

A common characteristic of the sand is its sorting into three distinct grain-size groups. The matrix is well sorted, fine to medium, subangular to subrounded sand. Scattered through the matrix are lenses and individual grains of coarse to granule-size, subrounded to well-rounded quartz; at some places as much as 25 percent of the sandstone is composed of these larger grain sizes. Pebbles ranging up to 1 inch (2.5 cm) diameter occur in lenses or scattered through the rock. Pebbles as large as 2.5 inches (6 cm) diameter occur at places, mainly in the northern part of the area (for example, loc. 5, Fig. 7 where they are locally derived). Many of these pebbles are subrounded quartzite, but the larger pebbles in the northern part of the area commonly are angular to subangular white vein quartz.

Usually, the sediments of the Del Padre do not directly reflect the lithology of the immediately underlying Precambrian rocks, except for locally present minor constituents. Probably the sediments were derived partly from the Early Proterozoic Ortega Quartzite in the northwestern part of the area (Fig. 5), from hills of Precambrian quartzites in the Rincon Range farther north and northwest (Baltz, 1969, fig. 3), and from other local sources. Some of the angular vein-quartz pebbles might have been derived from lag deposits on the pre-Mississippian surface.

The Del Padre Sandstone Member is mainly the littoral deposit of a shallow, transgressing sea. Sutherland (1963, plate 8C) reported irregularly bedded bouldery conglomerate in the Del Padre lying on the Ortega Quartzite in of the

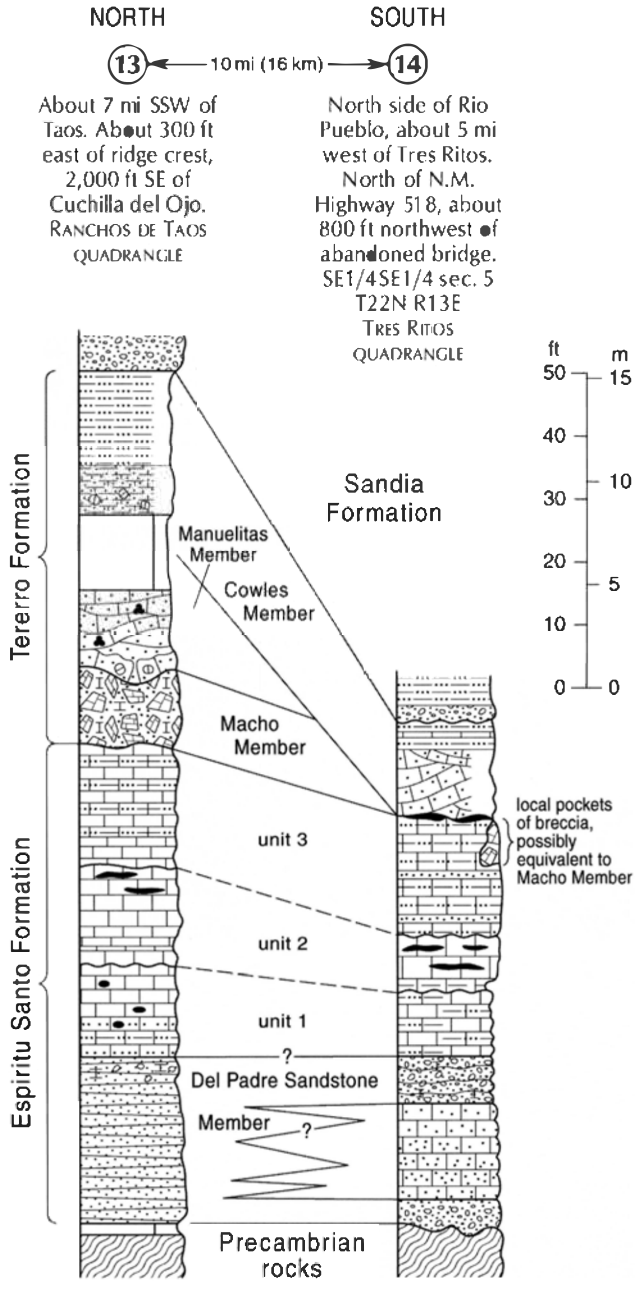


FIGURE 10—Stratigraphic sections of the Tererro and Espiritu Santo Formations in the western and central parts of the Sangre de Cristo Mountains northwest of area (Plate 1) of this report. Locality 13 is described near the end of this report. Modified slightly from Baltz and Read (1960, p. 1769). Locations of Taos and Tres Ritos are shown on Plate 2. Lithologic symbols explained in Figure 9.

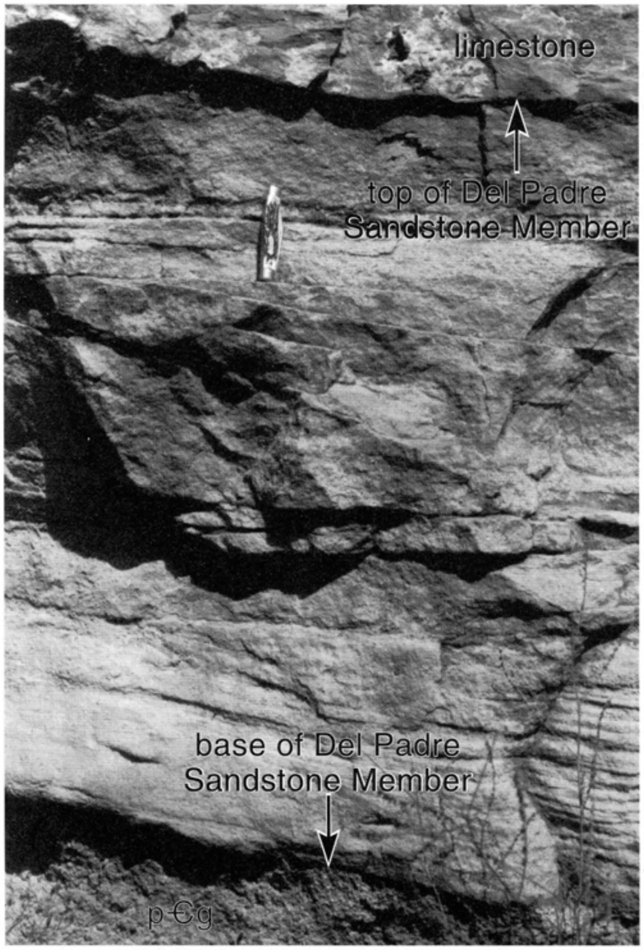


FIGURE 11—Del Padre Sandstone Member of Espiritu Santo Formation lying on Precambrian gneiss (p-Ꞓg) and overlain by recrystallized dolomitic limestone of the Espiritu Santo. Roadcut, New Mexico Highway 65, north side of Gallinas Creek canyon at locality 10 northeast of Trout Springs. Sandstone is fine-grained to very coarse-grained, contains granules and small pebbles, and is about 3 ft thick.

northwestern part of the area (Fig. 5). These conglomerates might be a partly nonmarine proximal facies on the margin of the residual quartzite highlands that were uplifted slightly during deposition of the Del Padre.

The carbonate part of the Espiritu Santo conformably overlies the Del Padre and correlates with the carbonate rocks at the type locality and elsewhere in the Pecos River area. Most of the carbonates in the area of this report are the sandy dolomitic limestone unit of Baltz and Read (1960, p. 1756). They (Figs. 7, 8) correlate with unit 1 (Fig. 10) of the carbonates of the Taos–Tres Ritos areas farther north. The rocks of unit 1 in the area of this report are gray to dark-gray, fine- to coarse-grained, dense limestone and dolomitic limestone (Fig. 12). Some of the rocks are ferruginous, containing tiny pyrite crystals and limonite pseudomorphs after pyrite; some of the carbonate is sideritic, and insoluble residues from some beds contain carbonaceous material. At places the lower beds contain thin lenses of calcareous quartz sandstone identical to that in the underlying Del Padre. Scattered quartz sand and granules occur also in the lower beds. However, at many places, the upper beds or all of the unit contain little or no sand or sandstone. Bedding generally is parallel to subparallel; beds average about 5 inches (13 cm) thick, and some beds are finely laminated. Bedding is commonly undulatory and some sandy beds are ripple marked.

At some places the carbonate rocks of unit 1 contain thin irregular bands, several inches long, of black chert. At many places distinctive smooth, slightly prolate, chert nodules occur within the carbonate beds. These nodules are internally concentrically banded; the bands alternate light and dark gray. The nodules range in size from about 0.25 inch (0.6 cm) to 6 inches (15 cm) in longest dimension.

Parts, or in places all, of the carbonate rocks are conspicuously recrystallized. Generally, the recrystallization has not obliterated the primary sedimentary structures, and some of the rocks fracture along curved cleavage surfaces as much as 5 inches (13 cm) across that cut across relict lamination. Some beds, that originally were clastic limestone, are now very coarse grained to sugary textured, although crossbedding still can be seen. In some beds the recrystallization has disrupted original sedimentary structures, and small parts of the rocks are masses of large crystals and locally contain radiating masses of white calcite. Although the recrystallization is common and characteristic, it has not occurred in all the beds at all localities.

At localities 2, 3, 9, and 12 (Figs. 7, 8), the highest part of the carbonates consists of thin beds of slightly recrystallized sandy limestone and calcarenite that lie with slight erosional unconformity on the carbonates of unit 1; at some places these upper beds contain limestone pebbles and angular, detrital-chert fragments. The stratigraphic position of these remnants and their unconformable relation to underlying rocks suggest a correlation with unit 2 (Fig. 10) of areas farther north and with similar thin remnants in similar stratigraphic position in the Pecos River area.

The lithology of the carbonate part of the Espiritu Santo of the area of this report indicates deposition in relatively shallow water that almost surely was marine, as is indicated also by rare small crinoid columnals and a few broken productoid brachiopods. However, the paucity of megafossils suggests that the water was highly saline, as do pseudomorphs of gypsum grains (Armstrong, 1967; Ulmer and Laury, 1984). At places thin, wavy laminations and undulatory bedding suggest thin algal-mat structure, and some insoluble residues contain large amounts of carbonaceous material. Armstrong (1967) liberally interpreted similar features in the stratigraphic position of the Espiritu Santo as stromatolitic throughout a wide region of northern New Mexico. The erosional unconformity and the limestone-pebble conglomerates in the upper part (unit 2) indicate shoaling of the sea, or perhaps a period of subaerial exposure and slight erosion followed by resumed marine deposition.

Contact with overlying rocks

The contact of the Espiritu Santo Formation and the Tererro Formation is unconformable throughout the area of this report. At many places (Figs. 7, 8) the carbonates of the Espiritu Santo are overlain by limestone breccia, assigned to the basal part of the Tererro (Fig. 13), that was produced mainly by subaerial solution and karsting of the upper part of the Espiritu Santo, as will be discussed more completely later in this report.

The breccia is absent from many places where the Espiritu Santo is overlain unconformably by well-bedded limestone-pebble and cobble-conglomerate and calcarenite of higher parts of the Tererro. Exposures of this erosional unconformity can be seen in road cuts on New Mexico Highway 65 along Gallinas Creek between localities 3 and 10 and at other places. Just west of Montezuma (loc. 12) the breccia is absent but, several hundred feet west, it intervenes between the Espiritu Santo and the overlying part of the Tererro.

In the northern part of the area south and north of Mora River the breccia generally is absent and the Espiritu Santo

FIGURE 12—Carbonate rocks of upper part of Espiritu Santo Formation lying on Del Padre Sandstone Member of Espiritu Santo Formation. Precambrian gneiss (p€g) crops out at base. Roadcut at locality 10. Limestones are ferruginous, dolomitic, conspicuously recrystallized, and exhibit some curved cleavage faces several inches across; ellipsoidal, concentrically banded chert nodules (cn) are in ledge near middle of unit. Upper carbonate bed lies on notch-forming calcareous shale (sh) above a slightly channeled disconformity. Upper bed is overlain by poorly exposed, brush-covered breccia of Macho Member of Tererro Formation. Total thickness of the carbonate rocks of the Espiritu Santo is about 12 ft (3.7 m). Thickness of Del Padre is 2.5 ft (0.75 m).

is overlain unconformably (locs. 6, 7) by higher units of the Tererro Formation. In the northwestern part of the area some outcrops show the Espiritu Santo and the breccia both missing and the higher part of the Tererro lying on the Precambrian. In the southern part of the area south of Ojitos Frios (Plate 1) and near Santillanes Creek (loc. 1), good exposures show that the breccia and the Espiritu Santo both are absent and the fossiliferous higher part of the] Tererro lies directly on Precambrian rocks.

Age

The Espiritu Santo Formation was assigned a Devonian(?) age by Baltz and Read (1960, p. 1758–1759). No identifiable megafossils were found in the Espiritu Santo by these writers, nor have any been reported since. Baltz and Read based their assignment on the stratigraphic position of the Espiritu Santo unconformably beneath the Tererro, which contains Mississippian megafossils, and on a general lithologic similarity to rocks of known Late Devonian age in Colorado. Sutherland (1963, p. 25, 27) also concluded that the Espiritu Santo in the western part of the mountains is unconformable with the Tererro Formation, but he believed that the lithologic correlation of the Espiritu Santo with Devonian rocks of Colorado was tenuous and inadvisable, and concluded that the Del Padre and the carbonate rocks of the Espiritu Santo could be any age from late Precambrian to Early Mississippian.

Armstrong, in a series of reports (Armstrong, 1955; Armstrong and Holcomb, 1967; Armstrong, 1967; Armstrong and Mamet, 1974), argued that there was no unconformity present within the pre-Pennsylvanian rocks of the Sangre de Cristo Mountains. He expressed changing and evolving opinions of the age of these rocks, based on studies of microfossils. Originally, Armstrong (1955) classified all the Arroyo Peñasco (including the Espiritu Santo) as Late Mississippian (Meramecian). Later, Armstrong (1967, p. 22) reported a sparse microfaunule of Early Mississippian (Osagean) age in chert nodules in Baltz and Read's (1960) Espiritu Santo in the Sangre de Cristo Mountains at Tererro, Agua Zarca, Rio Pueblo, and Ponce de Leon Springs. He noted that the foraminifera are rare and poorly preserved, and queried the identifications at several localities. In later more comprehensive regional studies of the microfossils (Armstrong and Mamet, 1979, p. 205; Armstrong et al., 1979,

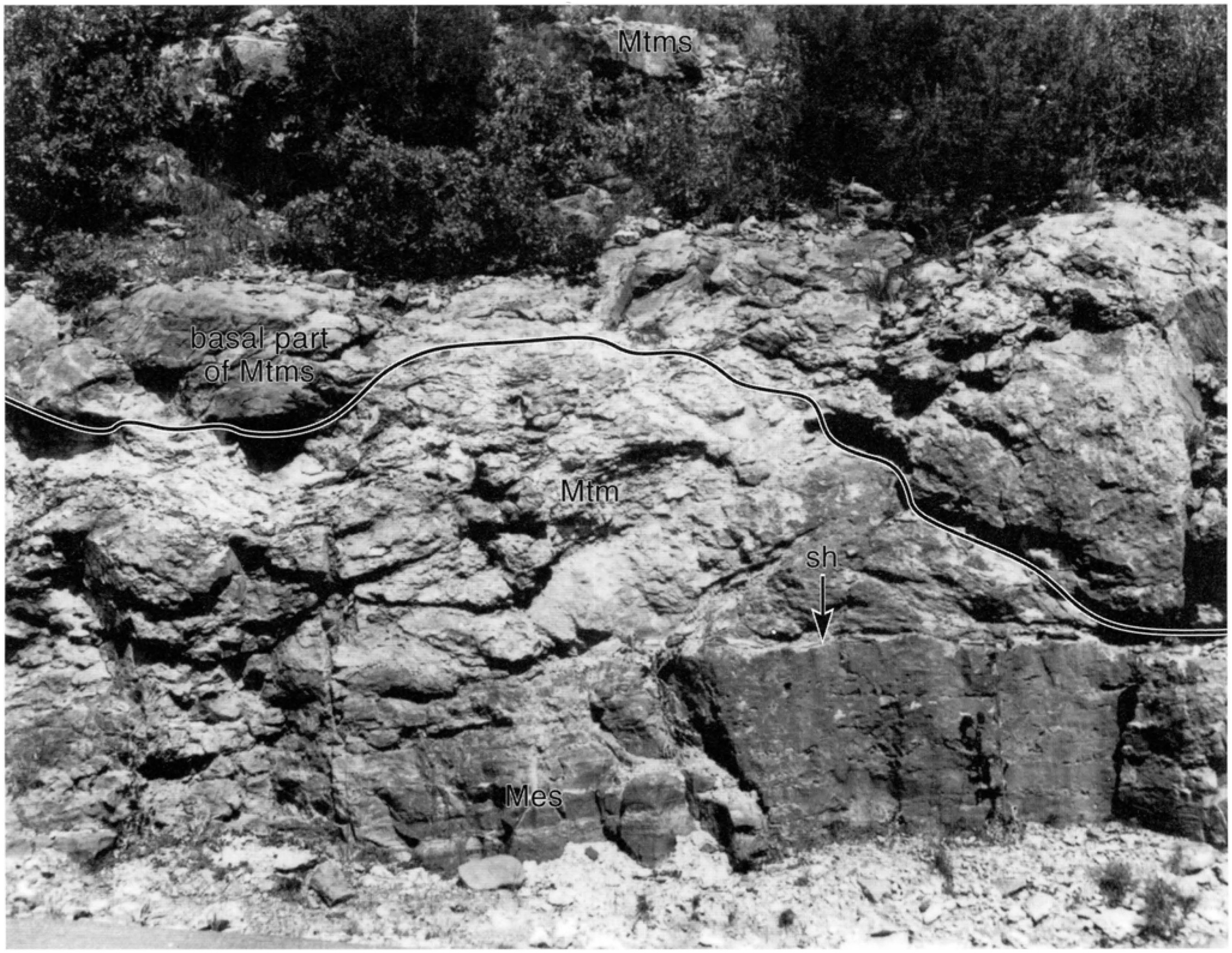


FIGURE 13—Recrystallized carbonate rocks of upper member of Espiritu Santo Formation (Mes) overlain by thin breccia of Macho Member of Tererro Formation (Mtm). Roadcut at locality 10. Dark-gray bed at lower right is about 3 ft (0.9 m) thick and is same as top bed of Espiritu Santo in Figure 12. Breccia of Macho Member lies on a thin, notch-forming shale (sh), apparently the relict base of the overlying unit from which part of the breccia was derived. Slightly collapsed bedded limestone of basal part of Manuelitas Member (Mtms) of Tererro lies on eroded surface of Macho Member. At right side of view, basal part of Manuelitas contains 1–3-inch (2.5–7.6-cm) limestone pebbles and chertified small crinoid columnals and lies in a channel cut in Macho Member.

fig. 2) the Espiritu Santo is indicated as being Osagean (Tournaisian) and as being unconformable with the Tererro Formation.

The present writers do not have any fossil data, and we assign the Espiritu Santo in the southeastern part of the mountains to the Early Mississippian (Osagean) on the basis of the microfossil zonation of Armstrong and Mamet (1979).

Tererro Formation

Definition

The name Tererro Formation was applied by Baltz and Read (1960, p. 1759) to limestone breccia, crystalline limestone, calcarenite, and calcareous siltstone that unconformably overlie the Espiritu Santo Formation on Pecos River just west of Tererro Post Office in the west-central part of the Sangre de Cristo Mountains. (The correct Spanish spelling is Terrero, but the post-office name was used because the town no longer exists.) At the type locality the Tererro is about 117 ft (36 m) thick and is overlain unconformably by the Sandia Formation of Early and Middle Pennsylvanian age. Three members of the Tererro were named by Baltz and Read. At the type locality these are as follows, in ascending order: Macho Member, consisting of massive, ledge-forming limestone breccia about 30 ft (9 m) thick; Manuelitas Member, consisting of calcarenite, limestone-pebble conglomerate and crystalline limestone, about 37 ft (11 m) thick; and Cowles Member, consisting of silty to sandy calcarenite and overlying calcareous siltstone and interbedded silty limestone, about 50 ft (15 m) thick. The three members are separated by erosional unconformities.

The Tererro Formation in the southeastern part of the mountains is lithologically similar to the type locality and all three members are present at places, but the formation is generally a little thinner than in the Pecos River area. Armstrong and Mamet (1974, 1979) described an additional member of the Tererro Formation, the Turquillo Member, named for a locality in the Rincon Range north of Mora. This member, in the Rincon Range, lies on the Macho Member and beneath the Manuelitas Member and is described (Armstrong and Mamet, 1979, p. 203–204) as being a thick-bedded mudstone-wackestone rich in foraminifers. In the area of the present report the Turquillo Member was said to be 2.5 m thick at Agua Zarca, 3 m thick at Gallinas Canyon, and 4.5 m thick at Mora River. We were not able to identify the Turquillo Member with assurance as a lithologic unit in the present area, and we do not use the term. Apparently, rocks biostratigraphically equivalent to the Turquillo are present at places in the lithologically complex sequence that we include in the Manuelitas Member.

Distribution and thickness

The Tererro Formation is widely distributed in the southeastern part of the mountains, but it is absent at places near the eastern front of the mountains and at two localities east of El Barro fault because of Late Mississippian–Early Pennsylvanian and Late Pennsylvanian–Early Permian erosion (Fig. 6). The Tererro is absent from the northwest part of the area west of the Gascon fault either because of pre-Pennsylvanian erosion, or because it was never deposited there on the quartzite terrane of the Ortega Quartzite (Fig. 5).

In measured sections, the thickness of the Tererro ranges from about 3 ft (1 m) near Montezuma (loc. 12, Fig. 8) to about 90 ft (27 m) east of Rociada (loc. 4, Fig. 7). The thickness varies considerably within these limits because of variations in thickness of the individual members; however, the formation thickens slightly northward and westward. At wells in the Las Vegas Basin (Fig. 18) the Tererro is 50–70 ft (15–21 m) thick.

Macho Member

The Macho Member is a breccia composed mostly of pebble-size to large-boulder-size (2–4 ft; 0.6–1.2 m) angular to slightly rounded limestone blocks that are randomly oriented in a matrix of silt- and sand-size limestone fragments and fine-granular calcite. The breccia clasts are mostly medium-gray, fine- to coarse-grained limestone, and silty or sandy limestone. Sand- to pebble-size, angular, detrital-chert fragments are common in the matrix; less commonly, cobble-size angular chert clasts are part of the breccia. At a few places (for example, locs. 10 and 3 and just south of loc. 2) the lower part of the breccia contains a few clasts of concentrically banded chert nodules and recrystallized limestone similar to unit 1 of the Espiritu Santo Formation. However, at most places the part of the Espiritu Santo that remains beneath the Macho Member is highly resistant to solution and has not formed part of the breccia. Many of the breccia clasts are similar to limestone of units 2 and 3 of the Espiritu Santo that are present in areas farther north (Fig. 10). In particular, banded light- and dark-gray and banded tan- and cream-colored chert, similar to chert lenses in unit 2 farther north, occurs at places in the Macho as clasts and interlayered in limestone clasts (Fig. 14). At places the upper part of the breccia includes a few well-rounded pebbles and cobbles of limestone that probably are, genetically, parts of the overlying Manuelitas Member. These limestone gravels appear to have collapsed slightly into spongy areas of breccia and mingled partly with the Macho Member breccia.

The Macho Member is overlain with erosional unconformity by the Manuelitas Member. Evidence of the unconformable surface is well displayed at many places where lenticular basal beds of the Manuelitas thicken and thin across the irregular top of the breccia. At places these basal beds of the Manuelitas also collapsed slightly into the breccia and are beveled and overlain with slight angular unconformity by stratigraphically higher beds of the Manuelitas. Such complex relationships are displayed in road cuts at locality 10 (Fig. 15). Additional evidence of the unconformity is that, at places, the breccia thins and is cut out in a few hundred feet (for example, between locs. 3 and 10 and west of loc. 12) and the Manuelitas Member rests unconformably on an irregular surface on the Espiritu Santo Formation.

In the southern part of the area the Macho Member is generally no more than 10–15 ft (3–4.5 m) thick. South of Ojitos Frios and near the Bernal and El Barro faults, where the Espiritu Santo is generally absent, the Macho also is absent, and the Manuelitas Member lies on Precambrian rocks. The Macho is thickest in the west central part of the area, being about 30 ft (9 m) thick at locality 8, and somewhat thicker to the northwest at places between Gallinas Creek and lower Hollinger Creek. To the north, at places in the vicinity of Mora River (locs. 6–7) the Macho is absent. In the northwest in the upper Sapello River–Maestas Creek area the Macho mainly is absent as is the Espiritu Santo Formation.

Manuelitas Member

The Manuelitas Member is composed of varied proportions of limestone-pebble and cobble conglomerate, calcarenite, sandy and silty limestone, marly shale, some oolite, and fine-grained crystalline limestone. The calcarenite is calcite sand whose grains have been transported far enough to become rounded, whereas in thin sections the oolite grains show evidence of accretionary banding. The clastic rocks weather buff or light yellowish gray, and the crystalline limestones weather medium to light gray. Where it is lithologically complex, the member weathers to series of small upward-retreating ledges, but where it is more homogeneous (locs. 1, 7, Fig. 7), it forms more massive ledges.

As much as 50 percent of the calcarenite and oolitic-limestone beds of the Manuelitas is quartz silt and coarse to granule-size, subangular to rounded, quartz sand. Pebbles of quartzite and vein quartz are present at places. In the southwestern part of the area, at Santillanes Creek where the Manuelitas rests on Precambrian rocks (loc. 1, Fig. 7), the lower part of the member is a highly calcareous, coarse-grained quartz sandstone containing fragments of crinoids and brachiopods and quartz pebbles. The overlying rocks of the member at Santillanes Creek also contain a large proportion of quartz sand in calcarenite beds and as interbeds of calcareous sandstone.

Gray to pink masses of opalescent chert are common as replacement features in the Manuelitas Member and are one of its distinguishing features. Commonly, the chert is oolitic to pisolitic; the oolites occur singly, as joined clusters, and as outer boundaries of larger masses of chert. Some of the chert is internally concentrically banded, but some is internally structureless, megascopically. Oolitic chert is common in calcarenite beds where it has replaced tiny fragments of crinoid columnals, calcareous oolites, and calcite sand grains. Oolitic chert is found sparingly also in the crystalline limestones.

Brown-weathering chert commonly occurs in irregular stringers and along fractures. On the Ojitos Frios anticline south of Ojitos Frios, blue and brown chert occurs as patches that replace highly fossiliferous brachiopod-bearing parts of limestone beds. Angular detrital chert, derived from the erosion of underlying rocks, is scattered through the lower part of the Manuelitas Member at places.

The Manuelitas Member is well bedded, although some of the beds are lenticular, and some persist only for a few tens of feet before they wedge out or are cut out by intramember erosional unconformities. At places these unconformities are slightly angular because of slight collapse of early-deposited beds of the Manuelitas Member into the underlying breccia of the Macho Member, as previously discussed.

At many places, distinct shallow sinkholes occur in the breccia of the Macho Member (Fig. 15); at these places repetitive sequences of several lithologic types occur in the Manuelitas. This can be seen at many places but is exemplified best east of Rociada at locality 4 (Fig. 7), which is the type locality of the Manuelitas Member (Baltz and Read,

FIGURE 14---Limestone breccia of the Macho Member of the Tererro Formation. Roadcut at locality 10. Knife is 4 inches (10 cm) long. Clasts beneath knife are parallel-banded chert. Light-colored clasts in lower part of photograph are coarsely recrystallized limestone.

1960, p. 1762). A description of locality 4 is given at the end of this report (p. 190). In the sinkhole at locality 4 the Manuelitas is 45–50 ft (14–15 m) thick, but nearby, outside the sinkhole, the member is only about half as thick. Angular unconformities between sets of beds near the edges of the sinkhole indicate a greater amount of sediment accumulation in the sink probably because of episodic collapse at the base of the Manuelitas and consequent lowering of the local base level of deposition. Some of the beds at locality 4 probably are equivalent to intramember disconformities and erosional unconformities in areas outside the sinkhole.

The predominantly clastic lithology, the crossbedding and lenticularity of beds, and the marine fossils of the Manuelitas Member indicate deposition on a flat, shallow-marine shelf that was subjected to relatively strong tidal and wind-driven currents. The Manuelitas sea advanced onto an irregular karst terrane of the Macho Member, and wave and current action locally scoured and removed parts or all of the breccia. Some of the upper part of the breccia was reworked into limestone pebbles and cobbles and was deposited in depressions, and perhaps in former solution cavities. The breccia may have been mainly uncemented blocks because it is penetrated intricately to depths of 10 ft (3 m) or more by irregular stringers of marly shale and calcarenite of the Manuelitas. Some of these stringers contain crinoid columnals and unbroken brachiopod shells.

Low-lying Precambrian terranes, such as at locality 1 in the southwestern part of the area, and probably the Early Proterozoic Ortega Quartzite in the northwestern part of the area (Fig. 5), contributed quartz silt, sand, granules, and at places, pebbles which were widely distributed through the shallow sea. Fossiliferous lime muds accumulated in areas protected from strong current action to produce the thin fine-grained limestones. Part of the calcite sand of the calcarenite beds was produced from reworking the Macho Member, but part was biogenic as manifested by the common presence of rocks formed of small, abraded crinoid columnals.

At measured sections, the Manuelitas Member ranges in thickness from about 3 ft (1 m) near Montezuma (loc. 12) to about 50 ft (15 m) east of Rociada (loc. 4). No systematic variation has been detected; the differences in thickness apparently are due mainly to local conditions of deposition and partly to the unconformable contact with the overlying Cowles Member.

Cowles Member

The Cowles Member, the uppermost unit of the Tererro Formation, lies unconformably on the Manuelitas Member and is overlain unconformably by the Lower and Middle Pennsylvanian Sandia Formation. In the southeastern part of the mountains, the Cowles is absent from places because of Late Mississippian and Early Pennsylvanian erosion (locs. 2, 5, 12, and elsewhere near the eastern front of the mountains). At measured sections the thickness ranges from about 6 ft (1.8 m) at locality 10 to 38-40 ft (11–12 m) at localities 4 and 7.

Where fully preserved, the Cowles consists of two lithologic units: a basal, silty to sandy calcarenite; and an upper siltstone unit that commonly contains interbeds of calcarenite, thin crystalline limestone, and, at a few places, marly shale. The lower unit is medium gray on fresh surfaces, but weathers yellowish gray to light brown. The upper unit commonly weathers olive green; it weathers olive gray where limestone is not present. The lower calcarenite unit weathers to form a strong ledge; the upper siltstone unit weathers to an upward-retreating slope with small ledges formed of interbedded thin limestones.

The lower unit is fine-grained, well-sorted calcarenite that consists partly of abraded fossil fragments. This rock contains a large proportion of quartz silt and fine quartz sand; insoluble residues are as much as 50 percent quartz. Mainly, the quartz is distributed throughout the calcarenite, but in places distinct layers of thin calcareous siltstone and fine-grained sandstone are interbedded with the calcarenite. The unit is conspicuously and characteristically crossbedded and cross-laminated; beds generally are 2–3 ft (0.6–1 m) thick. Chert is uncommon except as replacement bodies near the upper contact at places where the lower unit is overlain by the Sandia Formation. However, the rocks are generally siliceous and hard. Silica along bedding and laminations commonly stands in relief on weathered surfaces (Fig. 16).

The upper unit of the Cowles that is preserved at a few localities in the southeastern part of the mountains, varies from noncalcareous, shaly siltstone and thin-bedded, very fine grained sandstone at locality 4 east of Rociada, to siltstone and interbedded thin, irregular lenses of calcarenite at locality 3 north of Gallinas Creek.

At many places the contact of the Cowles and Manuelitas Members is irregular and apparently eroded. At a few places limestone-pebble conglomerate containing angular chert fragments is at the base of the Cowles. The surface of unconformity cuts across slightly tilted and collapsed beds of the Manuelitas, and the Cowles is not involved in the collapse. At a few places minor solution occurred along joints and fractures in the uppermost part of the Manuelitas, and the openings were filled with sediment of the Cowles. Armstrong (1967, fig. 15, p. 21) reported that, at Manuelitas Creek east of Rociada (loc. 4, Fig. 7), sinkholes were formed after deposition of the Cowles and prior to deposition of the Sandia Formation, but our observations of this locality indicate that the Cowles extends unbroken (except for recent slight slippage along joints) across the collapsed portion of the underlying Manuelitas Member.

The Cowles Member was deposited in a shallow marine-shelf environment under apparently relatively uniform conditions throughout much of the Sangre de Cristo

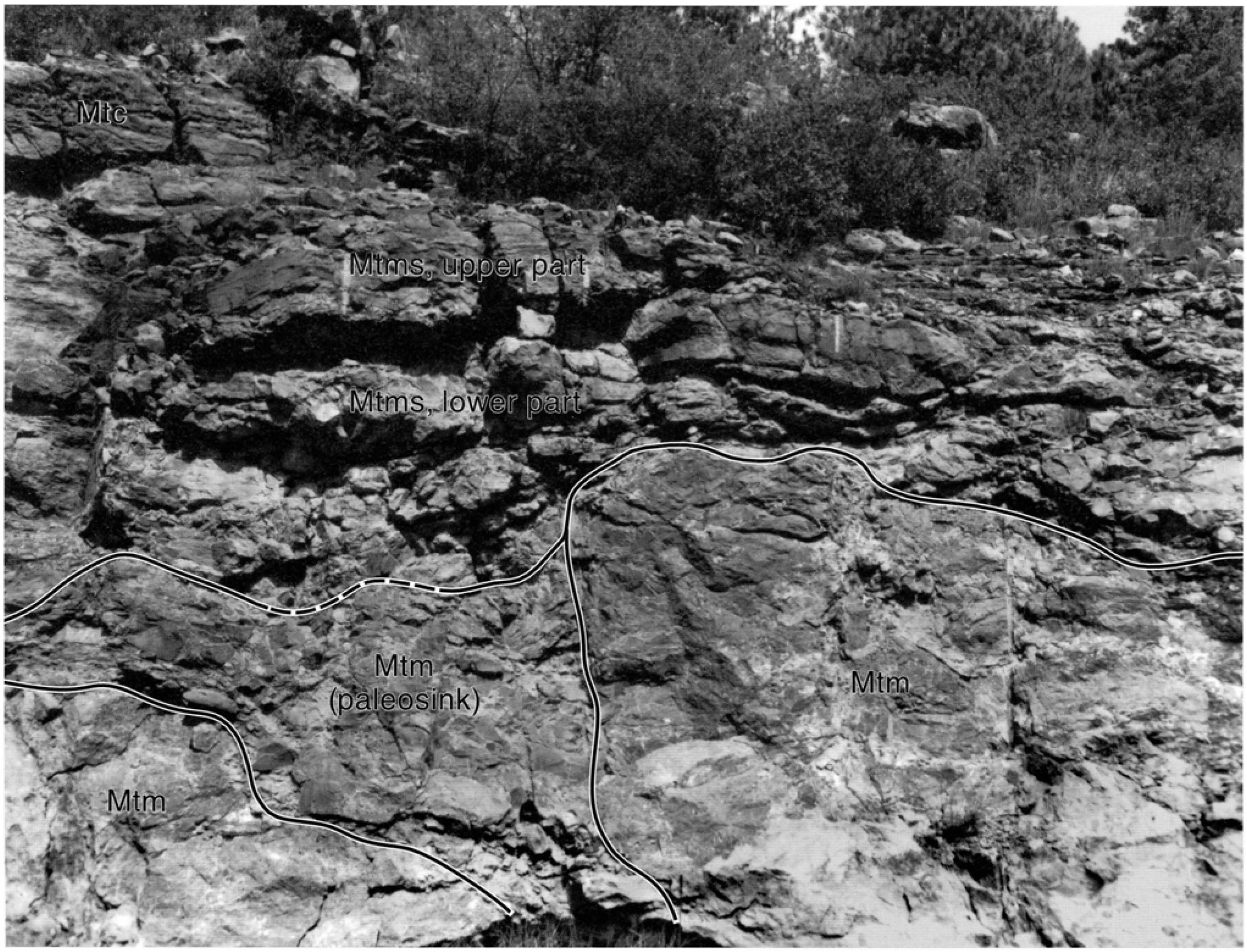


FIGURE 15—Contact of Macho and Manuelitas Members of Tererro Formation. Roadcut at locality 10. Massive rock (Mtm) is limestone breccia of Macho Member; bedded limestone and calcareous shale (Mtms) are the Manuelitas Member. Lower beds of Manuelitas Member thicken right to left into a paleosink in the Macho and are slightly brecciated because of continuing collapse of the Macho during Manuelitas deposition. Matrix and stringers of sandy calcisiltite between breccia blocks in the paleosink were deposited probably in earliest phase of Manuelitas sedimentation. Upper part of Manuelitas bevels most of lower part right of the paleosink and continues unbrecciated across the exposure. Small ledge of cross-laminated limestone (Mtc) at upper left is lower part of Cowles Member of the Tererro. Recent solution cavity near base of outcrop is 1 ft (30 cm) high.

Mountains. Probably, the Early Proterozoic Ortega Quartzite in the northwest part of the area and other quartzite terranes farther north were the main sources of the quartz silt and sand of the member. The unconformity at the base of the member probably represents a brief withdrawal of the sea in which the Manuelitas Member had been deposited. If so, the highly crossbedded sandy calcarenites of the lower part of the Cowles are littoral deposits representing the last transgression of the Mississippian sea in this region.

Contact with overlying rocks

In most of the area the contact of the Cowles Member and the overlying Sandia Formation seems structurally generally conformable, but the contact is erosional as shown by the thickening and thinning of the upper part of the Cowles. The contact at many places is channeled deeply enough to cut out the upper part of the Cowles (see Figs. 7 and 8). At some places the basal part of the Sandia contains limestone pebbles and angular detrital chert. The hiatus represented by the unconformity seems relatively short because the Cowles is Late Mississippian age (early Chesterian, according to Armstrong and Mamet, 1979), and the lower part of the Sandia is Early Pennsylvanian (Morrowan) age.

In the eastern part of the mountains north of Tecolote Peak, north of Montezuma, at Cañon Bonito, and just south of Rito Cebolla (Plate 1; Fig. 6), the contact of the Tererro Formation and the overlying Sandia Formation is clearly a slightly angular unconformity because the Sandia bevels gently across the entire Arroyo Peñasco Group to rest on Precambrian rocks. Similarly, in the northwest part of the area the contact may also be very gently angular (Miller et al., 1963, plate 1), although nondeposition of part or all of the Arroyo Peñasco Group may be involved also.

In the southwestern part of the area, at places adjacent to El Barro and Bernal faults, the abrupt local truncation of the Arroyo Peñasco Group (Plate 1) suggests angular unconformity between the Sandia and Tererro, perhaps on the crests of very low northwesterly trending anticlines. In the south, another angular unconformity is apparent on the Ojitos Frios anticline where the uppermost part of the Alamitos Formation of Middle Pennsylvanian to earliest Permian age locally cuts out the underlying Porvenir and Sandia Formations to lap onto the Manuelitas Member of the Tererro, which, in turn, is overlapped by the Sangre de Cristo Formation, here entirely Lower Permian.

In outcrops on the hill immediately south of New Mexico

FIGURE 16—Contact of Manuelitas and Cowles Members of Tererro Formation. Roadcut just west of locality 10. Massive ledge of limestone is upper part of Manuelitas Member (Mtms) and contains scattered small brachiopods, crinoid columnals, and other fossils. Irregular ledge of cross-laminated sandy limestone and the underlying thin-bedded limestone and marly shale are lower parts of the Cowles Member (Mtc). Contact (arrows) is a slightly irregular surface marked, at right, by a conspicuous notch weathered in thin marly shale of the basal part of the Cowles. Cliff of the Manuelitas Member is about 11 ft (3.4 m) high.

Highway 283, about 1 mi (1.6 km) west of Aqua Zarca (Plate 1), the Middle Pennsylvanian Porvenir Formation laps across the Sandia Formation, truncates the Tererro, and rests unconformably on the Espiritu Santo Formation. A little farther south, north of the head of Cañada del Alamito, the basal part of the Porvenir contains limestone-pebble conglomerate and angular chert fragments and pebbles and lies unconformably on Precambrian rocks and on a local remnant of the Espiritu Santo.

Age

The Tererro Formation is Late Mississippian. Armstrong and Mamet (1979) reported that, at the type locality of the Tererro and elsewhere, breccia blocks of the Macho Member contain microfossils of Early Mississippian (Osagean) age similar to those of the Espiritu Santo, but that the interclast matrix contains Meramecian microfossils similar to the Meramecian microfossils of the Manuelitas Member. They reported that the microfossils of the Cowles Member are early Chesterian.

The Manuelitas Member in the southeastern part of the mountains commonly contains megafossils, but generally they are sparsely distributed and difficult to collect. Three small collections from the vicinity of Gallinas Creek were reported previously by Baltz and Read (1960, p. 1765–1767). The fossils were identified by J. T. Dutro, Jr., and Helen Duncan. They are listed here for the sake of completeness and because the Mississippian megafaunas of this region are so poorly known.

Collection USGS 16686–PC. North side of Gallinas Creek canyon, 4.3 mi (6.9 km) west of Montezuma powerhouse, New Mexico Highway 65, locality 3, Figure 8 of this report.

Zaphrentites? sp.
Syringopora cf. *S. aculeata* Girty
Fenestella cf. *F. tenax* Ulrich
Linoproductus aff. *L. laevicostus* (White)
Spirifer sp. (two small species)
Torynifer? sp.
Aviculopecten? sp.

Collection USGS 16687–PC. North side of Gallinas Creek canyon, 300 ft (90 m) east of turnoff to Trout Springs, New Mexico Highway 65, about 4.8 mi (7.7 km) west of Montezuma powerhouse. Thin ledge-forming limestone 5–8 ft (1.5–2.4 m) above basal conglomerate of Manuelitas Member exposed in road cut.

Zaphrentoid coral, indet.
Fenestella sp.

Linoproductus? sp.
Spirifer sp. (small, as in 16686–PC)

Collection USGS 16688–PC. South wall of Gallinas Creek canyon, about 300 ft (90 m) southwest of steel bridge on New Mexico Highway 65, about 0.4 mi (0.6 km) west of Montezuma powerhouse. Collected from poorly exposed gray limestone cropping out above breccia of Macho Member. About 400 ft (120 m) west of locality 12, Figure 8 of this report.

Productella aff. *P. pyxidata* Hall
Avonia? sp.
"*Productus*" sp.
Linoproductus? sp.
Torynifer? sp.
Crurithyris? sp.
Nucleospira? sp.
Dielasma aff. *D. formosum* Hall
Naticopsis (Jedria) sp.
Straparollid gastropod, indet.
Phillipsia sp.
Ostracodes, indet.

An additional collection was obtained from the Manuelitas Member where it is mainly gray limestone that lies on Precambrian rocks on the west flank of the Ojitos Frios anticline (Plate 1), about 2 mi (3.2 km) south of Ojitos Frios. This collection was identified by J. T. Dutro, Jr. (written comm., 1980).

Collection USGS 27812–PC.

Echinoderm debris, indet.
Fenestrate and ramose bryozoans, indet.
Cystodictya? sp.
Spirifer cf. *S. bifurcatus* Hall (abundant)
Cleiothyridina? sp.
Composita sp.
Eumetria? sp.
Punctate spiriferoid fragment, indet.

Concerning collection 27812–PC, Dutro said that the *Spirifer* is closest to *S. bifurcatus* Hall, which originally was described from the early Meramecian Salem Limestone. Although the species identification is not certain, a Meramecian age is suggested.

Origin of Macho Member

The physical characteristics of the breccia of the Macho Member, its stratigraphic relations to overlying and underlying rocks, and its origin have been controversial (Baltz and Read, 1960; Sutherland, 1963; and Armstrong, 1967). Baltz and Read (1960) originally described the Macho Member of the southern part of the mountains as nonbedded, randomly oriented, angular blocks of limestone, derived mainly from the upper part (units 2 and 3, Fig. 10 of this report) of the Espiritu Santo Formation. According to them, the Macho formed only thin and discontinuous units in areas to the north where the upper parts of the Espiritu Santo still exist beneath the Tererro. They concluded that the breccia had formed mainly during a period of very slight uplift and northwest tilting, subaerial exposure, and karst formation. Preceding and during the incursion of the Manuelitas sea, collapse of cavernous parts of the Espiritu Santo were said to have formed breccia. The advancing Manuelitas sea completely eroded parts of the breccia, and reworked and redeposited it as conglomerate, calcarenite, and calcareous mud of the Manuelitas Member. Further local collapse of spongy or cavernous breccia, because of the weight of accumulating sediments, was thought to have caused the irregularities in thickness and bedding in the Manuelitas Member. The Manuelitas sea was thought to have withdrawn briefly, and the Manuelitas Member was slightly eroded and weathered. The sea transgressed again, and the Cowles Member was deposited unconformably and relatively uniformly across the region. The breccia of the Macho was stabilized by preceding events, and the Cowles is not involved in collapse.

Sutherland (1963, p. 27–28) wrote that the Macho Member in the upper Pecos River region is a limestone conglomerate composed of rounded to subrounded, nonoriented limestone pebbles to boulders and that it includes rounded boulders of chert and quartzite, one more than 4 ft long. He reported that the Macho has poorly developed irregular bedding, but locally has bedded limestone lenses in the lower part, and that the contact with the Espiritu Santo Formation is invariably sharp, continuous, and undulating. Sutherland (1963, p. 28) cited evidence for these contact relations mainly from exposures at the mouth of Jacks Creek in the Pecos River area, a locality that was not examined by Baltz and Read (1960). Sutherland reported that he had not found any boulders that show definite similarity to the distinctive lithologies of the recrystallized part of the Espiritu Santo (unit 1 of Baltz and Read and of the present report).

Sutherland (1963, p. 39) concluded that, prior to the deposition of the Macho, small solution features developed here and there on the eroded surface of the Espiritu Santo, but no extensive karst topography was formed. He concluded that the Macho is consistent in lithologic character over much of its areal extent, but that the mechanics of deposition are not clear. He believed that Meramecian rocks were deposited on the Espiritu Santo, partly or completely lithified, and elevated above sea level. With the readvance of the sea, this unit possibly was subjected as a cliff to wave action, which partly rounded the resulting eroded fragments and deposited them mainly in situ. Partial contemporaniety of deposition of the Macho and Manuelitas Members was considered likely. During deposition of the Manuelitas, marine deposition was thought to have been interrupted repeatedly by variations in sea level that exposed the area to erosion and allowed recurring development of karst topography. According to Sutherland (1963), the emergence-submergence characteristics then changed to sustained deposition as the Cowles Member was laid down.

Armstrong (1967, p. 18) described the breccia of the Macho Member as composed of rounded to angular fragments of limestone ranging in size from silt to blocks thirty feet across, stating that the lithology of the majority of clasts is the same as that of the overlying beds (the Manuelitas Member). He described the contact of the breccia with the underlying carbonates (Espiritu Santo Formation) as an even, almost flat surface, citing the same outcrops at Jacks Creek that were previously cited by Sutherland (1963). Armstrong (1967, p. 8) did not believe that unconformities existed within the pre-Pennsylvanian sequence, and he interpreted the brecciation as resulting from solution, by meteoric ground-water, of bedded and nodular gypsum and the subsequent collapse of interbedded dolomites and overlying limestones. He postulated that these events occurred after the deposition of all the Mississippian rocks and after the pre-Pennsylvanian erosion surface had developed, citing evidence of relations at a sinkhole at Manuelitas Creek gap (loc. 4, Fig. 7 of the present report).

Baltz (1969) reviewed much of the regional evidence and varied interpretations; therefore, the following summary is concerned with the salient points of evidence of origin of the breccia, mainly in the light of relations observed in the southeastern part of the mountains.

1. The contact of the breccia of the Macho Member and the underlying Espiritu Santo is at places smooth, at places highly irregular, and at places transitional. The position of the contact varies stratigraphically in terms of the underlying units of the Espiritu Santo (Figs. 7, 8, 10). We interpret this as being the result of differing

depths of solution during subaerial weathering of the Espiritu Santo. Some of the places where the contact is relatively smooth probably represent smoothly floored solution cavities developed at the top of the recrystallized dolomitic limestones of the lower part (unit 1) of the Espiritu Santo that seem to have been highly resistant to solution. Evidence of this resistance to solution can be seen where present-day caves and solutional cavities are developed only in the rocks overlying the Espiritu Santo as, for example, near its type locality (Baltz and Read, 1960, fig. 9).

The undulating, smooth contact at Jacks Creek, cited by Sutherland (1963, p. 27–28) and Armstrong (1967, fig. 4) as the contact of the Espiritu Santo and the Macho, is actually the contact of units 1 and 2 of the carbonate part of the Espiritu Santo. The thin-bedded lenses above the contact, that Sutherland (1963, p. 28, plate. 10C) assigned to the Macho, are slightly brecciated remnants of unit 2 of the Espiritu Santo from which the Macho was derived. These remnants grade upward into progressively more brecciated beds that are overlain by the main mass of breccia of the Macho.

2. In the Pecos River area and the area of this report, the breccia consists of randomly oriented nonbedded angular clasts similar to limestone of units 2 and 3 (Fig. 10) of the upper part of the Espiritu Santo that are preserved farther north in the mountains. In particular, some of the chert clasts and chert stringers within limestone clasts are light gray and cream, parallel banded, and are similar to banded chert in unit 2. The finding of Osagean (late Tournaisian) microfossils in the Espiritu Santo and in breccia blocks of the Macho Member in the Pecos River area, the area of this report, and farther north by Armstrong and Mamet (1979, p. 201–203, 208–209) supports the lithologic interpretation that the Macho was derived from the upper parts of the Espiritu Santo. Generally, the breccia does not contain clasts of the strongly recrystallized dolomitic limestone of unit 1 of the Espiritu Santo, which, of course, is still present beneath the breccia. However, at a few places (for example, at loc. 10, Fig. 8) concentrically banded nodular chert and some clasts of strongly recrystallized limestone, similar to those of unit 1, are present in the lower part of the breccia.
3. The upper part of the breccia at places contains bedded rounded pebbles and cobbles that occur in erosion channels and solution pockets in the more angular breccia. These gravels are reworked and transported, and depositionally are related to the Manuelitas Member. Stringers of sediment of the Manuelitas Member extend downward into the breccia and form part of its matrix. This lithologic interpretation is supported by the finding of Meramecian (Visean) microfossils in the matrix in the Pecos River area, in the area of this report, and elsewhere by Armstrong and Mamet (1979, p. 203, 207, 209–210). Additionally, clearly recognizable finer grained bedded rocks of the Manuelitas Member have slumped slightly into the upper part of the angular breccia at places. These relations probably account, at least partly, for the presence of Meramecian microfossils in brecciated beds that were assigned to the Macho at a few places in the upper Pecos River area by Sutherland (1963) and Armstrong (1967).
4. An erosional unconformity separates the Macho Member from the overlying Manuelitas Member. This is seen in many places where bedded rocks of the Manuelitas lie on a clearly defined surface on the breccia. This surface has a relief of a few inches to several feet; basal beds of the Manuelitas thicken and thin depositionally in response to the relief on the surface (for example, see Fig. 15). Where early-deposited beds of the Manuelitas have collapsed slightly into sinkholes in the breccia, they are beveled by younger beds that also lie with erosional unconformity on the breccia outside the collapsed areas. Such relations are clear at the type locality of the Tererro Formation (Baltz and Read, 1960, fig. 9) as well as in the southeastern part of the mountains. At places the breccia has been eroded completely, and the Manuelitas lies directly on the Espiritu Santo. Good outcrops in the Gallinas Creek area along New Mexico Highway 65 show that the Manuelitas locally cuts out the Macho, and that the Manuelitas and Macho rocks are not facies equivalents that were deposited partly simultaneously as was postulated by Sutherland (1963, p. 40). Additional new evidence of this unconformity is presented by the outcrops south of Ojitos Frios (Plate 1) and at Santillanes Creek (loc. 1, Fig. 7) and elsewhere in the southwestern and northwestern parts of the area where the Macho Member and the Espiritu Santo Formation both are absent, and the Manuelitas Member laps onto Precambrian rocks. As described earlier in this report, the Manuelitas contains much quartz sand and quartz pebbles derived from Precambrian terranes from which older Mississippian rocks must have been absent.
5. The Cowles Member is erosionally unconformable on the Manuelitas Member and is not involved in the local collapse features that characterize the Manuelitas Member, a relation reported also in the Pecos River area (and elsewhere) by Baltz and Read (1960) and by Sutherland (1963, p. 28). The reported (Armstrong, 1967, fig. 15) collapse of rocks equivalent to the Cowles Member into a sink hole at the type locality of the Manuelitas Member (loc. 4, Fig. 7), that was said to indicate post-Mississippian formation of the breccia, instead is the result of slight slippage of the Cowles on joint surfaces as a result of present-day erosional processes.

In conclusion, we believe that the evidence from the southeastern part of the mountains (and elsewhere) indicates (1) that the breccia of the Macho Member was produced by subaerial weathering and karsting of the upper part of the Espiritu Santo Formation and that the breccia existed prior to the deposition of the Manuelitas Member of the Tererro Formation; (2) that the breccia was eroded partially and was slightly reworked by waves and currents of a transgressing Manuelitas sea; and (3) that additional local collapse of the breccia occurred during deposition of the Manuelitas Member. These events were completed prior to deposition of the Cowles Member. The causes of the local syndepositional collapses of the Manuelitas Member are still not clear. Baltz and Read (1960) suggested that the collapses of the lower part of the Manuelitas were related to local, relict, spongy or cavernous conditions in the breccia and were caused primarily by the weight of accumulating Manuelitas sediments, an interpretation that is supported by the fact that the breccia commonly is thinner in the collapse areas than in the immediately adjacent places.

Armstrong (1967) interpreted evidence, mainly from thin-section studies of rocks now included in the Espiritu Santo, to indicate that ground-water dissolution of a 5–30-ft-thick bed of gypsum occurred in Late Mississippian or Early Pennsylvanian time and caused the collapse of the rocks that formed the breccia of the Macho Member. Later, Armstrong and Mamet (1979, p. 205) also mention that evaporites might have been present in the Espiritu Santo and that their dissolution may have produced the breccia. However, they interpret the breccia as a product of subaerial erosion of the Espiritu Santo whereby percolating groundwater formed a karst with a thick blanket of collapse breccia that formed a chaotic land surface prior to transgression of the Manuelitas sea, an interpretation similar to that of the present report.

Ulmer and Laury (1984) reported the results of studies of diagenesis of the Arroyo Peñasco Group at places in the Sangre de Cristo Mountains, including Trout Springs, Montezuma, and Mora River localities within the area of this report. They, also, interpreted evidence from thin-section studies that pseudomorphs after gypsum grains indicate the carbonates of the Espiritu Santo originally contained gypsum nodules and "horizons" that were altered extensively during diagenesis to produce dolomites and dedolomites. They indicated that the rocks from which the breccia of the Macho Member were derived also originally contained interbedded gypsum "horizons" that were dissolved during subaerial weathering, resulting in collapse and brecciation. The depth of solution and brecciation was said to have been controlled by the paleo-water table; rocks below the top of the water table were recrystallized rather than being brecciated.

Ulmer and Laury (1984) indicated (p. 93 and fig. 4) that the Espiritu Santo and Tererro Formations are continuously present throughout much of the southern part of the mountains and that the breccia of the Macho Member of the Tererro is present everywhere except in the high central part of the mountains. These reported distributions of stratigraphic units do not accord with the data of Baltz and Read (1960), Sutherland (1963), Armstrong and Mamet (1974, 1979), or with the data of this report. Ulmer and Laury's (1984) concept of apparently widespread gypsum "horizons" in the pre-breccia rocks of the Espiritu Santo does not seem to accord well with the regionally varying stratigraphic position to which brecciation has occurred in the Espiritu Santo (for example, between the localities of Figs. 8 and 10) unless the stratigraphic positions of the postulated gypsum horizons also varied regionally.

The petrographic work of Ulmer and Laury (1984) appears to establish the widespread former occurrence of crystals and grains and, possibly, small nodules of gypsum as minor constituents of some of the carbonates of the Espiritu Santo Formation. The presence of these evaporite constituents could have facilitated early stages of solution of the Espiritu Santo during subaerial weathering, perhaps abetting solution along joints and bedding. However, the former existence of extensive gypsum beds is not established and is not a condition necessary for the production of limestone karst.

Mississippian Paleotectonics

The regionally widespread presence of the thin Arroyo Peñasco Group (Armstrong et al., 1979) indicates that, in most of Mississippian time, north-central New Mexico was a shallow-marine shelf. Submergences and emergences probably were mainly responses to epeirogeny or eustatic sea level changes with only small local tectonic influences. The local absence of both the Espiritu Santo Formation and the Macho Member of the Tererro in the southeastern part of the Sangre de Cristo Mountains (Fig. 6) suggests that some areas that became Pennsylvanian and Permian uplifts also were uplifted very slightly in mid-Mississippian time.

Pennsylvanian rocks

Sandia Formation

Definition

Throughout most of the southern Sangre de Cristo Mountains, the Arroyo Peñasco Group is overlain unconformably by a heterogeneous assemblage of gray shale, carbonaceous shale, fine- to coarse-grained sandstone and conglomerate, and subordinate amounts of generally thin limestone. These rocks are the Sandia Formation of Early and Middle (Morrowan and Atokan) Pennsylvanian age. The Sandia is overlain by the Middle Pennsylvanian Porvenir Formation of the Madera Group. At a few localities the Sandia lies directly on Precambrian rocks, and near Agua Zarca southwest of Las Vegas, it is overlain with angular unconformity by Lower Permian rocks of the Sangre de Cristo Formation (Plate 1). On the Ojitos Frios anticline northwest of Tecolote, the Sandia is absent, apparently having been overlapped by younger Pennsylvanian rocks and the Sangre de Cristo Formation.

C. L. Herrick (1900, p. 114–115) applied the name "Sandia series" to "a siliceous series with a few limestone bands whose fossils seem to be of undoubted Coal Measure age" in the Sandia and Manzano Mountains of central New Mexico. The Sandia was described by Herrick as being overlain by limestone containing shale and having a fauna similar to that of his "Upper Coal Measures" in Ohio. C. H. Gordon (1907, p. 808–811) provided more detailed observations of equivalent rocks in the Magdalena Mountains of central New Mexico (p. 807), reviewed the published nomenclature, and (p. 816) classified Herrick's (1900) units as being in the Magdalena Group. He used the term Sandia Formation for the lower part of the group, and the term Madera Limestone for the upper part of the group.

No type section for the Sandia Formation was specified by Herrick. However, the regional map of north-central New Mexico by Read et al. (1944) included generalized sections of these rocks in parts of the Manzano, Sandia, and southern Sangre de Cristo Mountains, thereby generally specifying the contacts and lithologic contents of the Sandia Formation. Read and Wood (1947) also included graphic sections and a summary of ages, as then known, for the Sandia and for other Pennsylvanian and Permian rocks.

Baltz and Myers (1984) reviewed the history of nomenclature of the Pennsylvanian rocks and the results of mapping and paleontologic work in the Sandia Mountains (Kelley and Northrop, 1975) and the Manzano Mountains (Myers, 1969, 1973; Myers and McKay, 1976) that further established the rock-stratigraphic and age limits of the Sandia Formation in its type region. Baltz and Myers (1984, p. 18) concluded that the general heterogeneous character, the stratigraphic relations to bounding rocks, the thickness variations, and the minimum age (late Atokan) of the Sandia of central New Mexico are similar to those features of the Sandia Formation in much of the southern margin of the Sangre de Cristo Mountains; therefore, the term Sandia Formation was retained for the southeastern Sangre de Cristo Mountains. Usage of the term Magdalena Group was discontinued for the southeastern part of the Sangre de Cristo Mountains (Baltz and Myers, 1984, p. 13–14), as usage of Magdalena Group had been discontinued previously for the central New Mexico region (Myers, 1973, p. F4). A summary of the stratigraphic nomenclature and age assignments

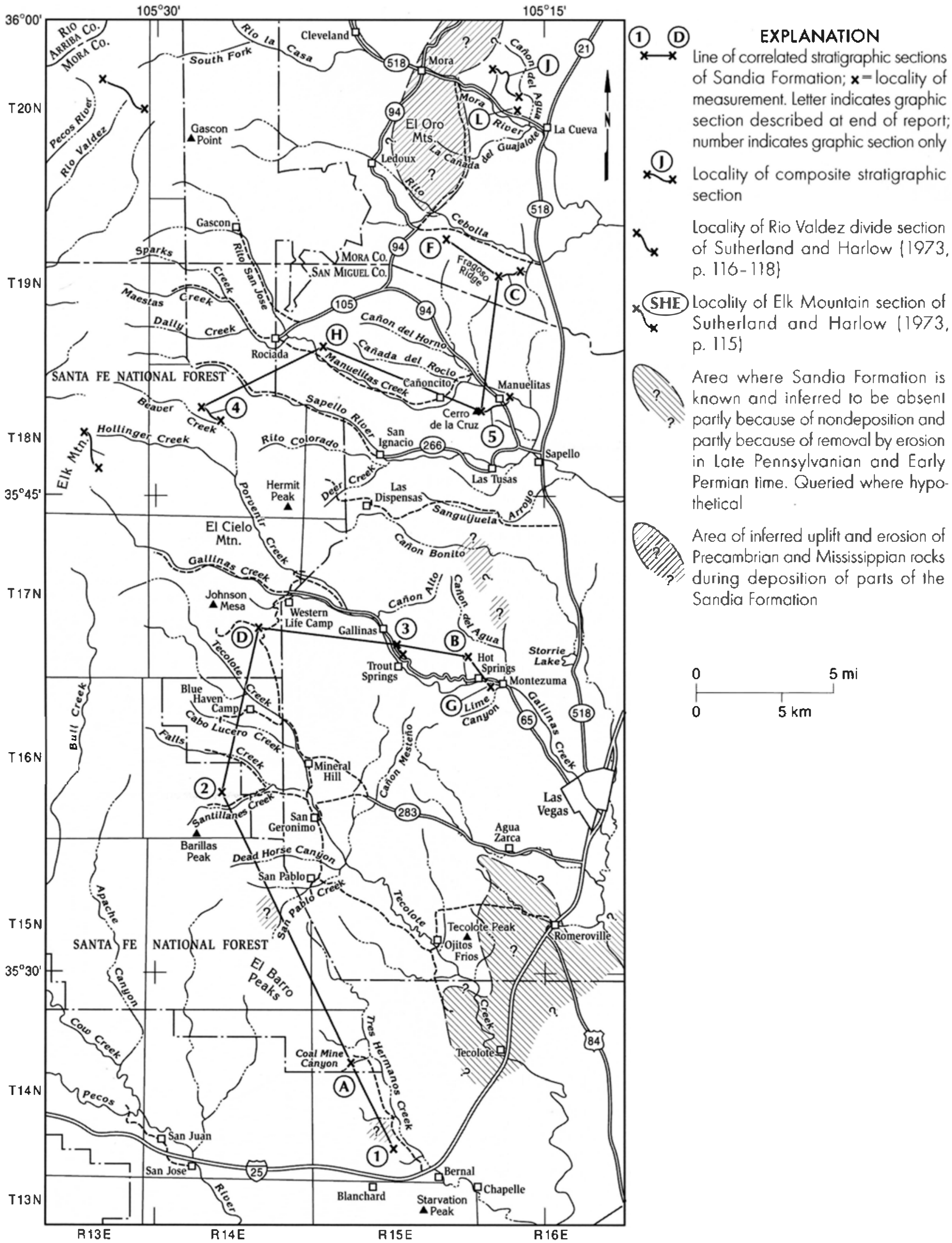
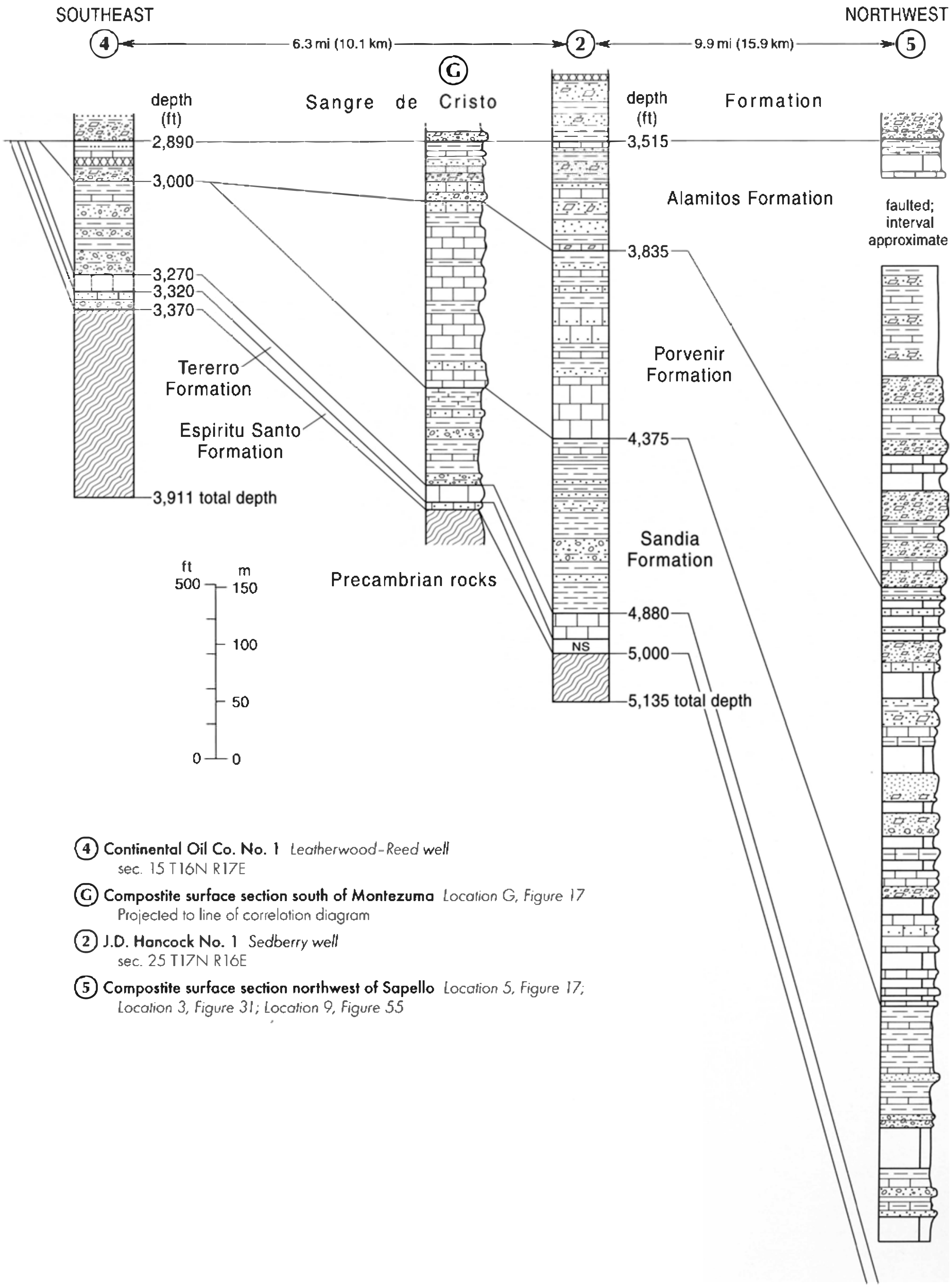


FIGURE 17—Index map of southeastern Sangre de Cristo Mountains showing localities of stratigraphic sections of the Sandia Formation. Area extends slightly west of area of Plate 1.



(4) **Continental Oil Co. No. 1** *Leatherwood-Reed well*
sec. 15 T16N R17E

(G) **Compostite surface section south of Montezuma** *Location G, Figure 17*
Projected to line of correlation diagram

(2) **J.D. Hancock No. 1** *Sedberry well*
sec. 25 T17N R16E

(5) **Compostite surface section northwest of Sapello** *Location 5, Figure 17; Location 3, Figure 31; Location 9, Figure 55*

FIGURE 18—Correlation of subsurface Mississippian, Pennsylvanian, and Lower Permian rocks of southern part of Las Vegas Basin with surface rocks of Sangre de Cristo Mountains. Line of diagram shown on Plate 4A. About 7 mi (11 km) southeast of locality of well 4, the Sangre de Cristo Formation lies on Precambrian rocks at Phillips Petroleum Company no. 1 Leatherwood well (sec. 2 T15N R18E). Lithologic symbols are explained in Figure 9. In lower part of log of well 2, NS designates interval from which no samples were reported.

of the Sandia Formation and equivalent rocks in the Sangre de Cristo Mountains of New Mexico is shown in Figure 2 of this report.

The Sandia Formation mapped for this report (Plate 1) is generally the upper clastic member of the Sandia of Read et al. (1944) and Northrop et al. (1946) and is the Sandia Formation of Baltz (1972) and Baltz and O'Neill (1984, 1986). The Sandia corresponds to the Morrowan and Atokan lower part (units 25–96) of the La Pasada Formation of Sutherland (1963, p. 59–60) at its type locality along Pecos River in the southwestern part of the Sangre de Cristo Mountains.

Distribution and thickness

The Sandia Formation is present throughout most of the southeastern Sangre de Cristo Mountains and the subsurface of the adjacent part of the Cenozoic Las Vegas Basin, except where Cenozoic erosion has removed it from structurally and topographically high parts of the mountains. Southwest and southeast of Las Vegas it is absent from outcrops and from the subsurface Sierra Grande uplift partly because of nondeposition and partly because of Late Pennsylvanian and Early Permian erosion. Outcrops of the Sandia Formation are shown on Plate 1, and the thicknesses are shown by isopachs on Plate 4. Localities of measured sections of the Sandia are shown in Figure 17.

The Sandia Formation is thinnest at the south (Plate 4). Near the southernmost exposures northwest of Bernal (loc. 1, Fig. 17) the Sandia is about 33 ft (10 m) thick. In the eastern part of the mountains, north of Tecolote Peak (Plate 1), the Sandia is only 8–20 ft (2–6 m) thick. About 1.2 mi (1.9 km) west of Agua Zarca the Sandia thins southward abruptly and is overlapped by the Porvenir Formation, which locally rests on the Espiritu Santo Formation and on Precambrian rocks (Plate 1).

The Sandia thickens northward depositionally and, in the north-central part of the area near Manuelitas Creek and Rito Cebolla (locs. H and C, Fig. 17), the Sandia is about 1,000 ft (305 m) thick. From locality C northward in the easternmost part of the mountains the Sandia thickens rapidly; about 6 mi (9.7 km) to the north it is more than 5,000 ft (1,525 m) thick at locality J (Fig. 17) north of Mora River. At locality J an unknown amount, possibly 500–600 ft (150–180 m), of section is cut out near the base by the Cenozoic Romero fault (Plate 1). Paleontologic data from localities C and J indicate that the age span (Morrowan through Atokan) is the same at both localities and that the northward thickening of the Sandia is intraformational.

In the Las Vegas Basin, data from wells south of Sapello River indicate that the Sandia thickens northwestward away from the northwest flank of the buried Sierra Grande uplift (Fig. 18). Although the Sandia is truncated by younger rocks on the flank of the Sierra Grande uplift, the northwest thickening probably is mainly intraformational. The Sandia is thicker in the basin than it is at adjacent outcrops in the mountains. This suggests that a shallow, north-plunging structural and depositional trough existed in what is now the western part of the Las Vegas Basin.

The Amoco Production Co. "A" no. 1 Salman Ranch well (Plate 3) is the only well that penetrates Pennsylvanian rocks of the Las Vegas Basin in the northeastern area of Plate 4. This well on the east flank of the Cenozoic Ocate anticline (Plate 2), penetrated about 5,090 ft (1,550 m) of rocks referable to the Sandia. However, about 310 ft (94 m) of the Sandia seems to be repeated by a reverse fault at a depth of about 6,000 ft (1,830 m). Some steep dips (from a dip-meter log) below the probable position of the fault cause some apparent thickening. Therefore, the original thickness may have been a little less than the 4,700 ft (1,432 m) shown on Plate 4. The Amoco "B" no. 1 Salman Ranch well (Plate 3), near the surface crest of the Ocate anticline about 2 mi (3 km) north of the "A" well (north of the area of Plates 1 and 4), also penetrated a reverse fault that repeats the lower part of the Sandia, the Arroyo Peñasco Group, and a thin slice of Precambrian rocks (Plate 3). The Sandia above the fault at the "B" well is about 4,000 ft (1,220 m) thick. The apparent differences in thickness of the Sandia between the wells, and the surface section (loc. J) at Mora River, suggests that the area of the present Ocate anticline was a low anticline that was active during deposition of parts of the Sandia.

Farther north in the Las Vegas Basin, between Ocate and Black Lake, the True Oil Co. no. 34 Arguello and no. 21–25 Medina wells penetrated about 4,600–4,700 ft (1,400–1,430 m) of rocks similar to the Sandia Formation, but at these localities, the Sandia contains a smaller proportion of sandstone than farther south. About 14 mi (22 km) northeast of the Amoco wells, the Shell Oil Co. no. 1 Mora Ranch well east of Ocate penetrated about 1,800 ft (550 m) of rocks referable to the Sandia, indicating eastward thinning of the formation toward the Sierra Grande uplift. (See Fig. 72 for location of wells.)

The patterns of thickening and thinning of the Sandia Formation at outcrops in the mountains indicate several Paleozoic intrabasinal uplifts and basins that have some correspondence to Cenozoic structural features. In this report separate names are given to Paleozoic intrabasinal uplifts and complementary local basins (Plate 4) to distinguish them from their Cenozoic counterparts. North of Montezuma the Sandia thickens westward from the Cenozoic La Sierrita dome into the Cenozoic Las Gallinas and Las Dispensas synclines (Plates 1 and 4). The Sandia also thickens northward from the dome toward Manuelitas Creek. At the south, west of Agua Zarca, the Sandia thickens westward from the Cenozoic Creston anticline toward the Cenozoic Chapelle syncline. These established relations of Paleozoic and Cenozoic anticlines and synclines were used as general guides for establishing isopachs in the south-central part of the area where the Sandia is concealed by younger rocks. In the south-central part the Sandia is relatively thin at exposures along El Barro fault but probably is thicker west of the ridge of Precambrian rocks, which suggests that low, northwest-trending anticlinal folds developed in the area of Cenozoic uplift during deposition of the Sandia. On the Cenozoic structural block that includes Hermit Peak, the isopachs trend northeast at a high angle to the isopachs east of the block, and the formation is thinner than to the east and north. These relations suggest that the Hermit Peak block subsided less than the adjacent areas during deposition of the Sandia.

In the northwestern part of the area, the Sandia Formation thickens northward. North of the San Miguel–Mora County line the Porvenir and the top of the Sandia have been eroded except for one area of probable Porvenir Formation north of Gascon (Plate 1), and the data are insufficient to show more than a minimum thickness of about 1,600 ft (490 m).

According to Sutherland and Harlow (1973, p. 116–118), rocks of Morrowan and probable Atokan ages are overlain by lower Desmoinesian rocks of the La Pasada Formation on the divide at the head of Rio Valdez (Fig. 17) not far west of the northwestern part of the area of Plate 4*A*. The Morrowan and probable Atokan rocks of their section 47 correspond generally to our Sandia Formation and are reported to be about 2,130 ft (650 m) thick. This control point provides some guidance for positioning the isopachs to determine the restored total thickness of the Sandia in the northwest part of the area.

About 2 mi (3.2 km) north of the northwestern part of the area of Plate 4 the Sandia is capped by limestone of the basal

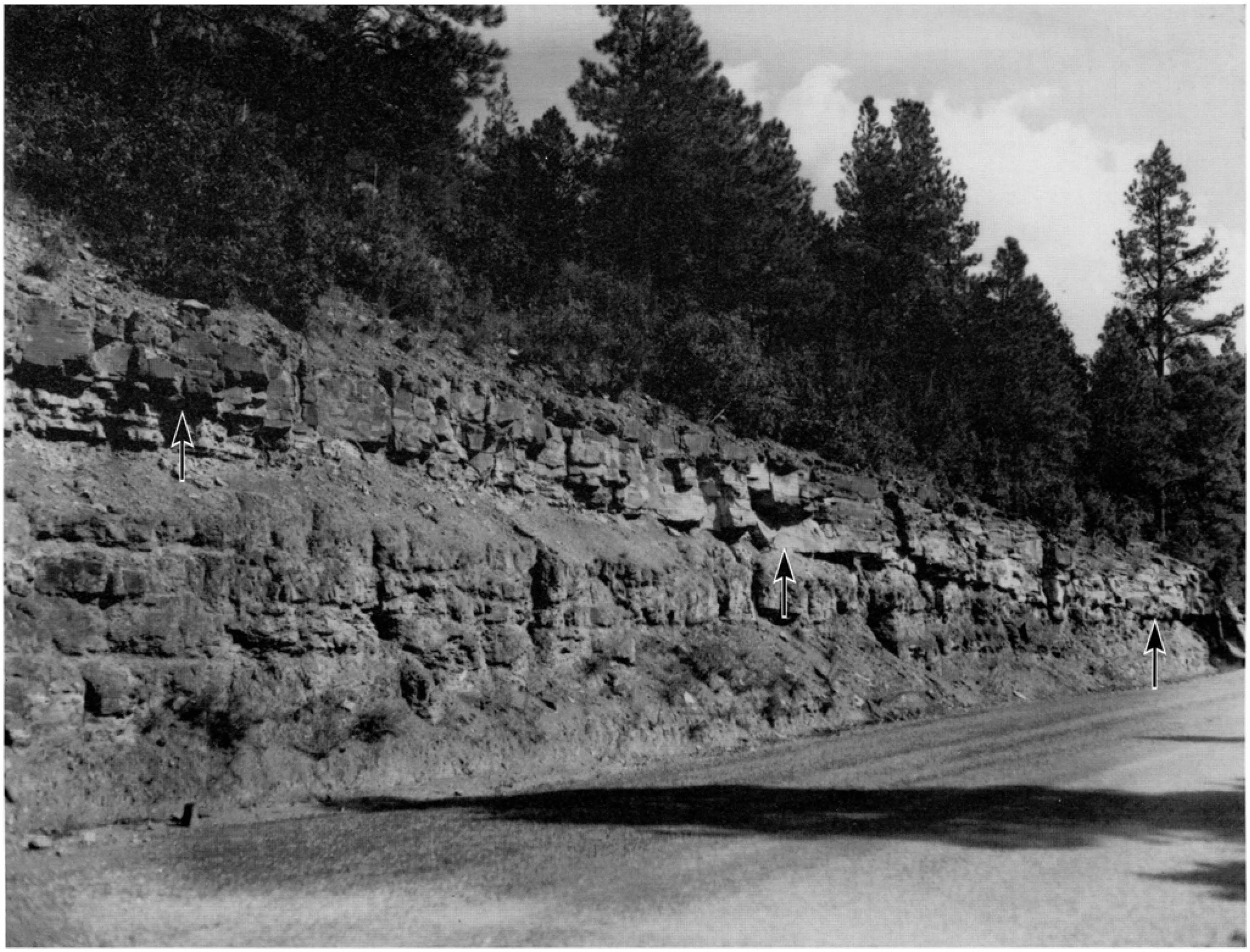


FIGURE 19—Local slightly angular unconformity (arrows) in lower part of Sandia Formation in roadcut on New Mexico Highway 65, Gallinas Creek canyon. Outcrop is near middle of locality 3, Figure 17. Ledge-forming channel sandstone in upper part of outcrop gently bevels underlying shaly rocks toward the right (east). Base of sandstone shown by arrows. Sandstone is 2–6 ft (0.6–1.8 m) thick.

part of the Porvenir Formation on a flat-topped ridge near the top of the north wall of Osha Canyon, a minor tributary of the North Fork of Rio la Casa. These outcrops lie in the axial part of the syncline east of the Gascon fault in secs 29 and 30 (projected) T21N R14E. (USGS Holman quadrangle). The lithologic assignment of these rocks to the Porvenir is confirmed by the early Desmoinesian fusulinids *Beedeina* aff. *B. arizonensis* and *Wedekindellina* aff. *W. minuta* (f10334),[1] which occur along a Forest Service road about 10 ft (3 m) above the base of the limestone. The thickness of the Sandia Formation between these outcrops and the vicinity of Cleveland, where the base of the formation is exposed (Plate 1), is estimated to be about 3,300 ft (1,000 m). The estimate is based on construction of cross sections of the lower part of the formation near Cleveland and on field-reconnaissance measurement with topographic maps of the remainder of the formation along Rio la Casa and its North Fork.

The difference in thickness of the Sandia Formation at Rio Valdez (2,100 ft) and along Rio la Casa (3,300 ft) suggests that the block west of the Cenozoic Gascon fault did not subside as much during deposition of the Sandia as did the block to the east. If so, the differential movements of Pennsylvanian time may have occurred along an east-facing monocline or along a precursor of the Gascon fault.

[1]USGS fusulinid collection. Localities of collections are described in Appendix III.

North and northwest of the area of this report a thick section of the Sandia Formation is exposed dipping steeply west from its contact with the Arroyo Peñasco Group in the high parts of the Rincon Range. The middle part of the Sandia dips steeply west across the upper valley of Mora River, and the upper part dips gently west along the slopes of Holman Hill and nearly to the top of the drainage divide traversed by New Mexico Highway 518. Thick limestone beds at and just east of the Mora–Taos County line along Highway 518 (Highway 3 on USGS Holman quadrangle) are the basal part of the Porvenir Formation and contain the early Desmoinesian fusulinid association of *Beedeina* aff. *B. arizonensis* and *Fusulinella* aff. *F. juncea* (f10150, f10151), as do the lower beds of the Porvenir in the area of this report. Estimation of the thickness from topographic maps shows that the Sandia is probably more than 3,000 ft (900 m) thick, as it is at Rio la Casa.

The restored thickness of 1,600–2,500 ft (490–760 m) for the Sandia in the northwestern part of the area of this report (Plate 4) presents problems for positioning isopachs because the formation is more than 5,000 ft thick in the adjacent eastern part of the mountains near Mora River (Plate 3). The problems are compounded south of Mora River because Cenozoic faults (Plate 1) obscure the stratigraphic relations within the southward-thinning Sandia Formation. However, the upper 1,950 ft (595 m) of the Sandia in the eastern part of the mountains, from about Rito Cebolla northward past the northern part of the area, contains thick units of micaceous sandstone and feldspathic to arkosic conglomerates. The lithologies of these rocks (Plate 3) suggest that their sediments were derived from the Precambrian rocks of the eastern part of El Oro Mountains near Mora and the Rincon Range to the north. The hypothetical zero isopach in the El Oro–Rincon area of Plate 4 indicates our interpretation of a possible west-tilted block with local angular unconformities in Pennsylvanian rocks on its western flank and with Precambrian rocks exposed to erosion on its eastern flank, at least late in Sandia time. For these and other reasons to be discussed later in the report, we suggest that, during deposition of at least the upper part of the Sandia, a major reverse fault or faults were active at the eastern margins of the present El Oro Mountains.

Inasmuch as the age span of the formation (Morrowan through Atokan) seems to be the same where the formation is thin (sec. D, Fig. 20) as where it is thick (sec. C, Fig. 22), multiple intraformational unconformities and disconformities probably are present at many places across the southeastern part of the Sangre de Cristo Mountains. Direct evidence of small intraformational unconformities can be observed at a few places (Fig. 19) and some relatively abrupt thickness variations seem to require local angular unconformities. However, the exposures are generally poor, and the Cenozoic structure is complex enough in various hogback belts that we have only a modest understanding of the details of internal thickness variations, mainly because of a lack of paleontologically controlled stratigraphic markers.

General lithology

Throughout the area the Sandia Formation is dominantly shale that contains interbedded thin to thick sandstones and granule to pebble conglomerates and subordinate amounts of generally thin limestone beds. A primary characteristic of the formation is its vertical and lateral heterogeneity that indicates highly complex marine and nonmarine environments of deposition.

The shales of the Sandia Formation are lithologically varied. Clay shale and argillaceous siltstone are common throughout the Sandia in units ranging in thickness from a few inches to about 50 ft (15 m). These rock types grade vertically and laterally into each other. The shales are mainly gray to dark gray, but olive brown, yellowish gray, and orangish gray are common colors of weathered surfaces and even fresh surfaces of some of the rocks. Calcareous shale, thin shaly limestone beds, and marly clay shale containing limestone nodules also are present at intervals throughout the formation. Carbonaceous material is common in many of the shales; it ranges from pervasively distributed microscopic fragments to megascopic plant fragments on bedding planes. Although parts of the shales are nonmarine many of them contain marine megafossils and interbedded thin fossiliferous marine limestones.

Thin, discontinuous coaly shale and shaly coal beds (a few inches to several feet thick) are present throughout the formation at places, especially in the lower part of the Sandia in the southwestern part of the area and in the subsurface at the northeast. None of the coal observed appears to be of sufficient purity, thickness, or lateral continuity for mining, although the thicker units of coaly shale have been prospected at places in the southwestern part of the area.

Sandstone beds ranging from a few inches to as much as 30 ft (9 m) thick are present in the Sandia, in varying proportions to the shales, throughout the area. At the north, multiple sets of sandstone are very thick, ranging up to 450 ft (135 m) in the vicinity of Mora River. Grains range from very fine to pebbles and cobbles. In the southern half of the area, the clasts of many of the thick sandstones are, characteristically, irregularly shaped but subrounded, medium sand to granules of gray, translucent quartzite and vein-quartz; these sandstones commonly contain small, subrounded pebbles that also are quartzite and milky vein quartz. The sandstones are cemented mainly by silica, but partly by clay and iron-oxide. Flakes of muscovite and weathered, gray and yellowish-gray feldspar grains are minor constituents of the sandstones in the southern part of the area. The sandstones of the Sandia commonly weather light to medium brown; fresh colors often are light yellowish gray to light brownish gray. Limonite-replaced fossil wood ranging from small fragments of twigs and leaves to logs are present in many sandstones throughout the area. Many logs are recognizable as *Calamites* sp. and *Lepidodendron* sp.

From about Manuelitas Creek northward in the eastern part of the mountains the sandstones are feldspathic, and at Mora River some sandstones in the upper part of the formation are arkosic; some pebble conglomerates in the upper part of the formation contain ragged, fresh-appearing, white, yellowish-gray or pink, angular feldspar granules and feldspar pebbles that are commonly 0.25–0.5 inch (0.6–1.3 cm) across and range up to 1.5 inches (3.8 cm) across.

Bedding of the sandstones ranges from very thin to massive. Some units are parallel to subparallel bedded and sheetlike; others are inclined bedded and lenticular, and others are crossbedded, irregularly shaped, channel deposits that thicken and thin abruptly. Some of the sandstones are terrestrial, but others are marine.

Fossiliferous marine limestones commonly are scattered vertically through the Sandia, although they are a small portion of the formation. Generally, the limestones are thin, ranging from a few inches to 2 or 3 ft (0.6–0.9 m) thick. Locally, units of limestone, 15–30 ft (4.5–9 m) thick, occur in the lower and upper parts of the formation. The limestones range from shaly to relatively massive, and most are well bedded. Sandy limestones are common, and in places they grade laterally into calcareous sandstone. A common and characteristic limestone type in the Sandia is micrite that contains usually unbroken brachiopods, gastropods, and other fossils "floating" in the matrix. Phylloid algae occur in limestones in places, some limestones are finely banded stromatolites, and some bioclastic limestones are shallow-water bank deposits. All the limestones weather gray or yellowish gray, but they are commonly dark gray and occasionally black on fresh surfaces, reflecting a large content of organic matter. At places the upper 50–100 ft (15–30 m) of the formation contains thin, coarsely bioclastic limestones that weather light yellowish brown to light orangish brown and contain fusulinids.

Areal stratigraphy and lithology

Southern half of area—Northwest of Bernal, at exposures near the Bernal and El Barro faults (locs. 1, A, 2, Fig. 20), the Sandia generally consists of a thin, coarse-grained, basal sandstone overlain by shaly siltstone and sandstone with a few limestone beds, in turn overlain by gray clayey shale with interbedded thin marine limestones. Commonly, the lower shaly siltstone and sandstone are carbonaceous. At places, coaly shale occurs at or near the base of the formation as in the canyon east of locality A (Fig. 17). About 0.6 mi (0.95 km) north of locality 1 (Fig. 17) the Sandia is composed almost entirely of coarse-grained sandstone about 100 ft (30 m) thick that might be derived locally from the Precambrian, but about 0.8 mi (1.3 km) farther north, the upper part of the formation again contains gray shale and thin limestones. Just north of San Pablo Creek (SW¼NE¼

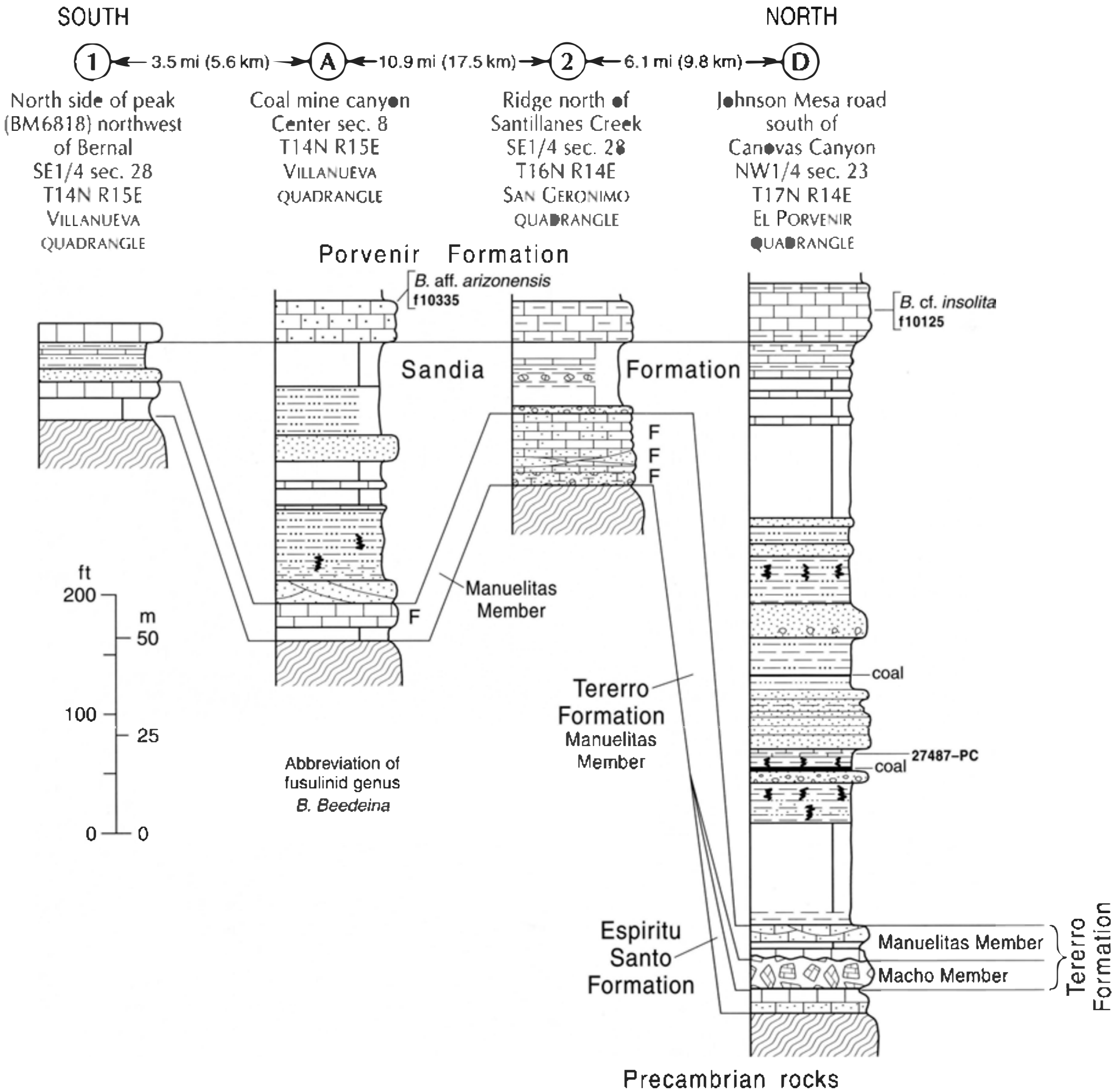


FIGURE 20—Stratigraphic sections of Sandia Formation, Tres Hermanos Creek–Gallinas Creek area. Localities of measurement and line are shown in Figure 17. Lithologic symbols are explained in Figure 9.

sec. 14 T15N R14E, USGS San Geronimo quadrangle), where the Arroyo Peñasco Group is absent, sandstone in the lower part of the Sandia contains nodular clasts of concentrically banded chert similar to nodules of the Espiritu Santo Formation, suggesting at least a small nearby area of uplift and erosion of Mississippian and possibly Precambrian rocks in Early Pennsylvanian.

To the north, in the vicinity of Cabo Lucero Creek, the formation thickens generally northeastward and becomes more complex internally; in particular, at locality D, it includes a lower unit, predominantly shale, which contains Morrowan megafossils (collection 27487–PC). In USGS El Porvenir quadrangle between Cabo Lucero Creek and locality D, the basal part of the Sandia contains coaly shale and shaly coal at Topside Canyon (NW¼ sec. 4 T16N R14E) and near Encinoso Canyon (SW¼ sec. 27 T17N R14E). Coaly shale occurs at the base of the Sandia also in the upper part of Gallinas Creek (SE¼ sec. 8 T17N R14E).

Near the eastern front of the mountains, at exposures along New Mexico State Road 283 about 2.3 mi (3.7 km) northwest of Agua Zarca, the Sandia is about 120 ft (36 m) thick. Lenticular conglomeratic sandstone is present at the base at a few places, but the formation is mainly olive-brown-weathering clayey shale with interbedded siltstone and thin fine-grained sandstone. These rocks contain thin carbonaceous-shale layers and fossil-plant impressions. The upper quarter of the formation contains a few limestone nodules, calcareous gray shale, and a few 2-inches- to 1-ft (5–30-cm) thick beds of gray fossiliferous limestone. About 1 mi (1.6 km) west of Agua Zarca the Sandia is 0–20 ft (0–6 m) thick and is almost entirely conglomeratic sandstone, as it is farther southwest where it is overlapped by the Sangre de Cristo Formation north of Tecolote Peak (Plate 1).

Throughout the southern part of the area, the upper gray shale with interbedded limestones forms a marine unit that is conformable with the overlying Porvenir Formation. About 1.3 mi (2.2 km) northwest of locality 1 (Fig. 17), the unit contains late Atokan fusulinids (loc. f10306). These rocks were deposited during transgression of the sea across most of the southern shelf that culminated in Desmoinesian

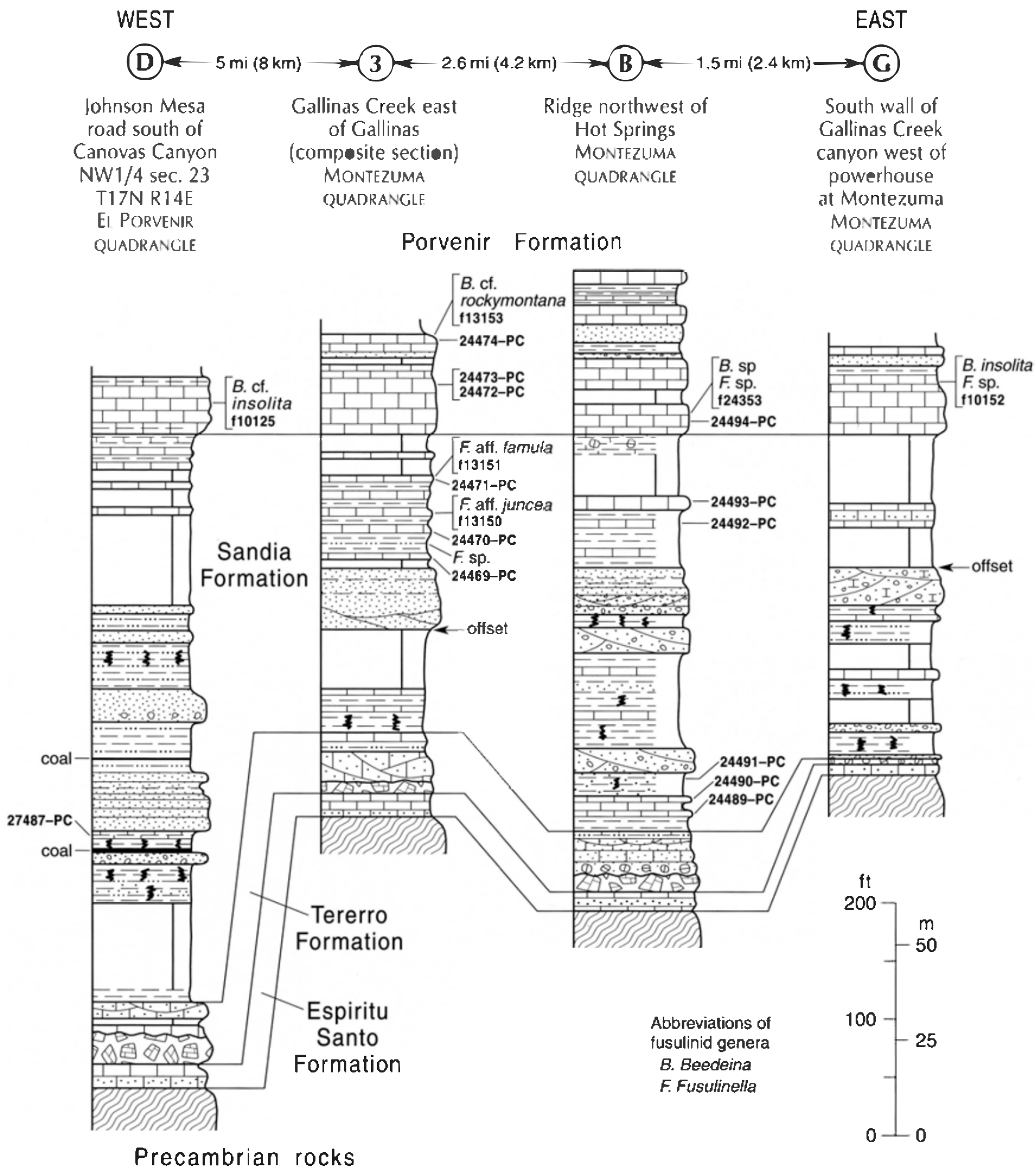


FIGURE 21—Stratigraphic sections of Sandia Formation, Gallinas Creek area. Localities of measurement and line are shown in Figure 17. Lithologic symbols are explained in Figure 9.

time when the mainly marine Porvenir Formation was deposited.

Gallinas Creek—The Sandia Formation is exposed widely in the Gallinas Creek area (Fig. 21) where it forms ledgy slopes beneath a caprock of limestones of the Porvenir Formation. Exposures commonly are poor because of extensive colluvial cover; however, enough exposures exist to determine the general character of the formation. A threefold stratigraphic subdivision exists. The lower part is generally shaly but contains thin fossiliferous limestones, some sandstone, carbonaceous shale, and some thin coal, as at the powerhouse at Montezuma. The medial part contains shale and several ledge-forming sandstones and conglomeratic sandstones. The upper part is gray clayey shale and calcareous shale, and interbedded thin, gray fossiliferous limestones and some sandstone. South of Montezuma, the thick, conglomeratic sandstone near the middle of the Sandia at locality G (Figs. 21 and 85) bevels down, westward, across underlying beds, locally eliminating most of the lower part of the formation; the Sandia is only about 100 ft (30 m) thick a few hundred yards west of locality G, but the lower part thickens northwestward toward locality B (Figs. 17 and 21).

A similar sequence, 300–400 ft (90–120 m) thick, is present in the Johnson Mesa area west of locality D (Figs. 17 and 21) and on El Cielo Mountain between Gallinas and Porvenir Creeks southwest of Hermit Peak (Fig. 17). Shales in the lower part commonly are carbonaceous and at places coaly. However, north of Porvenir Creek the Sandia thickens to at least 900 ft (275 m) in hogbacks along the southeast side of Hermit Peak and the shaly units throughout the formation become much thicker northward to where the formation is cut out by the Hermit Peak fault (Plate 1).

Near the eastern front of the mountains, north of Montezuma, the Sandia thins rapidly north of the mouth of

Cañon del Agua and consists mainly of sandstone and some shale (probably the middle and upper parts of the formation) that is about 100 ft (30 m) thick just south of the point where it is cut out by the Montezuma fault (Plate 1). Farther north the Sandia is exposed again west of the Montezuma fault, is about 300 ft (90 m) thick, and is lithologically generally similar to the Sandia near Montezuma. However, north of Cañon Bonito, where the formation lies on the Precambrian, the basal part is feldspathic conglomerate whose clasts are similar to underlying Precambrian granitic gneisses.

Beaver Creek–Manuelitas—In the central part of the area, north of Hermit Peak and Cañon Bonito, the Sandia Formation thickens to 900–1,000 ft (275–300 m) and contains thick units of gray shale (Fig. 22). To the west, in exposures along the Cenozoic Beaver Creek syncline from Hollinger Creek northward past Sparks Creek (Plate 1), thick pebbly sandstones in the lower part of the Sandia (loc. 4, Fig. 22) are similar to the medial zone of sandstones in the Gallinas Creek area (Fig. 21), and the thickening of the formation seems to have occurred mainly in the rocks equivalent to the upper shales, sandstones, and thin limestones of Gallinas Creek. The shales in the Beaver Creek syncline are generally gray to dark gray, calcareous clayey shale and silty clayey shale. Thin- to shaly-bedded, fossiliferous, marine limestones occur in the shales, and a few thick beds of gray bioclastic and sandy limestone occur. Ledge-forming, medium to very coarse grained quartz sandstones, 10–20 ft (3–6 m) thick, are interbedded with the shales at stratigraphic intervals of 20–200 ft (6–60 m). These sandstones are parallel bedded to inclined bedded and form sheet-like bodies, some of which can be traced or correlated for more than a mile (1.6 km) and probably are more extensive areally.

The same general lithologic character persists northward in the Cenozoic Sparks syncline (Plate 1) and the syncline east of the Gascon fault (the Paleozoic Rociada Basin, Plate 4*A*), where the northward-thickening Sandia is more than 1,600 ft (490 m) thick. The formation is dominantly shale but contains interspersed thin to thick fine-grained to conglomeratic sandstones. North of the area of this report (Plate 1), along New Mexico Highway 518 west of Holman, the upper half of the Sandia is mostly dark gray shale that contains some thick limestones but only a small proportion of sandstone. The Sandia in that area probably is more than 3,000 ft (900 m) thick.

To the east, in the hogbacks east of Rociada (loc. H, Fig. 87), the overall lithology of the Sandia is similar to that of the Beaver Creek area, but we are uncertain whether the basal sandstones are equivalent to the medial sandstones of the Gallinas Creek area or whether the medial sandstones are not represented east of Rociada. The Sandia east of Rociada contains a greater proportion of limestone than to the west. At places east of Rociada, the upper part contains one or two relatively thick units of light-gray finely bioclastic limestone that are lithologically similar to some of the limestones of the overlying Porvenir Formation.

In the eastern part of the mountains on the Paleozoic Manuelitas saddle (Plate 4*A*), the Sandia Formation is exposed extensively on the flanks of the Cenozoic Cerro de la Cruz anticline (Plate 1), but the lowest part of the formation is not exposed in this area. A composite section, the base of which is not exposed, was measured from Manuelitas Creek southwestward up the north side of Cerro de la Cruz (loc. 5, Figs. 17, 22). The Sandia is at least 680 ft (207 m) thick. The exposed part of the formation is similar to the section farther west, consisting mainly of gray and dark-gray shale that contains a small proportion of interbedded thin to shaly bedded fine-grained sandstone and thin, dark-gray, commonly carbonaceous, bioclastic to micritic limestones. Ledge-forming sandstones are widely dispersed, stratigraphically, through the shale. The sandstones are medium to very coarse grained; beds of granule to small-pebble conglomerate are present. These rocks are mainly quartzose, although traces of mica and deeply weathered yellowish-gray feldspar are present in some beds.

In the vicinity of Manuelitas, a zone of ledge-forming sandstones with interbedded shale occurs in the upper part of the Sandia, approximately 150–200 ft (45–60 m) below the top; the sandstones are parallel to subparallel bedded, sheet-like, and form a persistent zone (Fig. 23) that can be traced around the north side of Cerro de la Cruz and around the north side of the anticline north of Manuelitas Creek. On the north side of Cerro de la Cruz, sandstone of this zone is irregularly bedded and cross-laminated and contains numerous limonite-replaced wood twigs. An unusual conglomerate that contains large limestone clasts forms a prominent, vertical ledge about midway up the north slope of Cerro de la Cruz. This conglomerate occurs also in the ridges of the Sandia east of Manuelitas but may wedge out west and north of Manuelitas. The matrix of this rock is very fine to coarse quartz sand and granules; quartzite and vein quartz pebbles as much as 2 inches (5 cm) diameter are abundant. About 35 percent of the lower 6–8 ft (1.8–2.4 m) of the rock is clasts of limestone that range from tiny pebbles to boulders 1 ft (0.3 m) across. The limestone pebbles and boulders are in irregular layers in the poorly sorted sand, and the clast size becomes smaller upward. Many of the limestone clasts are dense micrite, but other clasts are finely banded stromatolite, and a few are fragments of *Chaetetes*. Some of the limestone cobbles and boulders are highly irregular in shape and do not appear to have been transported for more than a short distance; they may have been ripped up from subjacent beds of the Sandia. The quartz pebbles, however, were derived from a Precambrian terrane. Crossbedding and laminae are inclined toward the northwest suggesting that the source terrane of Precambrian detritus was at the southeast or south, possibly on the northern part of the Paleozoic Tecolote uplift near Cañon Bonito where the Sandia is only about 300 ft (90 m) thick and lies on Precambrian rocks.

The upper 200 ft (60 m) of the Sandia is a generally shaly interval that contains areally varying proportions of thin to shaly, light-gray limestones and lenticular coarse-grained sandstones. Much of the shale is dark gray, and some is carbonaceous, especially near the top of the formation. Ledge-forming sandstones are most common in the upper shaly interval on the southeast limb of Cerro de la Cruz anticline north of Sapello River and, locally, southwest of Las Tusas (Plate 1) in the area closest to the northern part of the Paleozoic Tecolote uplift (Plate 4).

Rito Cebolla—Near the eastern front of the mountains, on the northeast slopes of Fragoso Ridge a short distance south of Rito Cebolla (loc. C, Figs. 17, 22), Precambrian rocks are exposed in two small canyons on the east flank of the Woods anticline (Plate 1). The Espiritu Santo Formation is present in the southern of the two canyons. This is the only place in the eastern part of the mountains between Cañon Bonito and Mora River where the entire Sandia Formation is exposed; it is about 1,000 ft (305 m) thick. The lithology is similar generally to that at the southwest except that sandstones in the lower and upper parts are more feldspathic at locality C than they are farther south. Morrowan megafossils (collection 28676–PC) occur in marly shale and interbedded thin limestone 100–150 ft (30–45 m) above the base, and late Atokan fusulinids (loc. f10132) were found at locality I (Figs. 31, 46) at the north side of Rito Cebolla in thin coarsely bioclastic limestone about 75 ft (23 m) below the top of the Sandia.

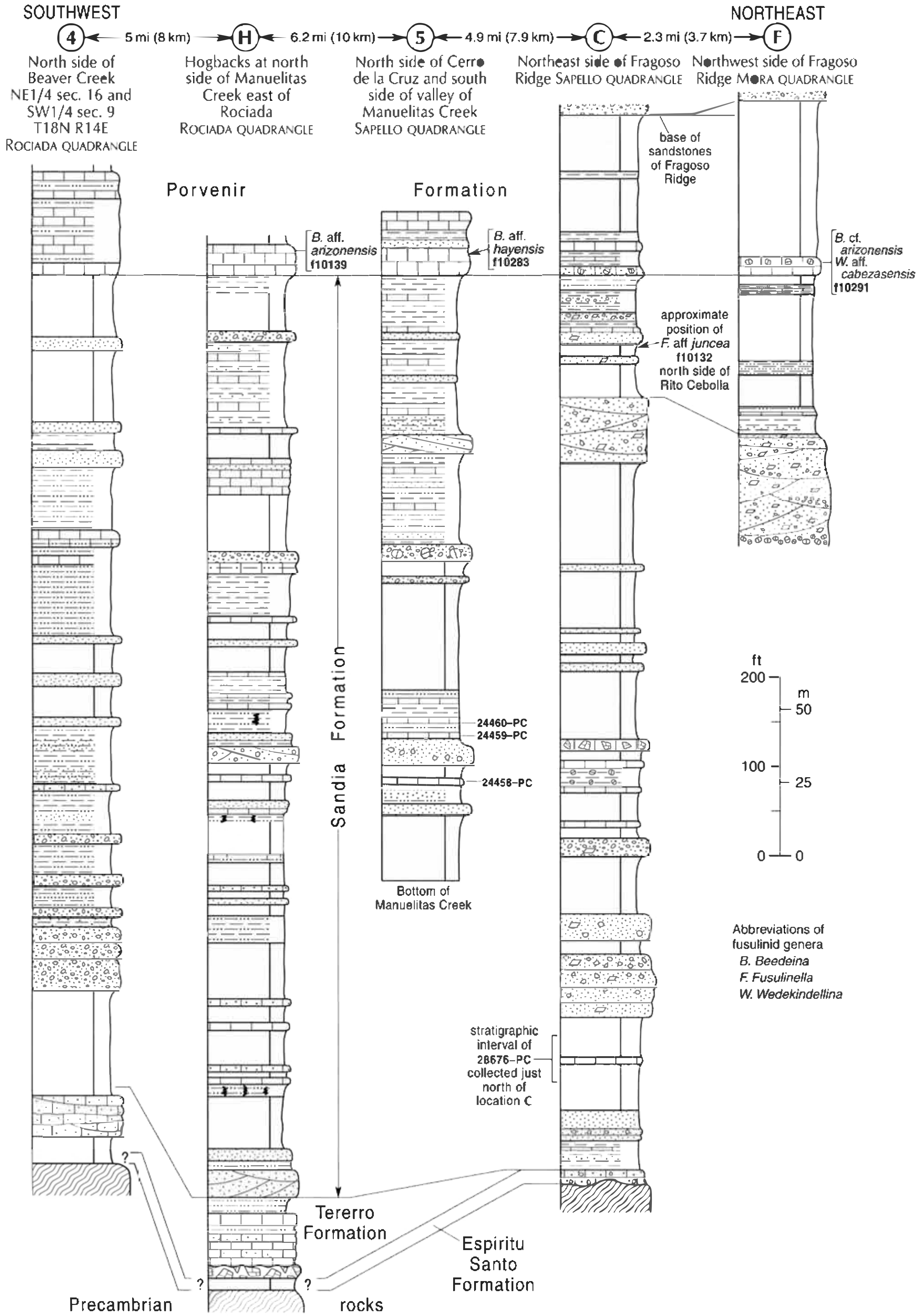

SOUTHWEST
NORTHEAST
4
5 mi (8 km)
H
6.2 mi (10 km)
5
4.9 mi (7.9 km)
C
2.3 mi (3.7 km)
F
North side of Beaver Creek NE1/4 sec. 16 and SW1/4 sec. 9 T18N R14E ROCIADA QUADRANGLE
Hogbacks at north side of Manuelitas Creek east of Rociada ROCIADA QUADRANGLE
North side of Cerro de la Cruz and south side of valley of Manuelitas Creek SAPELLO QUADRANGLE
Northeast side of Fragoso Ridge SAPELLO QUADRANGLE
Northwest side of Fragoso Ridge MORA QUADRANGLE
Porvenir
Formation
B. aff. arizonensis f10139
B. aff. hayensis f10283
base of sandstones of Fragoso Ridge
B. cf. arizonensis W. aff. cabezasensis f10291
approximate position of F. aff juncea f10132 north side of Rito Cebolla
Sandia Formation
24460–PC
24459–PC
24458–PC
Bottom of Manuelitas Creek
ft
200
100
0
m
50
25
0
Abbreviations of fusulinid genera
B. Beedeina
F. Fusulinella
W. Wedekindellina
stratigraphic interval of 28676–PC collected just north of location C
?
Tererro Formation
Espiritu Santo Formation
Precambrian
rocks

FIGURE 22—Stratigraphic sections of Sandia Formation, Beaver Creek to Fragoso Ridge. Localities of measurement and line are shown in Figure 17. Lithologic symbols are explained in Figure 9.

FIGURE 23—Subparallel-bedded, coarse- to granule-grained conglomeratic sandstones and interbedded gray shale of locally persistent zone in upper part of Sandia Formation, north side of Manuelitas Creek about 0.5 mi (0.8 km) northwest of Manuelitas. Zone is about 200 ft below top of formation. Sandstone beds are 10–20 ft (3–6 m) thick.

The lower ledge-forming sandstones at locality C (Fig. 22) and in low cliffs north of Rito Cebolla and west of the Sapello fault (Plate 1; Fig. 88) are mainly coarse grained to conglomeratic; about 20 percent of the clasts is granule size. About 5 percent of all clasts is yellowish-gray feldspar. The clasts are angular to subround, with the coarser grains being mainly angular. The grain size increases upward and, near the top, the clasts are mostly granules and pebbles as much as 0.25 inch (0.6 cm) diameter. Bedding is subparallel to slightly inclined.

Much of the higher part of the Sandia at locality C is poorly exposed or is concealed by colluvium. Where concealed intervals can be seen nearby, they are mainly gray shale that contains some thin sandstone and some thin micritic limestone. A relatively thick limestone, below the middle of the Sandia at locality C, contains traces of fine algal banding, angular limestone breccia, and scattered crinoid columnals. This unit has undulatory bedding that forms small mounds and is stromatolitic. Near the middle of the formation, thick gray shale contains several beds of coarse-grained sandstone and granule conglomerate that are well sorted and whose bedding is parallel to gently inclined.

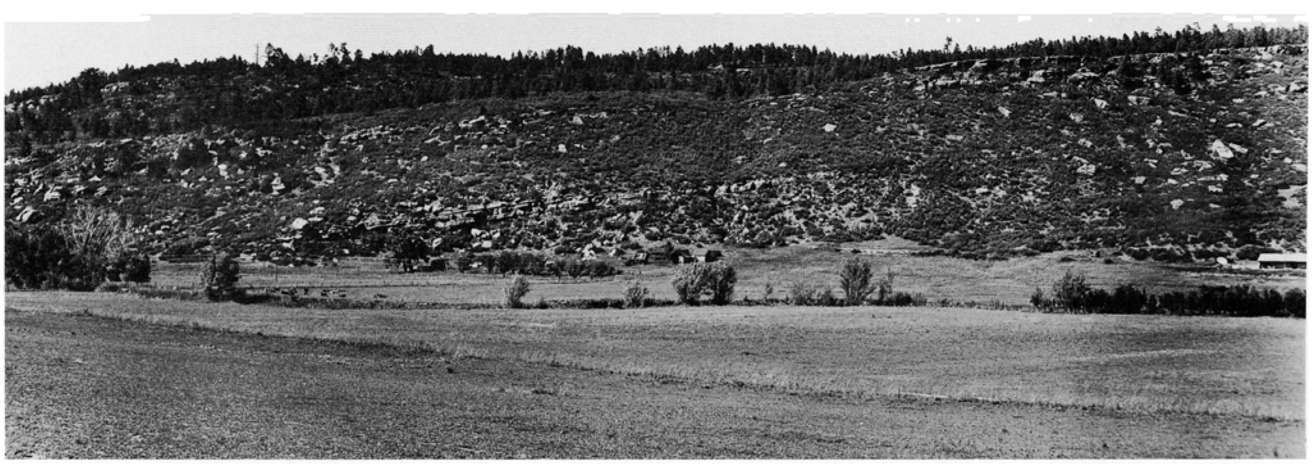


FIGURE 24—Sheet-like sandstones in thick units of gray shale near middle of Sandia Formation. Sandstones form small ledges on slope and top of bench in middle ground. Slopes are mainly shale. Bedding of sandstones is subparallel to gently inclined. Hills north of Rito Cebolla about 2 mi (3.2 km) west of New Mexico Highway 518.

These sandstones correlate generally with similar sheetlike sandstones in thick shale near the middle of the Sandia north of Rito Cebolla (Fig. 24).

The upper part of the formation at locality C contains a unit of conglomeratic sandstone, about 75 ft (23 m) thick (unit 33, described in section C), that is composed of very coarse to granule-size, angular to subangular quartz clasts and quartz pebbles as large as 1 inch (2.5 cm). These rocks contain a trace of yellowish-gray, weathered feldspar. The unit is irregular bedded to crossbedded with scour-and-fill structures. The unit thickens northwestward and, a little more than 2 mi (3 km) to the northwest, it is more than 120 ft (35 m) thick on the west limb of the Capulin syncline (Plate 1) north of Rito Cebolla, and on the axis of the adjacent anticline south of the stream at locality F (Figs. 17, 22). At locality F the unit (unit 2, described in section F) is coarser than farther east and about 20 percent of the clasts, including pebbles as large as 0.25 inch (0.6 cm), are yellow to yellowish-pink feldspar. The unit at locality F contains lenses and scattered pebbles, 0.5–2 inches (1.3–5 cm) in diameter, of subangular to subround vein quartz, and, near the base, limestone pebbles. The unit probably is a southeastward thinning fan of detritus eroded partly from underlying sedimentary rocks but mainly from Precambrian rocks that may have been exposed in the area of the present El Oro Mountains. Similar rocks occur in about the same stratigraphic position at Mora River farther north (loc. J7, Fig. 26).

The highest part of the Sandia Formation in the vicinity of Rito Cebolla consists of gray shale, interbedded thin gray fossiliferous limestone, and thin feldspathic and micaceous sandstone. This part of the section, which thickens slightly northwestward between localities C and F, is well exposed at places in the axial part of the Capulin syncline north of Rito Cebolla.

The Sandia in the fault-bounded triangle north of Rito Cebolla (Plate 1) is stratigraphically and lithologically similar to the Sandia at locality C (Fig. 22) except that the formation is thicker north of Rito Cebolla. At least 1,500 ft (460 m) of Sandia is exposed in hogbacks on the west limb of the Capulin syncline just north of Rito Cebolla but the lower (western) part is cut out by thrust faults and the total thickness is not known. About 2 mi (3.2 km) north of Rito Cebolla the triangular structural block is terminated by a mainly concealed, northeast-trending, strike-slip fault (Baltz and O'Neill, 1984; Plate 1) that throws the lower part of the Sandia north of the fault against the upper part of the Sandia south of the fault. The Sapello fault north of Rito Cebolla has thrust the lower and medial parts of the Sandia across the upper part and locally cuts out the lower part of the Porvenir Formation. The great northward thickening and pronounced facies changes of the Sandia take place mainly within this area of complex Cenozoic structure between locality C and Mora River.

Mora River area—North of Mora River (Paleozoic Rainsville trough, Plate 4) the Sandia Formation is exposed in a series of north-northeast-trending hogback ridges and intervening strike valleys that form an outcrop belt in some places as much as 7,500 ft (2,290 m) wide. The rocks dip east-southeast, generally. However, near the river and at outcrops along New Mexico Highway 518 (formerly New Mexico 3), the rocks are crumpled and the lower part of the section is disrupted by the northern extensions of the Guajalote and Sapello faults and by the Romero fault (Fig. 25; Plate 1).

A short distance north of the river the rocks generally dip 60–75° east-southeast. To the west the dips are locally vertical to overturned; at places the overturned beds dip west at angles as low as 45–50° in a belt just east of the Romero fault (Plate 1). From the upper drainage of Cañon del Agua north, the main part of the Sandia is sharply folded and broken by several reverse faults (Plate 1, sec. *A–A'*). In order to map the Cenozoic structure of this area and to determine a place suitable for measuring the thickness, the Sandia was subdivided into informal units north of Mora River by mapping the bases of five distinctive ridge-forming sandstones that were designated informally as the "a–e" sandstones (Baltz and O'Neill, 1984). A detailed geologic map of this area (Fig. 89) shows the offset localities of measurement (J1 through J7) of a composite section of the Sandia Formation (Fig. 26; Plate 3) at locality J. The section was measured in this manner in order to avoid, as much as possible, areas where the rocks are faulted or extensively concealed. This section is designated as a principal reference section for the Sandia Formation; it is described near the end of this report (Appendix II).

The Sandia is at least 5,030 ft (1,530 m) thick at locality J (Fig. 89), with an unknown amount cut out near the base by the Romero fault. The lower part, more than 700 ft (215 m) above the base, contains Morrowan megafossils (collection 27164–PC) similar to megafossils (collection 28676–PC) 100–150 ft (30-45 m) above the base of the formation at locality C south of Rito Cebolla (Fig. 22). Fossils were not obtained at locality J from the sparingly fossiliferous upper part of the Sandia. However, the Sandia appears to be mainly conformable with the overlying Porvenir Formation whose lower beds contain abundant early Desmoinesian fusulinids. Therefore, the upper part of the Sandia probably is late Atokan age at Mora River, as it is at the north side of Rito Cebolla where late Atokan fusulinids are present near the top.

The thickness of the Sandia Formation at locality J is considerably greater than previously reported thicknesses of the entire Pennsylvanian section (including rocks overlying the Sandia) at Mora River. Foster et al. (1972, p. 16) reported that the total thickness of known Pennsylvanian rocks at Mora River is 3,655 ft (1,114 m); they noted, however, that part of the section may have been cut out by thrusting, a suggestion that is substantiated by later work (Baltz and O'Neill, 1984). Isopachs by Roberts et al. (1976, figs. 4 and 5) indicated that the total thickness of the Morrowan and Atokan rocks near Mora is on the order of 2,000 ft (610 m). Casey (1980a, fig. 6) also indicated that Morrowan and Atokan rocks thin greatly eastward across the Pennsylvanian depositional basin through the Mora River area.

The difference in thickness of section J and the previously reported thicknesses probably is due mainly to previous measurements having been made near Mora River. There, the Guajalote and Sapello faults are obscured by Quaternary alluvium, and the effects of these faults on cutting out part of the section are not as apparent as in outcrops south of Mora River.

North of Mora River, the Sandia Formation, below the "d" sandstone (Fig. 26; Plate 3), consists of thick units of gray to dark-gray shale and interbedded fossiliferous limestones and thin to thick sandstones. Thin coal beds and carbonaceous shale occur sparingly. Some of the limestone units are thicker than they are in areas to the south. These thicker limestones commonly are light to medium gray, highly fossiliferous, and bioclastic; they contain brachiopods, bryozoans, crinoid columnals, algae, and other fossils. The thinner limestones mainly are dark gray, micritic, and sparingly fossiliferous; some are fetid.

The sandstones in the lower part range from fine to very coarse grained. Pebble conglomerates are present sparingly and contain angular to subangular quartz sand and granules and small quartzite pebbles as they do farther south. Most of the sandstones in the lower part of the Sandia are nonfeldspathic or contain only traces of weathered, yellowish-gray

FIGURE 25—Crumpled beds of lower part of Sandia Formation, along New Mexico Highway 518 on north side of Mora River valley about 2.5 mi (4 km) southeast of Mora. Beds at left (west) are on east limb of a syncline whose west limb is overridden by Precambrian rocks of the Romero fault about 1,000 ft west of area of photograph. Beds at far right dip steeply east forming the crumpled east limb of an anticline. Syncline and anticline are in the northern part of a plate of the lower part of the Sandia that has been thrust eastward along the Guajalote and Sapello faults (Plate 1) whose concealed traces are in an alluviated strike valley about 700 ft east of area of photograph. South of Mora River the crumpled plate of the lower part of the Sandia cuts out successively higher parts of the Sandia. (See Baltz and O'Neill, 1984; Plate 1 and Figure 89 of this report; and Baltz and O'Neill, 1990 fig. 3.15.)

feldspar. Sandstone "c" is the stratigraphically lowest unit in which feldspar is a major constituent (about 10 percent). Many of the sandstones are micaceous, particularly those that are fine to medium grained. Most of the sandstones are parallel bedded to inclined bedded.

Beginning at about the base of the "d" sandstone, the upper 1,950 ft (595 m) of the Sandia is a facies that is strikingly different from most of the Sandia farther south. Although thick parts of this interval are dark-gray shale containing micritic thin limestone, much of the interval is sandstone and conglomerate in units 50–450 ft (15–137 m) thick. The sandstones range from fine to coarse grained and some units are granule-and-pebble conglomerate; bedding ranges from very thin and parallel, to thick and crossbedded. Many sandstones are micaceous; as much as 25 percent of some finer grained beds is muscovite flakes. The coarser grained sandstones and conglomerates generally are feldspathic to arkosic; feldspar content ranges from 5 to 30 percent. Feldspar occurs in all clast sizes up to small pebbles and, occasionally, pebbles 1 inch (2.5 cm) across. Generally, the feldspars are weathered, white to yellowish-gray, and probably are mostly plagioclase. Pink potassium feldspar is common only above the "e" sandstone. Most clasts (quartz and feldspar) are angular to subangular; some feldspar clasts are highly irregular and ragged in shape. Vein-quartz granules and pebbles are common; fragments of granite pegmatite and dark-colored igneous rocks occur sparingly. Fossil plant fragments occur in some intervals, particularly in fine- to medium-grained sandstones; thin carbonaceous to coaly shale lenses are interbedded in the upper parts of some of the conglomeratic sandstone units. Upward-coarsening sequences occur; upward-fining sequences occur also.

This interval (sandstone "d" and above) is present at outcrops just south of Mora River, but it is cut out progressively southward by the Sapello fault, which throws a plate of southeast-striking rocks of the middle or lower part of the Sandia against progressively higher beds of the upper part of the Sandia (Fig. 89). A short distance south of La Cañada del Guajalote the upper part of the Sandia and the lower part of the Porvenir Formation both are cut out by the Sapello fault (Baltz and O'Neill, 1984; Plate 1).

Our reconnaissance indicates that the thick upper interval containing sandstones persists northward in the hogback ridges at least 6 mi (9.6 km) north of the area of this report, and possibly farther north to the vicinity of Guadalupita. The stratigraphic position of these rocks of the Sandia can be confirmed at places, as just south of the sharp north bend of the dirt road west of Los Cisneros (USGS Lucero quadrangle), where they are overlain by oolitic limestone containing the fusulinid *Beedeina arizonensis* (f10303) that occurs also

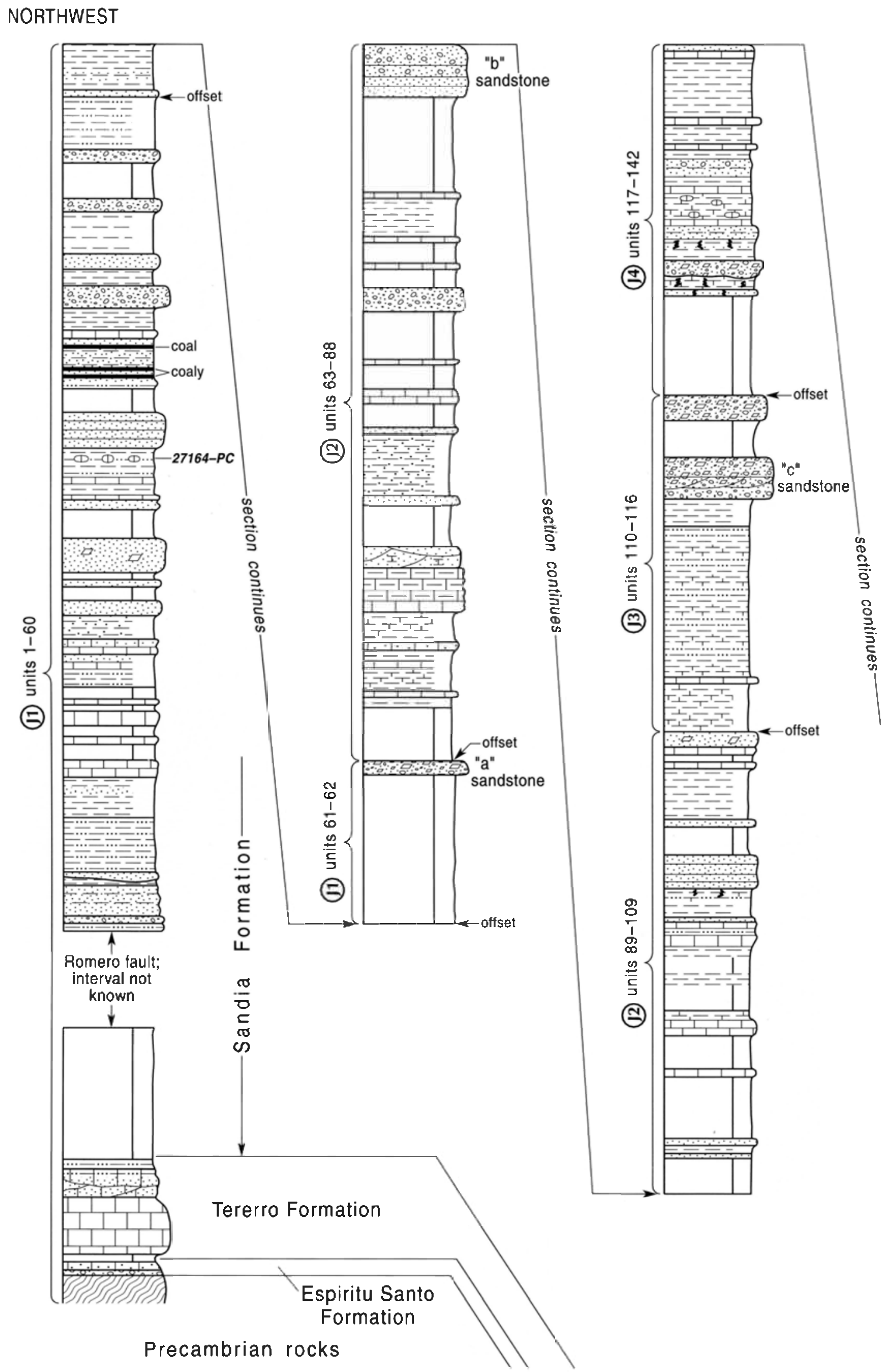
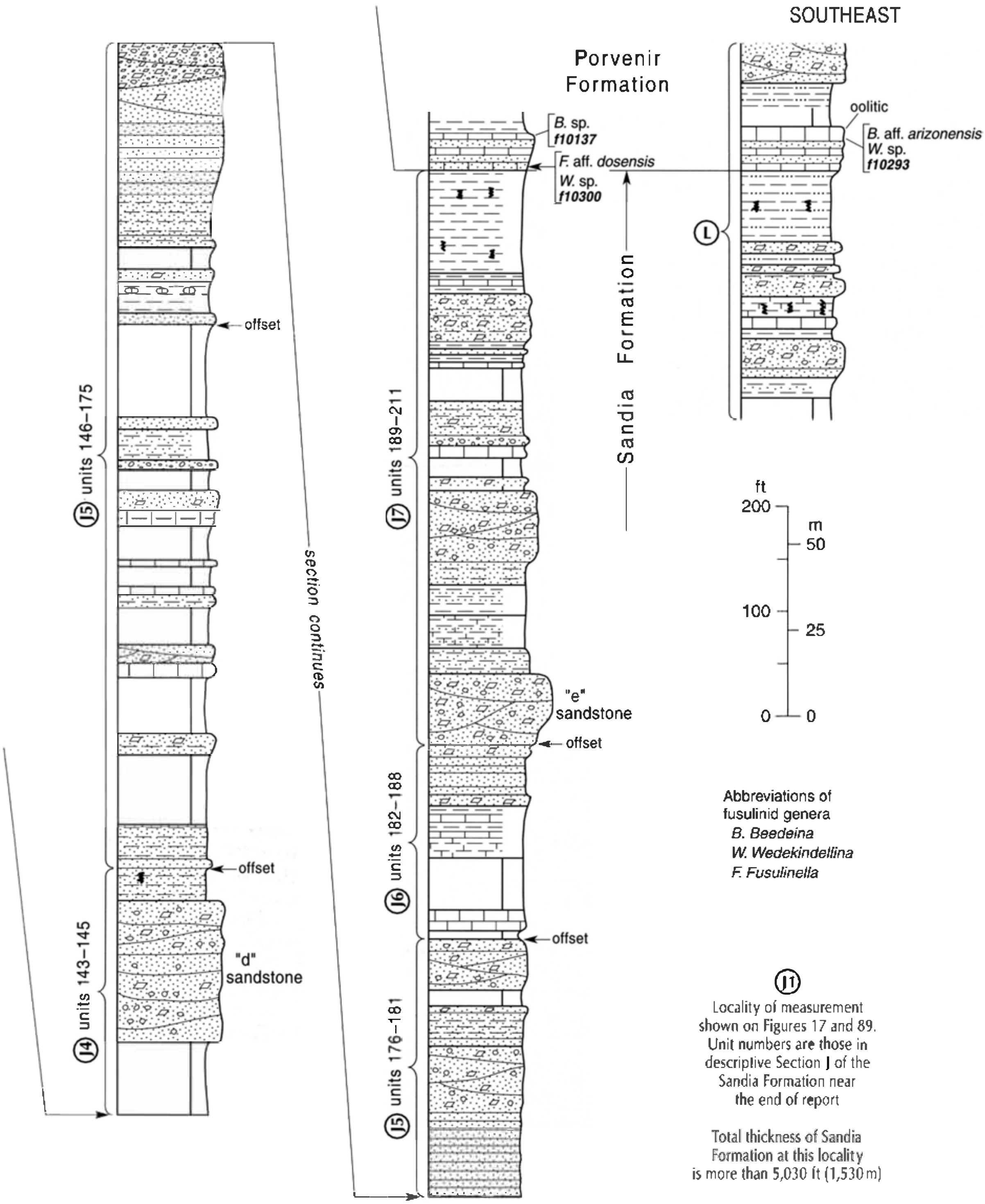


FIGURE 26—Composite stratigraphic section of Sandia Formation in hogbacks at localities J and L (Figs. 17, 89) about 1 mi (1.6 km) north of Mora River, Mora quadrangle. Lithologic symbols are explained in Figure 9.


SOUTHEAST
Porvenir Formation
B. sp.
f10137
F. aff. dosensis
W. sp.
f10300
oolitic
B. aff. arizonensis
W. sp.
f10293
Sandia Formation
L
J5 units 146–175
offset
offset
J4 units 143–145
"d" sandstone
section continues
J7 units 189–211
"e" sandstone
offset
J6 units 182–188
offset
J5 units 176–181
ft
200
100
0
m
50
25
0
Abbreviations of fusulinid genera
B. Beedeina
W. Wedekindellina
F. Fusulinella
J1
Locality of measurement shown on Figures 17 and 89. Unit numbers are those in descriptive Section J of the Sandia Formation near the end of report
Total thickness of Sandia Formation at this locality is more than 5,030 ft (1,530 m)

near the base of the Porvenir at many places farther south.

At the Amoco "A" and "B" no. 1 Salman Ranch wells (Plate 3), in the adjacent part of the Las Vegas Basin, the lithology of the Sandia Formation is similar to that at outcrops. At these wells the lower third of the Sandia is mostly dark-gray carbonaceous and calcareous shale that contains thin, mainly micritic limestones, some coaly beds, and quartzose to slightly feldspathic sandstones. The sandstones commonly are slightly micaceous and some are highly micaceous, containing muscovite flakes that range up to very coarse grain size. Chips of quartz-muscovite schist and garnetiferous muscovite schist occur in well samples from some beds. Generally, the sandstones are fine to medium grained, but some range up to very coarse grained.

The upper two-thirds of the Sandia at the wells also is mostly dark-gray carbonaceous and calcareous shale but contains some thin limestone and coal and thick units of sandstone. The thick sandstones are fine to coarse grained and commonly are feldspathic and micaceous. The feldspar grains probably are predominantly plagioclase, are nearly all white, and are generally slightly kaolinized. Pink potassium feldspar is present in trace amounts mainly in the upper part of the Sandia. Fragments of muscovite schist and green schist are common. Although thick sandstones are common in the upper 1,900 ft (595 m) of the Sandia at the wells, the proportion of sandstone to shale probably is less than in the equivalent interval (sandstone "d" and higher) at the outcrops at Mora River.

In general, the sandstones of the upper two-thirds of the Sandia at the Amoco wells seem to be finer grained than many of the sandstones at outcrops to the west where granules and pebbles are common constituents. However, this apparent finer grain size may be partly an artifact of the well-drilling method whereby clasts larger than very coarse size were ground to smaller sizes by the bit before they were transported to the surface.

Contact with overlying rocks

The Sandia Formation is generally conformable with the overlying Porvenir Formation. At many places in the southern part of the area as far north as Sapello River, the upper part of the Sandia contains calcareous shale and some interbedded thin, fine-grained to micritic limestones that contain late Atokan fusulinids at a few places. This upper part of the Sandia forms a transition zone, several feet to several tens of feet thick, beneath the light-gray, thick, ledge-forming limestone beds of the basal part of the Porvenir. Although the contact is generally conformable it marks, at most places, an abrupt upward change to the thick bioclastic and biostromal limestones of the Porvenir. In the southeastern part of the area, about 1.2 mi (1.9 km) southwest of Agua Zarca (Plate 1), the Sandia thins southward abruptly and is overlapped by thick limestones of the Porvenir that lie on the Lower Mississippian Espiritu Santo Formation and, a little farther south, on Precambrian rocks. Whether the overlap is a result of local unconformity between the Sandia and Porvenir is not known because we have no fossils to determine the series age of the Sandia in these outcrops. The basal limestones of the Porvenir west of Agua Zarca contain early Desmoinesian fusulinids as they do elsewhere in the region. The contact may be, simply, a depositional onlap by the Porvenir onto an area where the Sandia was never deposited.

North of Hermit Peak, the upper 50–100 ft (15–30 m) of the Sandia is mostly dark-gray shale. At places, these shale beds contain lenticular sandstones and interbedded thin limestone. In the Beaver Creek syncline, the basal part of the Porvenir is a thick unit of thin-bedded gray limestone and some interbedded shale, but on the ridge north of Daily Creek and the ridge north of Sparks Creek the basal part contains biohermal limestone mounds, overlain by coarse bioclastic limestone and coarse sandstone and limestone-pebble conglomerate. The contact between the Sandia and Porvenir (Baltz and O'Neill, 1986), where it can be observed directly, is conformable and probably transitional through a few feet. Farther east, in the hogbacks southeast and east of Rociada, the contact is an abrupt change from dark-gray shale of the Sandia to gray, bioclastic and biostromal, thick limestone of the Porvenir.

In the eastern part of the mountains from Manuelitas Creek north to Rito Cebolla, the uppermost part of the Sandia generally consists of gray to dark-gray shale with a few thin interbeds of fine-grained to micritic limestone and some thin sandstone. These rocks are overlain by a basal gray limestone of the Porvenir that locally contains banded stromatolitic limestone, low-mounded stromatolites and large biohermal and stromatolitic mounds. At places the lower part of the Porvenir contains thin limestone-pebble conglomerates. Northwest of Manuelitas (northeast of San Isidro cemetery, USGS Sapello quadrangle) the lower part of the Porvenir, above the basal limestone, contains a zone of thin, sandy limestone-pebble conglomerate that thickens eastward to become a massive sandstone that, directly north of Manuelitas, cuts out the lowest beds of the Porvenir and channels into the upper part of the Sandia. Traced northeastward to the vicinity of the north end of Cerro de la Cruz anticline, this sandstone thins and again becomes sandy limestone-pebble conglomerate within the Porvenir. Therefore, the unconformable contact of the Sandia and Porvenir north of Manuelitas does not represent an erosional break between deposition of the two formations but, instead, is an intra-Porvenir unconformity. Similarly, on the west flank of the Bahai anticline, near the county road south of the confluence of Cañon del Rocio and Manuelitas Creek, the basal limestone zone of the Porvenir is missing, but it is present on Cerro de la Cruz and to the southeast. This relation probably represents channeling by sandstone within the lower part of the Porvenir that rests on dark-gray shale of the upper part of the Sandia near the county road south of Cañon del Rocio.

Directly north of Rito Cebolla (loc. I, Figs. 31, 46) the basal part of the Porvenir is a steeply dipping thin unit of sandstone and medium-gray, fine-grained limestone that is distinguishable from the Sandia mainly by its stratigraphic position and by the occurrence of late Atokan fusulinids (f10132) in the underlying Sandia Formation. About 0.6 mi (0.95 km) north of Rito Cebolla the lower part of the Porvenir is cut out by the Sapello fault. Farther north the entire Porvenir is cut out by the fault and the upper part of the Sandia is thrown against the Alamitos and Sangre de Cristo Formations (Baltz and O'Neill, 1984; Plate 1); therefore, we have no data on the nature of the contact in that part of the area.

Farther north, about 2,000 ft (600 m) south of La Cañada del Guajalote, the upper part of the Sandia and the basal part of the Porvenir are exposed again east of the Sapello fault. The fusulinid-bearing lower Desmoinesian basal part of the Porvenir from here north past Mora River is a complex zone of intergrading oolitic and bioclastic sandy limestone, coarse-grained lenticular limestone, and, at the base, a unit of very fine grained sandstones and interbedded thin gray limestones. This sequence probably is generally conformable with the Sandia northward to at least locality J. North of locality L, tracing of individual beds within the lower part of the Porvenir shows that a sandstone about 85 ft (26 m) above the base of the Porvenir channels through the underlying beds of the Porvenir and rests unconformably on gray shale of the Sandia. From Cañon del Agua northeastward for about 1 mi (1.6 km) the basal beds of the Porvenir are absent and stratigraphically higher sandstone beds lie directly on the Sandia; but farther north, near the northern margin of the area, the basal limestone part of the Porvenir again is present. The areas of local unconformity between the Sandia and Porvenir north of Mora River are intra-Porvenir and involve less than 100 ft (30 m) of the Porvenir and no more than several tens of feet of the Sandia. The unconformity is similar, therefore, to the previously described local intra-Porvenir unconformity north of Manuelitas.

Age and fossils

The Sandia Formation is Early and Middle Pennsylvanian age and, from at least Gallinas Creek north, it contains rocks equivalent to both the Morrowan and Atokan provincial series of the Midcontinent. Our fossil collections are adequate to establish this overall age span, but the collections are not extensive enough to determine paleontologic or lithologic boundaries between Morrowan and Atokan. South of Gallinas Creek, where the Sandia is relatively thin, Atokan rocks are present and it seems likely that at least local veneers of Morrowan rocks were laid down and protected Upper Mississippian rocks from weathering and erosion during part of Early Pennsylvanian time. However, we cannot confirm the possible presence of Morrowan rocks in the southern part of the area by paleontologic data.

Megafossils—Morrowan brachiopods occur in the lower part of the Sandia Formation at Mora River (loc. J) where it is very thick, near Rito Cebolla (loc. C) where it is moderately thick, and in the Gallinas Creek area (loc. D) where it is relatively thin. The faunas at these localities are listed below.

Collection USGS 27164–PC, from about 700 ft (213 m) above the faulted lower part of Sandia Formation, locality J1 (Fig. 26) north of Mora River (Fig. 89). Identified by J. T. Dutro, Jr. (written comm., 1978).

Linoproductus nodosus (Newberry)
Sandia cf. *S. welleri* (Mather)
Tesuquea formosa Sutherland and Harlow
Spirifer goreii Mather
Anthracospirifer curvilateralis tanoensis Sutherland and Harlow
Hustedia cf. *H. gibbosa* Lane

Collection USGS 28676–PC, from interval 100–150 ft (30–46 m) above base of Sandia Formation, about 600 ft (180 m) north of base of locality C, south of Rito Cebolla (Fig. 88). Identified by J. T. Dutro, Jr. (written comm., 1983).

Schizophoria oklahomae Dunbar and Condra
Derbyia? sp.
Neochonetes sp.
Plicochonetes? sp.
Buxtonia grandis Sutherland and Harlow
Tesuquea? sp.
Pulchratia? cf. *P.? picuris* Sutherland and Harlow
Sandia? sp.
Desmoinesia? sp.
Linoproductus nodosus (Newberry)
Spirifer goreii Mather
Anthracospirifer sp.
Composita sp.
Punctospirifer morrowensis Sutherland and Harlow
Spiriferellina cf. *S. campestris* (White)

Collection USGS 27487–PC, from lower part of Sandia Formation about 140 ft (43 m) above base, locality D (Fig. 20), Johnson Mesa road south of Canovas Canyon (Fig. 81). Identified by J. T. Dutro, Jr., in consultation with John Pojeta, (written comm., 1979).

Rhipidomella trapezoida Sutherland and Harlow
Schizophoria sp.
Derbyia? sp.
Neochonetes? sp.
Tesuquea formosa Sutherland and Harlow
Antiquatonia sp.
Linoproductus sp.
Krotovia? sp.
Pulchratia? sp.
Anthracospirifer cf. *A. tanoensis* Sutherland and Harlow

J. T. Dutro, Jr. noted (written comm., Jan. 11, 1983) that these collections are similar to the Morrowan brachiopod assemblages described by Sutherland and Harlow (1973) from the lower part of their La Pasada Formation in the western part of the Sangre de Cristo Mountains. According to Dutro, the collections from the southeastern part of the mountains also appear to represent the age of the upper part of the type Morrowan of Arkansas and Oklahoma.

Three collections of brachiopods were obtained from the interval 10-40 ft (3–12 m) above the base of the Sandia at locality B north of Gallinas Creek on the ridge northwest of Hot Springs (Fig. 17, 21). These collections were identified by R. E. Grant, in consultation with E. L. Yochelson and Mackenzie Gordon, Jr. (written comm., 1971). The faunas are listed in stratigraphically descending order.

Collection USGS 24491–PC

Antiquatonia? sp.
Anthracospirifer sp.
Composita sp.
Neochonetes cf. *N. granulifer* (Owen)
Phricodothyris sp.
Punctospirifer sp.
productid indet. (*Juresania* or *Echinaria*?)

Collection USGS 24490–PC

Anthracospirifer sp.
Beecheria? sp. (fragment)
Composita sp.
Desmoinesia cf. *D. muricatina* (Dunbar and Condra)
Derbyia sp.
Hystriculina? sp.
Phricodothyris perplexa (McChesney)
Schuchertella sp.

Collection USGS 24489–PC

Hystriculina cf. *H. wabashensis* (Norwood and Pratten)
Composita sp.

The poorly preserved nature of many specimens does not allow for species identification. The stratigraphic position of the collections suggests they might be either Morrowan or Atokan.

Several brachiopod collections were obtained from the upper 110 ft (34 m) of the Sandia Formation in the Gallinas Creek area. This part of the section is well exposed north of Gallinas Creek in the western part of locality 3 (Figs. 17 and 21) about 0.75 mi (1.2 km) southeast of Gallinas. Collections from here were identified by R. E. Grant (written comm., 1971) and are listed in descending stratigraphic order.

Collection USGS 24471–PC

Composita sp.
Hystriculina sp.

Collection USGS 24470–PC

Antiquatonia sp.
Composita sp.
Phricodothyris perplexa (McChesney)
buxtoniid indet.

Collection USGS 24469–PC

Chonetinella sp.
Derbyia? sp.
Desmoinesia? sp.
Hystriculina sp.

These brachiopod collections from locality 3 do not provide a firm basis for determining the age of the upper part of the Sandia. However, they are associated at this locality with *Fusulinella* aff. *F. juncea* and *Fusulinella* aff. *F. famula* (f10286, f13151), which indicate late Atokan age.

Two other collections from the interval 50–75 ft (15–23 m) below the top of the Sandia Formation at locality B (Fig. 17, 21) were identified by R. E. Grant (written comm., 1971).

Collection USGS 24493–PC
- *Composita* sp.
- *Juresania*? sp.
- Orthotetacean (*Derbyia* or *Schuchertella* sp.)

Collection USGS 24492–PC
- *Anthracospirifer* sp.
- *Composita* sp.
- *Hustedia* sp.
- *Chonetinella*? sp.
- *Antiquatonia*? sp.
- *Chaetetes* sp.
- Trilobite pygidium indet.

Stratigraphic position and correlation with locality 3 suggests these fossils are Atokan.

Three brachiopod collections were made from the Sandia Formation at locality 5 (Figs. 17, 22) northeast of Cerro de la Cruz from the interval 500–570 ft (150–174 m) below the top of the formation. These collections, also identified by R. E. Grant (written comm., 1971), are listed in descending stratigraphic order.

Collection USGS 24460–PC
- *Antiquatonia* cf. *A. hermosana* (Girty)
- *Composita* sp.
- *Mesolobus* sp.
- *Orbiculoidea* sp.
- *Reticulatia* cf. *R. rugatia* Sturgeon and Hoare

Collection USGS 24459–PC
- *Cancrinella boonensis* (Swallow)
- *Chonetinella flemingi* (Norwood and Pratten)
- *Fimbriaria* sp.
- *Kozlowskia* sp.
- *Orthotichia*? sp.
- *Phricodothyris perplexa* (McChesney)

Collection USGS 24458–PC
- *Antiquatonia* cf. *A. costellata* Sturgeon and Hoare
- *Composita* cf. *C. trilobata* Dunbar and Condra
- *Desmoinesia*? sp.

According to Grant (written comm., May 4, 1971), collection 24458–PC does not warrant a firm age determination for this part of the Sandia, but both the upper collections suggest Desmoinesian age. However, the basal part of the overlying Porvenir Formation was mapped southward from locality 5 at Cerro de la Cruz (Baltz and O'Neill, 1986) to places where it contains early Desmoinesian fusulinids, and early Desmoinesian fusulinids occur in the lower part of the Porvenir east and southeast of Cerro de la Cruz. Therefore, the stratigraphic position of all three megafossil collections well below the base of the Porvenir suggests that they are Atokan.

Fusulinids—Fusulinids were collected from many places throughout the area of this report from Pennsylvanian and Lower Permian rocks. The localities of collections were given U.S. Geological Survey fusulinid-collection numbers, for example, f10306, which are referred to at places in the text. These localities are described in numerical (not stratigraphic) order in a description of fusulinid localities near the end of this report (Appendix III). Photomicrographs of identified genera and species from all the Pennsylvanian and Lower Permian formations are shown on Plates 6–14.

Fusulinids are rare in the Sandia Formation, but those we found in the upper part all indicate late Atokan age. South of Gallinas Creek the only fusulinids we found in the Sandia were in the upper part just east of the Bernal fault at the east side of the main valley in the SE¼ sec. 21 T14N R15E (USGS Villanueva quadrangle) about 1.3 mi (2.2 km) northwest of locality 1. Here, *Fusulinella* aff. *F. devexa* (f10306) occurs in shaly limestone about 90 ft (27 m) below the top of the Sandia. The occurrence of species of *Fusulinella* (collections f10286, f13150, f13151) near the top of the Sandia at locality 3 north of Gallinas Creek has already been mentioned. Some specimens of *Fusulinella* are shown on Plates 6 and 12. Farther north, *Fusulinella* cf. *F. devexa* (f10307) was found in thick limestone about 120 ft (37 m) below the top of the Sandia north of the county road in Sanguijuela Arroyo. At locality I (Fig. 46) at the north side of Rito Cebolla, *Fusulinella* aff. *F. juncea* (f10132, Plate 12) was found in bioclastic limestone about 75 ft (23 m) below the top of the Sandia.

Inasmuch as the contact of the Sandia and Porvenir Formations is mainly conformable and locally transitional through a few feet, there might be some minor local variation in its mapped stratigraphic position. Additionally, minor miscorrelations of the contact might have been made across covered areas, areas of Cenozoic faults, or areas of local minor interfingering of the two formations. Nevertheless, the available fusulinid data from the upper part of the Sandia and the abundant fusulinid data from the basal parts of the Porvenir indicate that, regionally, the rock-stratigraphic boundary is near the Atokan–Desmoinesian biostratigraphic boundary. The fusulinids from the Sandia correlate with the upper Atokan assemblage subzones of *F. devexa* and *F. whitensis* at the top of the Sandia in the Manzano Mountains (Myers, 1988a). (See Fig. 54 later in the present report.) They also correlate with fusulinid zone I (upper Atokan) of the La Pasada Formation of Sutherland and Harlow (1973, p. 10) of the western part of the Sangre de Cristo Mountains.

Paleotectonic interpretations

During deposition of the Sandia Formation, intrabasinal uplifts and intervening local structural basins began to develop on the southern shelf and in the deep northern part of the Rowe–Mora Basin. These structural features were recurrently active later in Pennsylvanian and Early Permian and directly influenced the facies and thicknesses of all the upper Paleozoic rocks.

Bernal uplift—The name Bernal uplift (Fig. 4) is applied here to a Pennsylvanian structural feature that occupied the area that is now part of a large Cenozoic uplift in the southwestern part of the area (Plate 1). As shown by isopachs of the Sandia Formation (Plate 4), the Bernal uplift probably consisted of north–northwest-trending echelon or subparallel low anticlines and intervening shallow synclines during deposition of the formation. We do not have thickness data for the Sandia of the western part of the uplift, but the Sandia probably thickens slightly westward into the San Jose Basin. This is suggested by a thickness of 320 ft (98 m) of Sandia measured by Read et al. (1944, loc. 22) west of the northern part of the uplift near Vallecitos Creek and Cow Creek (secs. 7 and 18 T16N R13E, west of the area of Plate 4). The existence of the Bernal uplift is illustrated more clearly by stratigraphic relations of younger Pennsylvanian and Lower Permian rocks, as will be discussed later.

At some exposures along the Bernal and El Barro faults (Plate 1), coarse-grained to pebbly sandstone of the Sandia cuts out the underlying Arroyo Peñasco Group to lie directly on Precambrian rocks. This suggests that Precambrian rocks of parts of the Bernal uplift contributed minor amounts of clastic sediments to adjacent areas during early phases of deposition of the Sandia Formation. However, the uplift, or at least parts of it, were the sites of deposition of sediments derived from other sources, at least in late Atokan time, as suggested by the finer grained nature of the upper part of the Sandia (Fig. 20) along the eastern margin and by the thin section of the Sandia deposited across the southern part of the uplift.

San Geronimo Basin—At least the northern part of the Cenozoic Chapelle syncline and the Las Gallinas syncline (Plate 1) were the sites of a structural basin during deposition of the Sandia Formation. This Pennsylvanian feature is here called the San Geronimo Basin (Plate 4). The San Geronimo Basin was a broad asymmetric syncline with a gently dipping east limb. The syncline plunged north and merged with the deeper Rociada local basin and Manuelitas saddle in which mainly marine shaly facies of the Sandia were deposited. The deepest northern part of the San Geronimo Basin was bounded at the west by the Hermit Peak structural block that did not subside as much as the adjacent basins.

Tecolote uplift—A Paleozoic uplift in the southeastern part of the mountains, first reported but not named by Northrop et al. (1946), was called the Tecolote arch by May et al. (1977, p. 5). We refer to it as the Tecolote uplift (Plate 4). The Tecolote uplift occupied the area of the Cenozoic Creston anticline and La Sierrita dome (Plate 1). Although control points are scanty, the isopachs of the Sandia Formation, especially near Montezuma, suggest that the eastern part of the Tecolote uplift had a series of northwest-trending right-echelon low anticlinal culminations on which the formation thinned. From Montezuma north, the places where the Sandia Formation is thinnest are transected by the Cenozoic Montezuma fault, suggesting that the northeastern part of the Tecolote uplift of Sandia time is buried in the adjacent western part of the Las Vegas Basin. At the south, also, the eastern part of the uplift seems to be in what is now the western part of the Las Vegas Basin. (See interpretation on cross section *I–I'*, Plate 1.)

At the south, where the Sandia Formation is last exposed north of Tecolote Peak, the formation is locally entirely coarse-grained to pebbly thin sandstone that cuts out the Arroyo Peñasco Group, indicating that the Precambrian of this part of the Tecolote uplift was a source of coarse clastics during part of Sandia deposition. Southwest of Agua Zarca the Sandia is overlapped locally by the overlying Porvenir Formation confirming that the Tecolote uplift existed prior to Desmoinesian time. No subsurface data are available for many miles farther south that might give evidence of the nature and extent of the Tecolote uplift or might indicate whether the uplift was an Early Pennsylvanian source of sediments for the area of this report.

At the front of the mountains, from north of Montezuma northward to Cañon Bonito, the Sandia Formation mainly bevels the Arroyo Peñasco and lies on Precambrian rocks. At Cañon Bonito the Sandia is about 300 ft (90 m) thick, and the clasts of its basal conglomerate are similar to underlying Precambrian rocks. As previously discussed, limestone- and quartz-pebble conglomerate, farther north near Manuelitas (loc. 5), lie on at least a local unconformity about 300 ft (90 m) below the top of the Sandia. The basal part of the Sandia at Cañon Bonito may be equivalent to the conglomerate within the Sandia at locality 5; if so, the lower part of the Sandia at locality 5 may be cut out southward toward the Tecolote uplift by an unconformity. This interpretation suggests also that coarse-grained to conglomeratic sediments derived from the Precambrian of the Cañon Bonito area might be present in the Sandia in the western part of the Cenozoic Las Vegas Basin along the buried east flank of the Tecolote uplift.

Scanty well data (Fig. 18) in the southern part of the Cenozoic Las Vegas Basin suggest that a shallow north-plunging local structural basin existed east of the Tecolote uplift and northwest of the adjacent part of the Sierra Grande uplift during deposition of the Sandia and younger Pennsylvanian rocks, all of which were removed by erosion before deposition of the Sangre de Cristo Formation on the margin of the uplift. Precambrian rocks of the Sierra Grande uplift probably were sources of clastics in Sandia time and later.

On the west flank of the Tecolote uplift south of Ojitos Frios, the core of the Cenozoic Ojitos Frios anticline locally is Precambrian rocks overlain at the west by the Upper Mississippian Tererro Formation and at the east by the onlapping Sangre de Cristo Formation. The Paleozoic anticline lies en echelon with the Tecolote uplift. Its Early Pennsylvanian history cannot be determined.

Hermit Peak uplift—Isopachs of the Sandia Formation on the Cenozoic Hermit Peak block indicate that the block subsided less than adjacent areas to the east and southeast during deposition of the formation (Plate 4). Possibly, the Paleozoic Hermit Peak uplift was bounded by precursors of the Cenozoic Hermit Peak and El Porvenir faults (Plate 1), as suggested by the considerable changes in thickness of the Sandia across these faults. However, Precambrian rocks of the eastern part of this uplift probably did not contribute sediments to adjacent basins during Sandia deposition, because much of the Precambrian is granite, and the coarse clastics of the Sandia adjacent to the block are not feldspathic, or only slightly so, but are mainly quartzose. The Sandia thickens northwestward across the Hermit Peak block into the Cenozoic Beaver Creek syncline in the northwest part of the area, indicating that the block was tilted northwest.

Manuelitas saddle—North of the vicinity of Cañon Bonito the Tecolote uplift plunged northward into what probably was a broad structural saddle in the area of the Cenozoic Cerro de la Cruz anticline (Plate 1) in the eastern part of the mountains. This Paleozoic feature, here called the Manuelitas saddle (Plate 4), may have been a low structural divide between the deeper Rociada Basin at the west and the southern part of the deep Rainsville trough at the northeast. Wells have not been drilled to Paleozoic rocks in the Las Vegas Basin east of the saddle and its structure and extent there can only be surmised. The Sandia Formation exposed on the saddle is a mainly shaly and marine facies, although it contains some units of probable nonmarine carbonaceous shale and conglomerate. At the northern margin of the saddle near Rito Cebolla, the Sandia begins to thicken rapidly northward and contains thick feldspathic conglomerates probably derived from the area of the Cenozoic El Oro Mountains.

Rociada Basin—North of Hermit Peak, in the Cenozoic Beaver Creek and Sparks synclines and the syncline east of the Gascon fault, the Sandia Formation thickens northward into a northerly trending, deep Paleozoic local basin here called the Rociada Basin. West of the area of this report this basin was bounded by the Paleozoic Pecos shelf, now incorporated in the western part of the Sangre de Cristo Mountains (Fig. 4), where the Morrowan and Atokan parts of the La Pasada Formation are much thinner (Sutherland, 1963, fig. 10) than in the Rociada Basin. Northwest of Mora the Rociada Basin merged into the eastern part of the deep Taos trough. The eastern part of the Rociada Basin probably was bounded by a Paleozoic west-tilted basement block in the area of the present El Oro Mountains and Rincon Range. The Sandia Formation in the Rociada Basin and eastern part of the Taos trough is a mainly marine shaly facies.

El Oro–Rincon uplift—From the vicinity of Mora northward almost to Black Lake (Plate 2) the Cenozoic eastern structural front of the Sangre de Cristo Mountains is a west-tilted basement block whose eastern boundary is a complex zone of west-dipping reverse and thrust faults. This block separates the uplifted Pennsylvanian rocks of the Taos trough at the west from the subsurface Pennsylvanian rocks of the Rainsville trough in the Cenozoic Las Vegas Basin at the east. In the area of this report, from about Rito Cebolla north, lithologic and thickness data suggest that the area of the Cenozoic uplift was a fault-bounded intrabasinal uplift also in Pennsylvanian time. The inferred Paleozoic uplift is here called the El Oro–Rincon uplift (Plate 4).

In the northern part of the area of this report the rapid thickening of the Sandia Formation north of Rito Cebolla (loc. C) suggests that faulting helped to produce the Paleozoic Rainsville trough (Plate 4), but Cenozoic structural complications in the eastern part of the mountains are such that none of the older faults has been identified clearly. A precursor to the northern part of the Cenozoic Sapello fault, or an older fault that was overridden by the Sapello fault, could have been involved. A concealed probable fault that cuts out a large amount of the Precambrian section just east of El Oro Mountains (Baltz and O'Neill, 1984) might have been active. The lithology of sandstones of at least the upper part of the Sandia near Rito Cebolla (secs. F and C, Fig. 22) and at Mora River (Fig. 26) seems to indicate that a source of fresh and coarse Precambrian detritus was not far distant. The coarseness and the angularity of many clasts, particularly the feldspars, and the poor mineralogical sorting and micaceous nature of some beds makes it unlikely that the sediments were transported from far-distant sources, such as the Uncompahgre or Sierra Grande uplifts, or even the Cimarron arch (Fig. 4). The Precambrian rocks exposed in El Oro Mountains and the southern part of the Rincon Range north of Mora (Fig. 5) are likely sources for the sediments of some of the upper part of the Sandia. The quartz-mica schists of Las Quebraditas could have provided an abundant supply of muscovite and fine to coarse quartz sand. Thick, pink granitic and gray gabbroic pegmatites that occur throughout the Precambrian, especially on the east side of El Oro Mountains, could have been sources for the locally abundant angular feldspar and vein-quartz granules and pebbles of the upper part of the Sandia. The quartzofeldspathic gneisses and interlayered coarse, micaceous quartzites and pegmatites in the core of the El Oro anticline (Baltz and O'Neill, 1984) could have been a source of plagioclase as well as potash feldspar and coarse quartzite sand.

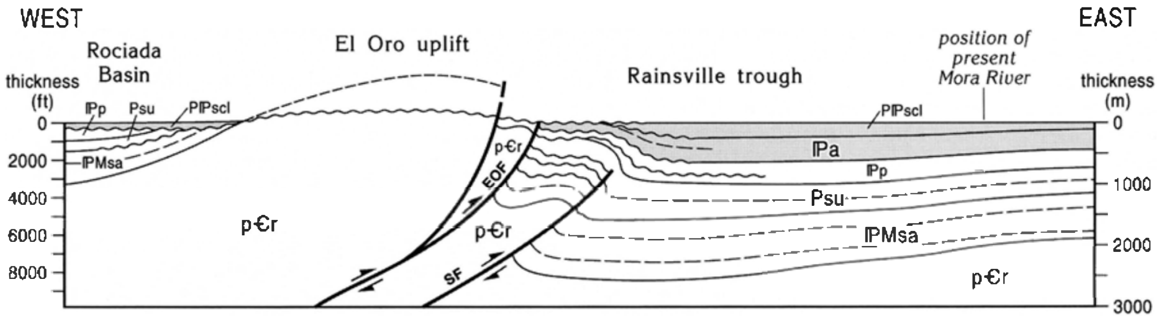
If the general area of the Cenozoic El Oro Mountains was the source for these sediments it was a relatively narrow uplift because the Arroyo Peñasco Group and the lower part of the Sandia Formation are still preserved just west of El Oro Mountains. However, the Sandia is thinner in the Rociada Basin west of El Oro Mountains than it is in the Rainsville trough to the east. The suggested model (Fig. 27) is that the El Oro Mountains block was tilted west, and that its eastern margin was an asymmetric anticline on which Precambrian rocks were exposed to erosion episodically. According to this model, the eastern part of the block was slightly elevated episodically along west-dipping reverse faults as the adjacent Rainsville trough was depressed during deposition of at least the upper 1,900 ft (580 m) of the Sandia at Mora River. Grus, eroded from an island on the El Oro Block, contributed to the episodic eastward building of progradational fans and deltas into the Rainsville trough. Some of the finer grained material may have had more distant sources, or may have been transported sufficient distances by long-shore currents to sort it mineralogically. At times, both the Rainsville trough and the El Oro block probably were submerged in deeper water in which shale, some sandstone derived from other more distant sources, and thin limestones were deposited. Some of the coarse sandstones in the lower part of the Sandia west of Ledoux and arkosic conglomerates of the upper part in the Rociada Basin also might have been derived from the El Oro area and spread westward.

This model (Fig. 27) requires that disconformities and relatively sharp angular unconformities existed in the Sandia on the west flank of the El Oro block before most of the Sandia was removed by Cenozoic erosion. The stratigraphic relations envisioned would be similar to those of the west limb of the Tecolote uplift west and southwest of Agua Zarca where each of the Pennsylvanian formations thins eastward relatively abruptly and all are truncated by the Sangre de Cristo Formation, which also thins eastward internally (cross sections *H* and *I*, Plate 1). The area immediately east of the El Oro block, where multiple unconformities are shown in Figure 27, was uplifted in Cenozoic time, and the rocks were mostly removed by erosion; therefore, we cannot demonstrate that all the unconformities occurred here in Pennsylvanian time. (Compare Fig. 27 with cross section *B–B'*, Plate 1.) Nevertheless, the stages shown in Figure 27 are an explanation of events that might have occurred and that could explain the great northward changes of thickness and facies of the Sandia from about Rito Cebolla north. Additional evidence of the existence of the Paleozoic El Oro uplift during deposition of younger rocks will be presented later in this report.

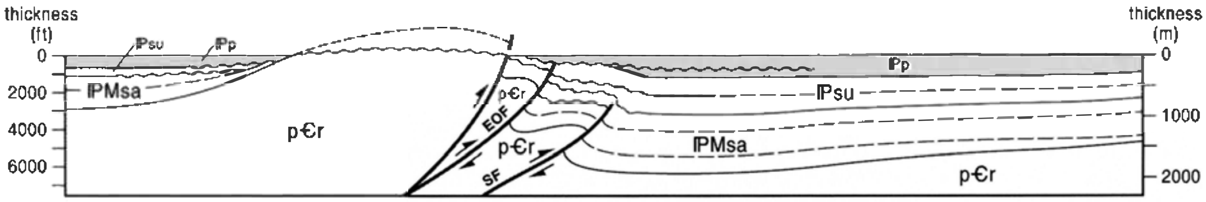
The zone of thick, generally arkosic and micaceous sandstones of the upper part of the Sandia persists northward from the area of this report in outcrops at the east side of the mountains. This suggests that additional sources of coarse Precambrian detritus existed in micaceous quartzite, quartzofeldspathic gneiss, and pegmatites at the eastern edge of the several Precambrian structural blocks that constitute the Cenozoic Rincon Range north of Mora (Plate 2). The lithology of many of the sandstones of the Sandia in the Amoco wells in the Las Vegas Basin (Plate 3) suggests a source terrane of mica schists, quartzofeldspathic gneisses, and quartzites, such as those in the Rincon Range.

Puzzling aspects of Sandia stratigraphy west and northwest of Mora might be explained if the Rincon Range structural blocks were elevated during deposition of the Sandia Formation. The lower part of the Sandia on the west flank of the El Oro Mountains and the Rincon Range contains thick sandstones interbedded in thick shale bodies, but the middle and upper parts, exposed farther west, are predominantly shale, although they contain some sandstones. The sandstones in the upper part of the Sandia west of Mora diminish northward in thickness and amount. Near Holman Hill and Chacon, west of the Rincon Range about 12 mi (19 km) northwest of Mora (Plate 2), the upper 1,200 ft (365 m), or more, of the Sandia is mainly dark-gray organic-rich shale (Baltz and Read, 1956, p. 50–51, 76) that is overlain by limestone equivalent to the Porvenir Formation. The organic-rich shale facies is in the northern extension of the Rociada Basin that merged into the Taos trough (Fig. 4). The shale facies is laterally equivalent westward to predominantly coarse sandstones and shale of part of Sutherland's (1963, fig. 10, sec. 60) Flechado Formation at Rio Pueblo in the western part of the mountains. The shale facies northwest of Mora is equivalent, also, to the zone of thick, coarse sandstones in the upper part of the Sandia east of the Rincon Range and at Mora River.

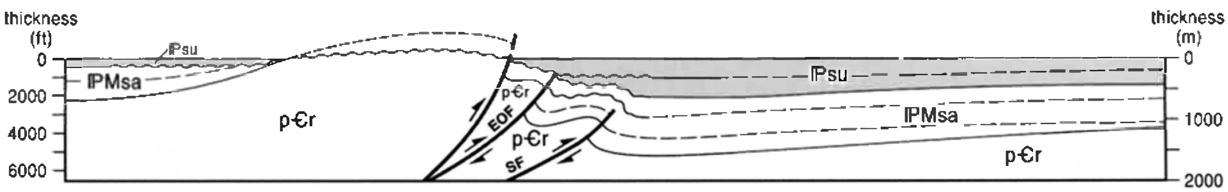
The sandstones of the Flechado Formation in the western part of the Taos trough were derived from the west, presumably from parts of the ancestral Brazos (or Uncompahgre) uplift. In this connection, Casey (1980a, p. 184–188) has described coarse sandstones and boulder conglomerates of Atokan and earliest Desmoinesian ages in the western part of the Sangre de Cristo Mountains. He interprets these rocks as braided stream, distal-fan, and



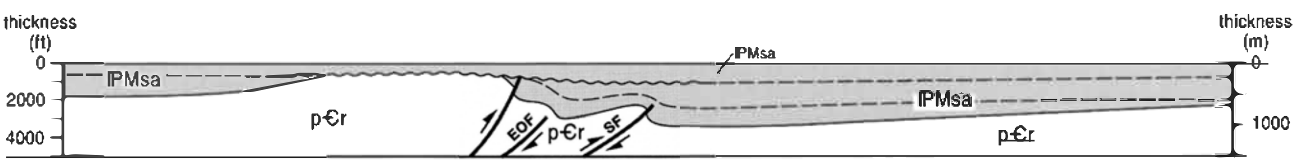
D. Late Desmoinesian, Missourian, and Virgilian(?). PIPscl is (Virgilian?) unit of purplish-pink arkoses and red shales that is lower part of Sangre de Cristo Formation from this vicinity north. IPa is Alamitos Formation.



C. Early, middle, and late Desmoinesian. IPp is Porvenir Formation.



B. Atokan(?) and Atokan. IPsu is upper part of Sandia Formation, including the "d" sandstone and higher rocks of the Mora River section (localities J4–J7, Figure 26).



A. Morrowan and Morrowan(?). IPMsa includes lower part of Sandia Formation and Mississippian Arroyo Peñasco Group; p€r is Precambrian rocks.

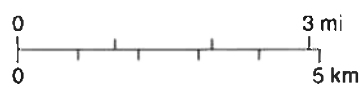


FIGURE 27—Cross sections showing hypothetical stages of Pennsylvanian evolution of southern part of El Oro–Rincon uplift. Pattern shows sediments deposited during each stage. Wavy lines represent unconformities; dashed lines represent bedding. EOF, El Oro fault; SF, precursory Sapello fault. Line of section extends east from vicinity of Ledoux near line of cross section *B–B′*. Thickness of rocks younger than the Sandia Formation are hypothetical in the Rociada Basin, because only the lower part of the Porvenir Formation is preserved (west of section).

fan-delta sequences that were built eastward into the Taos trough from the Uncompahgre uplift and that grade eastward into basinal shales. These interpretations are consistent also with the stratigraphic relations described for this area by Baltz and Read (1956, p. 50–51, 76). Therefore, it does not seem likely that coarse detritus of the upper part of the Sandia could have been transported eastward from the ancestral Brazos uplift across the eastern part of the Taos trough, where mainly thick shale was accumulating, to the Rainsville trough where stratigraphically equivalent coarse to conglomeratic sandstones were deposited.

If the area of the present Rincon Range had stood as a gently west-tilted uplift whose eastern edge was elevated episodically along west-dipping faults during deposition of at least the upper part of the Sandia, the uplift might have been both the east limb of the shale-facies basin and the source of first-cycle debris shed eastward in the manner postulated for the El Oro Mountains area. Alternatively, if the coarse sediments of the upper part of the Sandia in the Rainsville trough were derived from the Sierra Grande uplift at the east, or from the Cimarron arch at the north, the Rincon uplift might have been a barrier that prevented the coarse sediments from reaching the organic-rich shale facies.

If the Rincon Range Precambrian blocks were structurally high in Pennsylvanian time, they must have plunged northward as they do today (Plate 2). North of Mora the western parts of the Precambrian blocks are overlain by the Arroyo Peñasco Group and thin remnants of the Sandia Formation, and, about 18 mi (29 km) north of Mora, the northernmost block of Precambrian rocks plunges northward on a large Cenozoic anticline southwest of Black Lake and becomes overlain completely by the Sandia Formation that is, in turn, overlain by thick Desmoinesian rocks equivalent to the Porvenir Formation.

Notably, in the adjacent northern part of the Rainsville trough between Ocate and Black Lake, rocks equivalent to the Sandia are predominantly shale that contains a much smaller proportion of sandstone at the True Oil Company no. 21–25 Medina and no. 34 Arguello wells than at the Amoco "A" and "B" wells in the southern part of the trough. (See Fig. 72 for location of the True wells.) Additionally, the sandstones described in logs of the True wells by American Stratigraphic Company are generally finer grained than sandstones farther south, although some coarse-grained sandstones are present. This northward change to a finer grained facies of the entire Sandia in the northern part of the Rainsville trough accords with a Pennsylvanian northward plunge of Precambrian rocks of the Rincon Range and with the northward disappearance of this possible source of first-cycle sediments. The northward facies change in the Rainsville trough also suggests that northerly uplifts, such as the Cimarron arch (Fig. 4), were not the primary sources of coarse clastics of the southern part of the trough in Morrowan and Atokan time.

Summary of depositional environments and source areas

The general northward thickening of the Sandia Formation, its local variations in thickness and facies, and the coarseness and angularity of clasts of many of its sandstones all indicate that the formation in the area of this report was deposited in areas of locally strong and recurrent tectonic activity. Thick gray shales were deposited in deep marine water, but many of the sediments were deposited in relatively shallow water as shown by the stratigraphic recurrence of algal, stromatolitic, bioclastic, and sandy limestones and coarse-grained marine sandstones. Scour-and-fill structures in some sandstones, upward-coarsening progradational sequences, and thin coal beds indicate infilling and recurrent local aggradation to subaerial deposition. These factors suggest that the supply of clastic sediments, probably from multiple sources, was generally adequate to fill, or nearly fill, the depositional basin throughout recurring episodes of subsidence.

The southern two-thirds of the area of this report was part of the gently north-tilted Pecos shelf on which the Bernal, Hermit Peak, and Tecolote intrabasinal uplifts and the San Geronimo local basin began to develop in Morrowan and Atokan time. Most of the Sandia on the shelf was deposited in streams, floodplains, and swamps on a coastal plain that was episodically partly inundated by shallow-marine estuaries as the shelf was depressed. During deposition of the lower part of the Sandia, Precambrian rocks of parts of the Bernal uplift were minor local sources of coarse gravelly sand, as was the Precambrian of the southern and northern parts of the Tecolote uplift. Precambrian rocks of the Sierra Grande uplift may have been major sources of gravelly sand, as suggested by the coarse facies of the Sandia at the Continental Oil Co. no. 1 Leatherwood–Reed well (loc. 4, Fig. 18) on the margin of the uplift. In late Atokan the shelf was mainly submerged in a shallow sea, and gray shale and thin limestone and minor amounts of sandstone were deposited. As the Sandia Formation thickens northward onto the Manuelitas saddle and into the Rociada local basin, it contains progressively more gray, calcareous marine shale, thicker fossiliferous limestones, and sheetlike mainly marine sandstones. In the area southwest of Sapello the proportion of marine and nonmarine sandstone in the upper part decreases northward as the Sandia thickens away from the northern part of the Tecolote uplift toward the Manuelitas saddle. The facies is mainly marine, but some sandstone and carbonaceous shale probably were deposited subaerially as coastal-plain swamps and streams prograded episodically into the structurally deepening areas. As the Sandia thickens northward into the mainly marine shaly facies of the Rociada Basin the total amount of sandstone in the upper two-thirds becomes less, and, traced northward into the eastern part of the Taos trough northwest of Mora, the mainly marine upper two-thirds contains very little sandstone. These relations suggest that the major sources of coarse clastics of these deep-basinal areas were in southerly directions.

The sandstones and conglomerates of the Sandia Formation of the southern shelf, Rociada Basin, and southern part of the Manuelitas saddle are dominantly quartzose, as are those of the lower half of the formation in the Rainsville trough. Coarse clastics of the equivalent Morrowan and Atokan lower part of the La Pasada and Flechado Formations on the Pecos shelf and Taos trough of the western part of the mountains are almost entirely quartzose (Sutherland, 1963, figs. 12, 13). Quartzite granules and pebbles are abundant throughout the region and many beds are slightly micaceous. All these sediments appear to have been derived from Precambrian metamorphic terranes, probably mainly from quartzites of the ancestral Brazos uplift at the west, the Pedernal uplift at the south, and the Sierra Grande uplift at the east (Fig. 4). Very little is known about the Precambrian of the Sierra Grande uplift but metamorphic rocks occur on its flank southeast of Las Vegas at the Continental Oil Co. no. 1 Leatherwood–Reed well. Samples from the lower 540 ft (165 m) of this well, below the Arroyo Peñasco Group, are quartzite, quartz-mica schist, greenstone, and alaskitic granite, similar to Precambrian metamorphic rocks and pegmatites that crop out on the southern part of the Tecolote uplift. Conglomerates of the Sandia Formation at the well are primarily quartz and quartzite.

On the northern part of the Manuelitas saddle and in the Rainsville trough, the upper half of the Sandia Formation contains thick fine-grained to conglomeratic sandstones that are generally micaceous and feldspathic to arkosic. Plagioclase and potassium-feldspar clasts commonly range in size up to granules and small pebbles. This facies appears to have been derived locally from metasedimentary and metavolcanic rocks and pegmatites of the eastern part of the El Oro–Rincon uplift. The sandstones probably were deposited as eastward-prograding marine and nonmarine fan deltas whose distal parts mingled in the episodically subsiding Rainsville trough with mixed marine-nonmarine sediments derived from the Sierra Grande uplift at the east.

Pennsylvanian and lower Permian rocks

Madera Group

The term Madera was proposed first by Keyes (1903) for Upper Carboniferous limestones above the "Sandia series" of Herrick (1900) in the vicinity of La Madera in the Sandia Mountains of central New Mexico. C. H. Gordon (1907) provided better descriptions of these rocks, and he classified rocks above the Sandia Formation as the Madera Limestone. Read et al. (1944), Read and Wood (1947), and Northrop et al. (1946) extended the usage of the term Madera Limestone to the southern Sangre de Cristo Mountains. Baltz and Myers (1984) reviewed nomenclature problems and regional correlations, retained the term Madera, and raised it to group status for the southeastern part of the Sangre de Cristo Mountains. The Madera Group in this region includes the Porvenir Formation and the overlying Alamitos Formation. In the southern margins of the mountains these rocks are lithologically similar to the Madera Group of the Manzano Mountains of central New Mexico (Myers, 1973, 1982) and have the same age span of Middle Pennsylvanian (early Desmoinesian) through Early Permian (early Wolfcampian). A summary of stratigraphic nomenclature and age assignments of the Madera Group and equivalent rocks in the Sangre de Cristo Mountains of New Mexico is shown in Figure 2 of this report.

Porvenir Formation

Definition

The name Porvenir Formation was applied by Baltz and Myers (1984) to the mainly marine limestone, gray shale, and sandstone that conformably overlie the Sandia Formation and are overlain with local angular unconformity by the Alamitos Formation in the southeastern part of the Sangre de Cristo Mountains. The name was derived from the U.S. Forest Service El Porvenir Campground on Porvenir Creek south of Hermit Peak where these rocks form hogback ridges in the west-central part of the area of this report. The type section is along the U.S. Forest Service Johnson Mesa road south of Gallinas Creek near the center of sec. 23 T17N R14E (loc. D of the present report). Baltz and Myers (1984) described the general lithology of the type section and illustrated it graphically but did not include a detailed descriptive section. Therefore, a detailed description of the type section (sec. D) is included near the end of the present report (Appendix II). A geologic map of the type locality is shown in Figure 81 (Appendix I).

The Porvenir Formation consists of three laterally intergrading facies: (1) a southern, dominantly carbonate facies; (2) a northern sandstone-shale-limestone facies; and (3) a northwestern, dominantly shaly facies (Fig. 28). Throughout the southern two-thirds of the area, the Porvenir Formation is composed of thin to massive limestones and interbedded thin to thick gray shales and minor amounts of sandstone, all generally similar to those of the type locality (sec. D, Fig. 29). In the eastern part of the mountains, mainly north of Sapello River, the Porvenir consists of limestone, sandy and oolitic limestone, gray shale, and thin to thick quartzose and feldspathic to arkosic sandstone (secs. E, F, K, Fig. 29). In the northwestern part of the area, generally north of Hermit Peak, the southern carbonate facies of the Porvenir thickens northward into a facies consisting of gray shale containing subordinate amounts of thin to thick limestone, shaly limestone, and relatively minor amounts of sandstone. Only the lower part of this shaly facies is preserved in the Beaver Creek and Sparks synclines (loc. 2, Fig. 30). In the hogbacks south and east of Rociada the entire Porvenir Formation is present (sec. H, Fig. 30) and the shaly facies there grades northeastward gradually into the northern sandstone-shale-limestone facies south of the San Miguel–Mora County line. In the subsurface of Las Dispensas syncline (Plate 1), the shaly facies grades eastward into the northern sandstone-shale-limestone facies (sec. E, and loc. 3, Fig. 30). All the facies of the Porvenir Formation intergrade gradually and intricately over distances of several miles, and each facies contains some lithologic units that are typical of, and can be traced into, the other facies.

The Porvenir Formation is Middle Pennsylvanian (early to late Desmoinesian) age; its fusulinids are within the zone of *Beedeina* (formerly, the genus *Fusulina*). The Porvenir is the lower gray limestone member of the Madera Limestone of Read et al. (1944), Northrop et al. (1946), and Read and Wood (1947); the lower member of the Madera Formation of Baltz (1972); and the Porvenir Formation of Baltz and O'Neill (1984, 1986). The Porvenir is equivalent to the upper carbonate part (units 97–179) of the La Pasada Formation of Sutherland (1963, p. 56–60) at the type locality of the La Pasada along the Pecos River in the southwestern part of the Sangre de Cristo Mountains.

Distribution and thickness

The Porvenir Formation is present in much of the southeastern part of the Sangre de Cristo Mountains (Plate 1) and probably was present in most of the area (except at places on Paleozoic uplifts—Fig. 28; Plate 4) prior to Cenozoic uplift and erosion. In the southeastern part of the area the Porvenir is absent south of Ojitos Frios where it is truncated by the overlying Alamitos Formation and southwest of Agua Zarca, where it is truncated by the Sangre de Cristo Formation.

The Porvenir Formation is present in the subsurface of the Las Vegas Basin at the J. D. Hancock no. 1 Sedberry well (Fig. 18) where it is represented by the southern carbonate facies. It was encountered also by the Union Land and Grazing Co. no. 1 Fort Union well drilled on Turkey Mountain dome (Plate 2) northeast of the area of this report. At this well it is intruded by thick sills of Tertiary quartz-monzonite(?) porphyry, confirming the reasoning of Hayes (1957, p. 954–955) that this large dome was elevated by an underlying intrusive body. In the subsurface east of Turkey Mountain and southeast of Las Vegas the Porvenir and underlying sedimentary rocks are truncated by the Sangre de Cristo Formation on the northwest flank of the Paleozoic Sierra Grande uplift (Northrop et al., 1946; Baltz, 1965; Foster et al., 1972; Roberts et al., 1976).

In the subsurface of the northern part of the Las Vegas Basin, the northern sandstone-shale-limestone facies of the Porvenir is present at the Amoco "A" and "B" no. 1 Salman Ranch wells where it is about 500 ft (150 m) thick (Plate 3). Fossils were not found in cuttings from these wells and the upper and lower contacts are assigned on the basis of lithologic correlation with outcrop areas and partly by electric-log correlations between wells. Northeast of the area of this report, the Shell Oil Co. no. 1 Mora Ranch well (sec. 5 T22N R19E) penetrated about 550 ft (170 m) of rocks also similar to the northern facies of the Porvenir.

Farther north in the Las Vegas Basin, the Continental Oil Co. no. 1 Mares–Duran well penetrated rocks similar to the northern facies of the Porvenir and the True Oil Co. no. 34 Arguello and no. 21–25 Medina wells penetrated 700-800 ft (215–245 m) of rocks similar to the Porvenir, but correlations are tenuous because of the likelihood of much caving of well

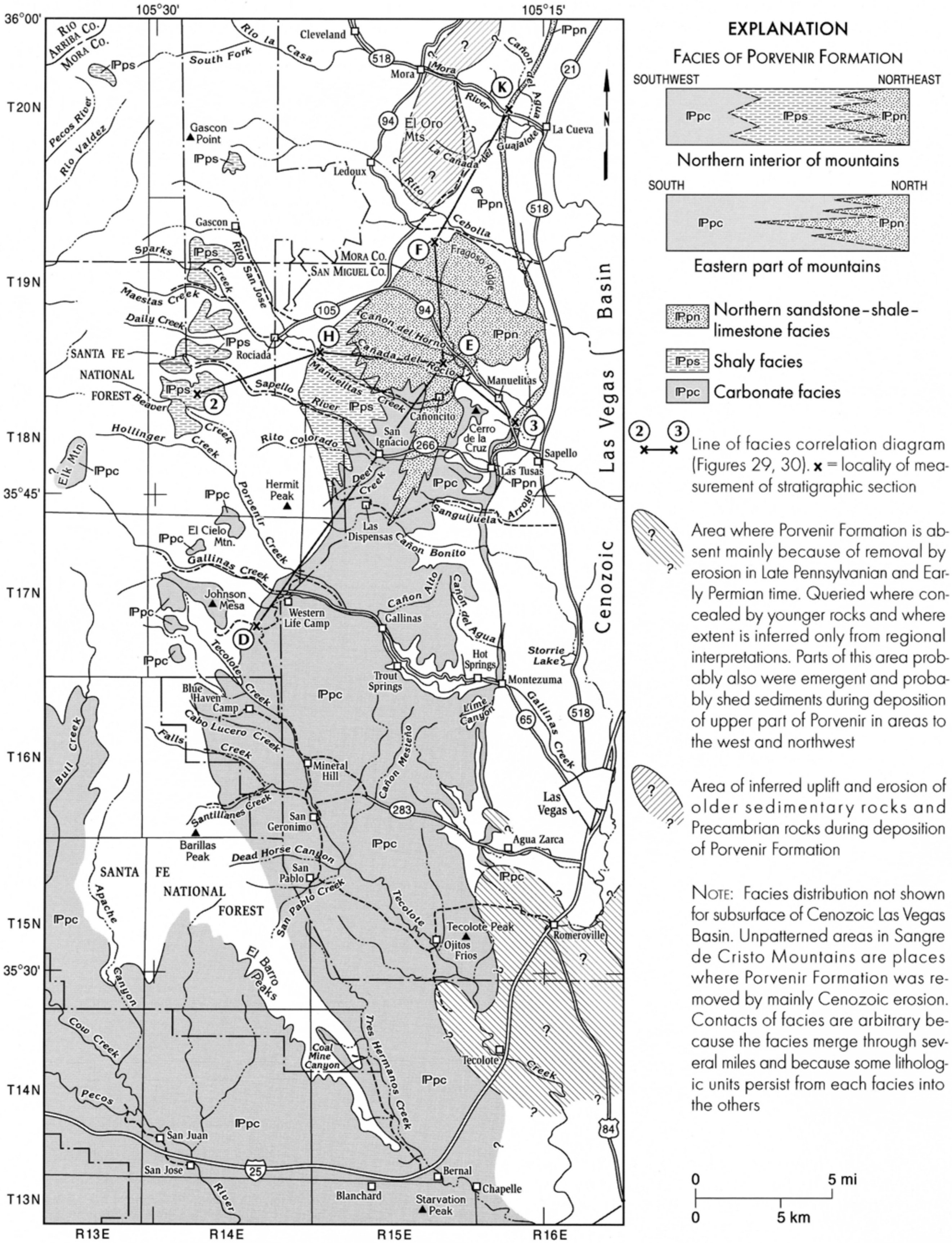


FIGURE 28—Index map of southeastern Sangre de Cristo Mountains and westernmost part of Las Vegas Basin showing distribution of facies of Porvenir Formation, lines of facies correlation diagrams (Figs. 29, 30), and areas of erosion. Area extends slightly west of area of Plate 1.

cuttings. (See Fig. 72 for location of wells.) Samples from the True Medina well contain Desmoinesian fusulinids at reported depths of 7,190–7,480 ft, and Atokan fusulinids similar in age to those of the upper part of the Sandia Formation in samples from reported depths of 7,610–7,750 ft that were identified by W. E. King (oral comm., 1990). Our tentative lithologic correlations suggest that these samples may represent cavings as much as 3,500 ft (1,100 m) below their original stratigraphic positions. Nevertheless, the Desmoinesian fossils show that rocks equivalent in age to the Porvenir are present in that area.

The thickness of the Porvenir Formation in the area of this report is shown by isopachs on Plate 4. The formation thickens generally northward across most of the area; the maximum known thickness in the area is 1,614 ft (492 m) at locality H (Fig. 31) east of Rociada. Part of the northward thickening is intraformational, for example between the type locality (loc. D), where the Porvenir is 1,065 ft (324 m) thick, and locality H.

In the southwestern part of the area, adjacent to the Paleozoic Bernal uplift (Plate 4), the entire Porvenir is present at places but is several hundred feet thinner than at the type locality. Part of the southward thinning is intraformational, but part is the result of unconformity with overlying rocks. A thickness of about 600 ft (180 m) is estimated for the Porvenir between Bernal and Blanchard. This estimate is based partly on data from the Rockwell no. 1 Des Marias well that was spudded in upper beds of the lower part of the Porvenir and was reported to bottom in Precambrian rocks at a depth of 552 ft (168 m). At the surface south of this well the lower part of the Porvenir is overlain unconformably by the Sangre de Cristo Formation.

In the subsurface of the Paleozoic San Jose Basin south and southwest of the area, rocks equivalent to the Porvenir thicken southwestward as shown by scattered wells. (See Figure 72 of this report and Foster et al., 1972, fig. 7, for total thickness of Pennsylvanian rocks.) At the surface in secs. 7 and 18 T16N R13E, west of the area of this report, Read et al. (1944, loc. 22) show that rocks of the carbonate facies of the Porvenir are about 850 ft (260 m) thick.

At the surface in the southeastern part of the area only the lower 115–550 ft (35–168 m) of the Porvenir is present in the area of the Paleozoic Tecolote uplift. At places on this uplift the Porvenir is overlain unconformably by the Alamitos Formation and at other places by the Sangre de Cristo Formation (Fig. 32). To the south the Porvenir is absent because of the unconformities.

In the northwestern part of the area, in the Cenozoic Beaver Creek and Sparks synclines (Plate 1), only the lower 1,000 ft (300 m) and less of the Porvenir is preserved from Cenozoic erosion; therefore, the thicknesses at outcrops east and northeast of Rociada provide the main basis for determining the isopachs in this part of the area. However, the Porvenir in the Beaver Creek and Sparks synclines is part of the shaly facies, probably indicating that a subsiding basin (the Rociada Basin of Plate 4) existed there during deposition of the Porvenir and that the formation was at least as thick there as it is east of Rociada.

In the eastern part of the mountains, between Sapello River and Manuelitas Creek, the Porvenir is 1,155–1,200 ft (352–366 m) thick at localities E and 3 (Fig. 31). These rocks are on the Paleozoic Manuelitas saddle between the Rociada Basin at the west and, possibly, a Paleozoic trough at the east in the western part of the Cenozoic Las Vegas Basin north of Sapello.

From about Rito Cebolla north, the Porvenir thins. At locality I (Figs. 46 and 88), just north of Cebolla Creek, most of the Porvenir is cut out by the Sapello fault (Plate 1), but about 0.5 mi (0.8 km) north of there most of it is present east of the fault, as shown by fusulinid data, and is about 900 ft (275 m) thick. Northward from there to La Cañada del Guajalote the lower part of the Porvenir is cut out by the Sapello fault and its total thickness is not known. At Mora River the Porvenir is 680 ft (207 m) thick (sec. K, Figs. 46 and 89), and near the north edge of the area it is about 550 ft (168 m) thick. Our fusulinid data from this northern part of the area indicate that the upper part of the Porvenir is absent because of unconformity with the overlying Alamitos Formation. As was previously discussed, intraformational unconformities in the lower part of the Porvenir also diminish its thickness locally north of Mora River. Therefore, it appears that uplifting occurred on the west flank of the Rainsville trough during and after the deposition of the Porvenir (Fig. 27*C*, *D*).

The data from the Amoco no. 1 "A" and "B" Salman Ranch wells (Plate 3) are interpreted to indicate a small amount of uplift, in late Desmoinesian, of the area of the Cenozoic Ocate anticline. This interpretation is similar to the postulated uplift of this area during deposition of the Sandia and is subject to the same uncertainties because of lack of other nearby subsurface data.

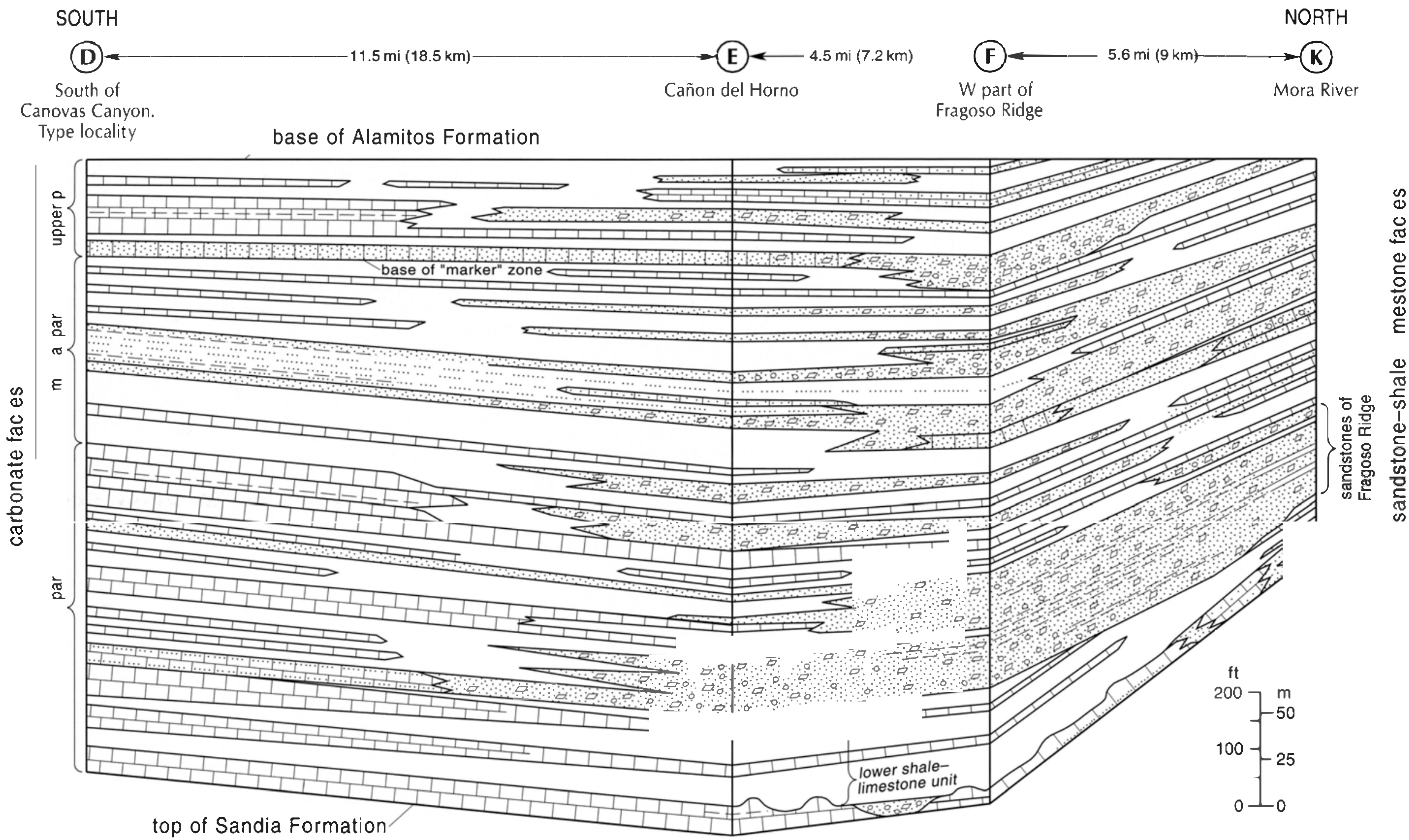
At outcrops west of Los Cisneros (USGS Lucero quadrangle), about 5 mi (8 km) north of the area of this report, the upper part of the Porvenir is present as shown by late Desmoinesian fusulinids (loc. 4, Plate 3). The basal and middle parts are present also, but the total thickness is not known because of Cenozoic structural complications west of Los Cisneros.

Southern carbonate facies

Lithology and stratigraphy—The lithology of the Porvenir Formation in the Gallinas Creek area (Fig. 33) is typical of the carbonate facies of the southeastern Sangre de Cristo Mountains from about Cañon Bonito south. A threefold stratigraphic division of the carbonate facies (Fig. 29) occurs where the formation is completely preserved: (1) a thick lower part characterized by thick limestones and interbedded shale; (2) a medial part that is mainly shale and shaly sandstone; and (3) a thin upper part that has a widespread, basal "marker" zone of sandy bioclastic limestone.

At the type locality (sec. D, Fig. 33) the lower 590 ft (180 m) of the Porvenir consists of thick, ridge-forming gray limestones (Fig. 34) and intervening nonresistant units of gray, calcareous, silty, clayey shale, shaly limestone, nodular limestone, and minor amounts of ledge-forming to shaly sandstone. Thin units of carbonaceous to coaly shale occur at several horizons (Fig. 35). The limestones generally contain abundant brachiopods, some pelecypods, crinoid columnals, bryozoans, echinoid spines, zaphrentid and chaetetid corals, some filamentous and phylloid algae, and, sporadically, fusulinids. Some of the shale and sandstone contains marine fossils, and some sandstones contain fossil-plant debris. Ledge-forming sandstones near the top of the lower part contain traces of subrounded, fine to medium, yellowish, weathered feldspar clasts. One or two ledge-forming sheet-like bodies of slightly feldspathic sandstone occur in similar stratigraphic position through a large part of the western Gallinas Creek area (for example, loc. 1, Fig. 33).

The medial part of the Porvenir in the carbonate facies at the type locality is mainly gray- to light-olive-brown-weathering calcareous shale and clayey siltstone that contains some interbedded fine-grained shaly sandstone and some thin, gray limestone beds. Thin beds of highly carbonaceous shale occur at several horizons. This shaly medial part of the Porvenir is about 340 ft (104 m) thick at the type locality and its equivalent in all three facies is recognizable, on a zonal basis, through much of the central part of the area (Fig. 36)



0FIGURE 29—Diagram showing correlation of carbonate facies and northern sandstone-shale-limestone facies of the Porvenir Formation between the type locality south of Gallinas Creek (sec. D) and Mora River (sec. K). Correlations are zonal and ar not intended to portray the lateral extents of individual beds. Unpatterned units are dominantly shale; other lithologic symbols are explained in Figure 9. Line of diagram shown in Figure 28.

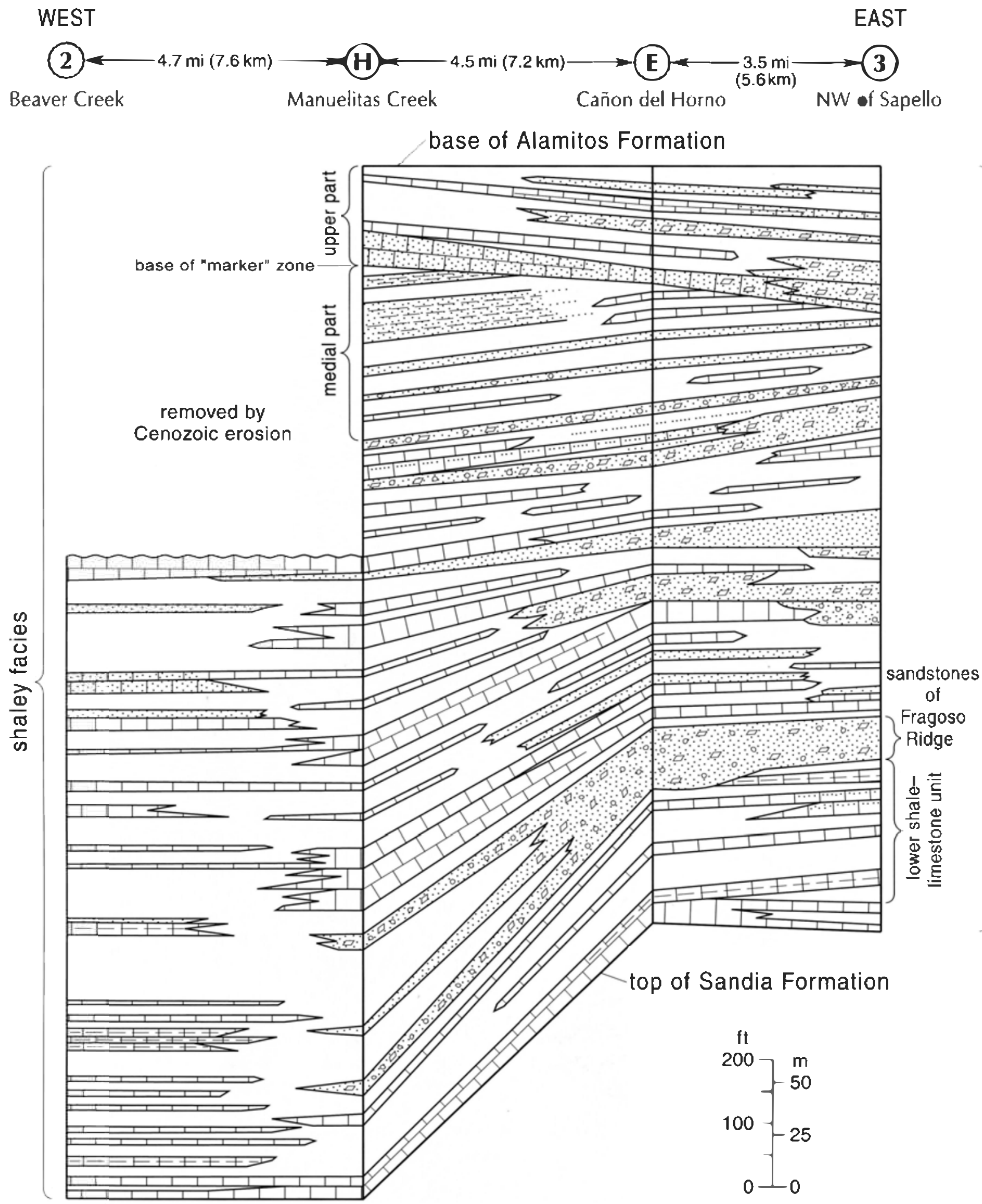


FIGURE 30—Diagram showing correlation of shaly facies and northern sandstone-shale-limestone facies of the Porvenir Formation between Beaver Creek (loc. 2) and Sapello (loc. 3). Correlations are zonal and are not intended to portray the lateral extents of individual beds. Unpatterned units are dominantly shale; other lithologic symbols are explained in Figure 9. Line of diagram shown in Figure 28.

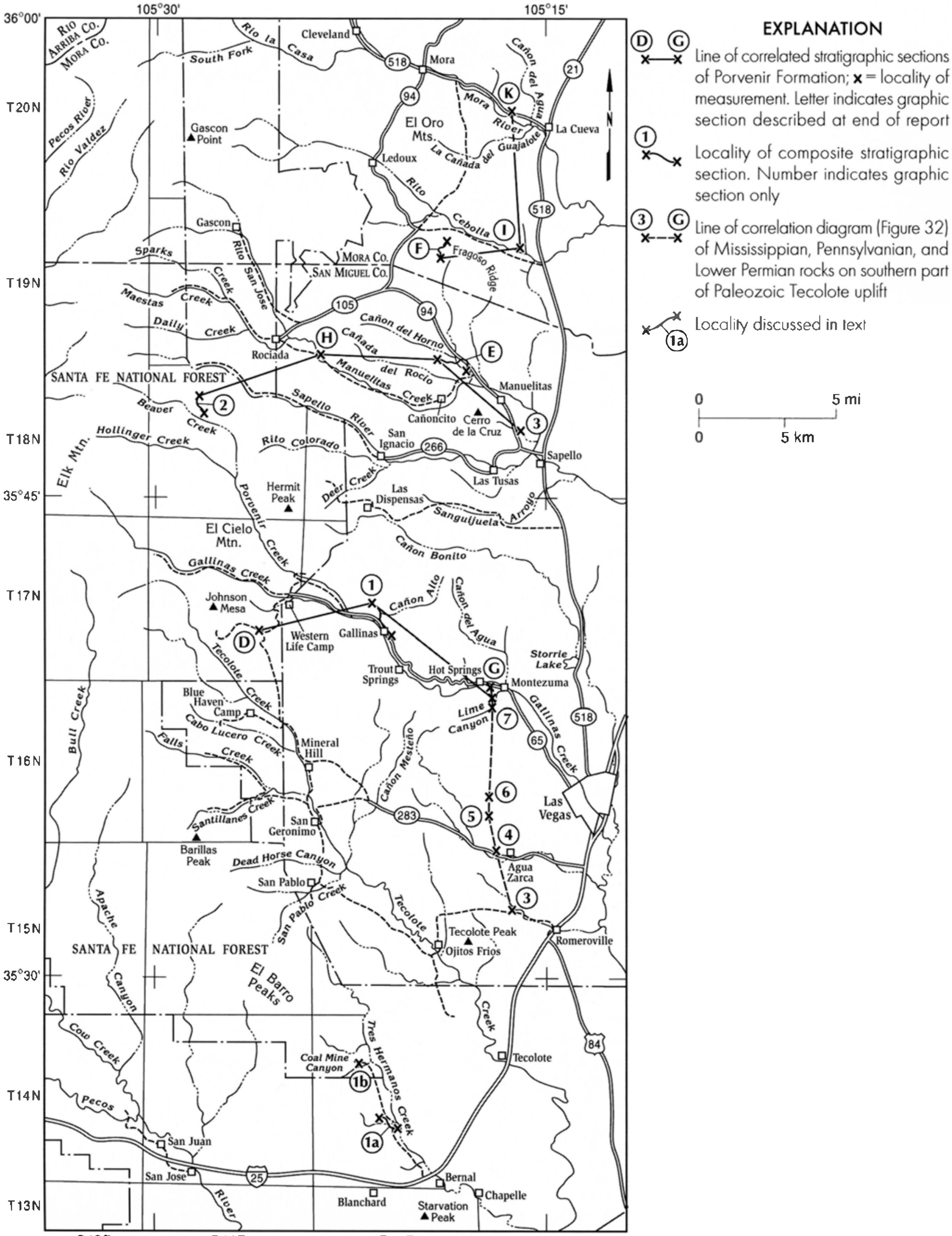


FIGURE 31—Index map of southeastern Sangre de Cristo Mountains showing localities of stratigraphic sections of the Porvenir Formation and line of correlation diagram (Fig. 32) of Mississippian, Pennsylvanian, and Lower Permian rocks of Tecolote uplift in southeast part of area. Area extends slightly west of area of Plate 1.

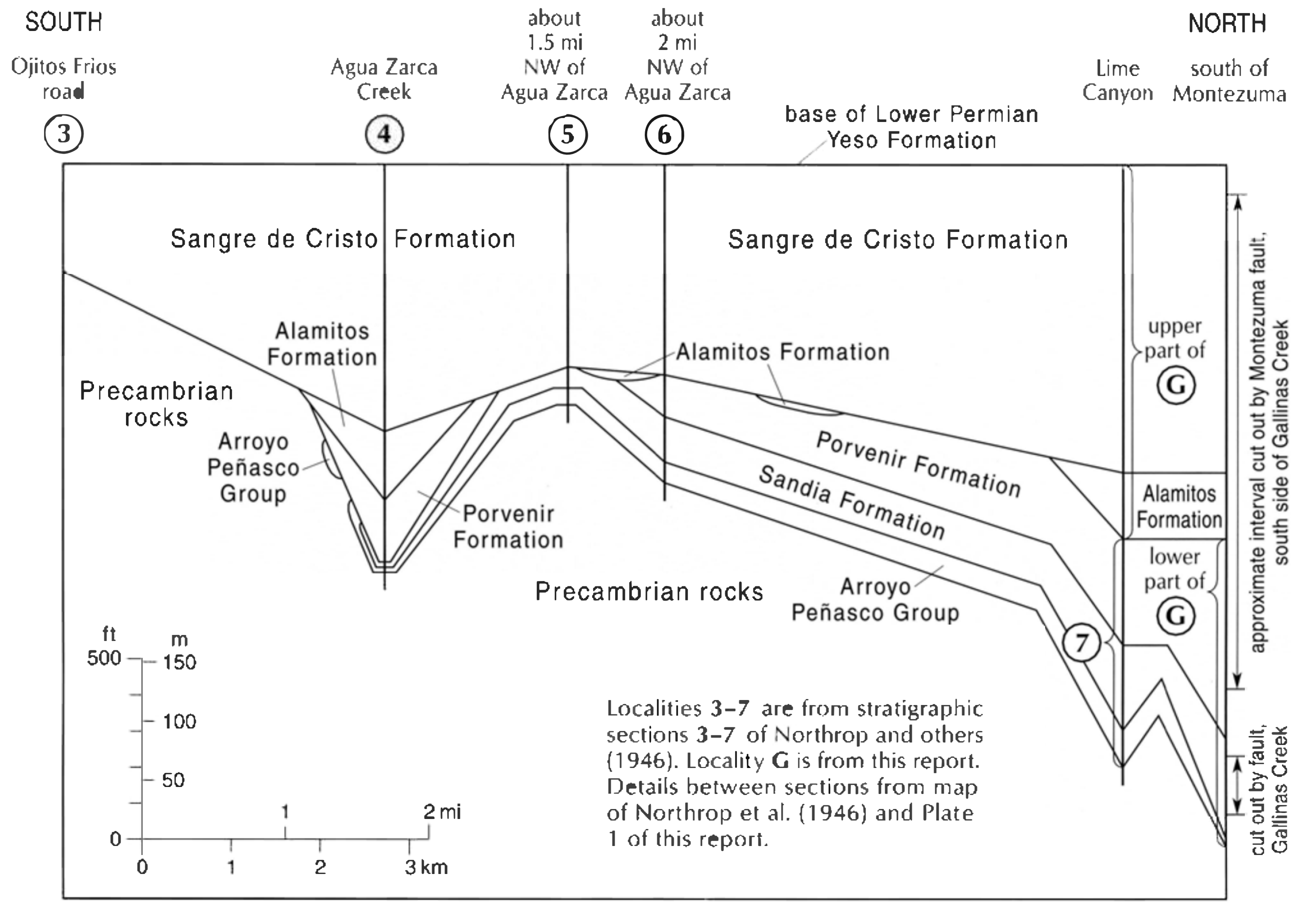


FIGURE 32—Correlation diagram of Mississippian, Pennsylvanian, and Lower Permian rocks on southern part of the Paleozoic Tecolote uplift south of Montezuma. Line of diagram shown in Figure 31.

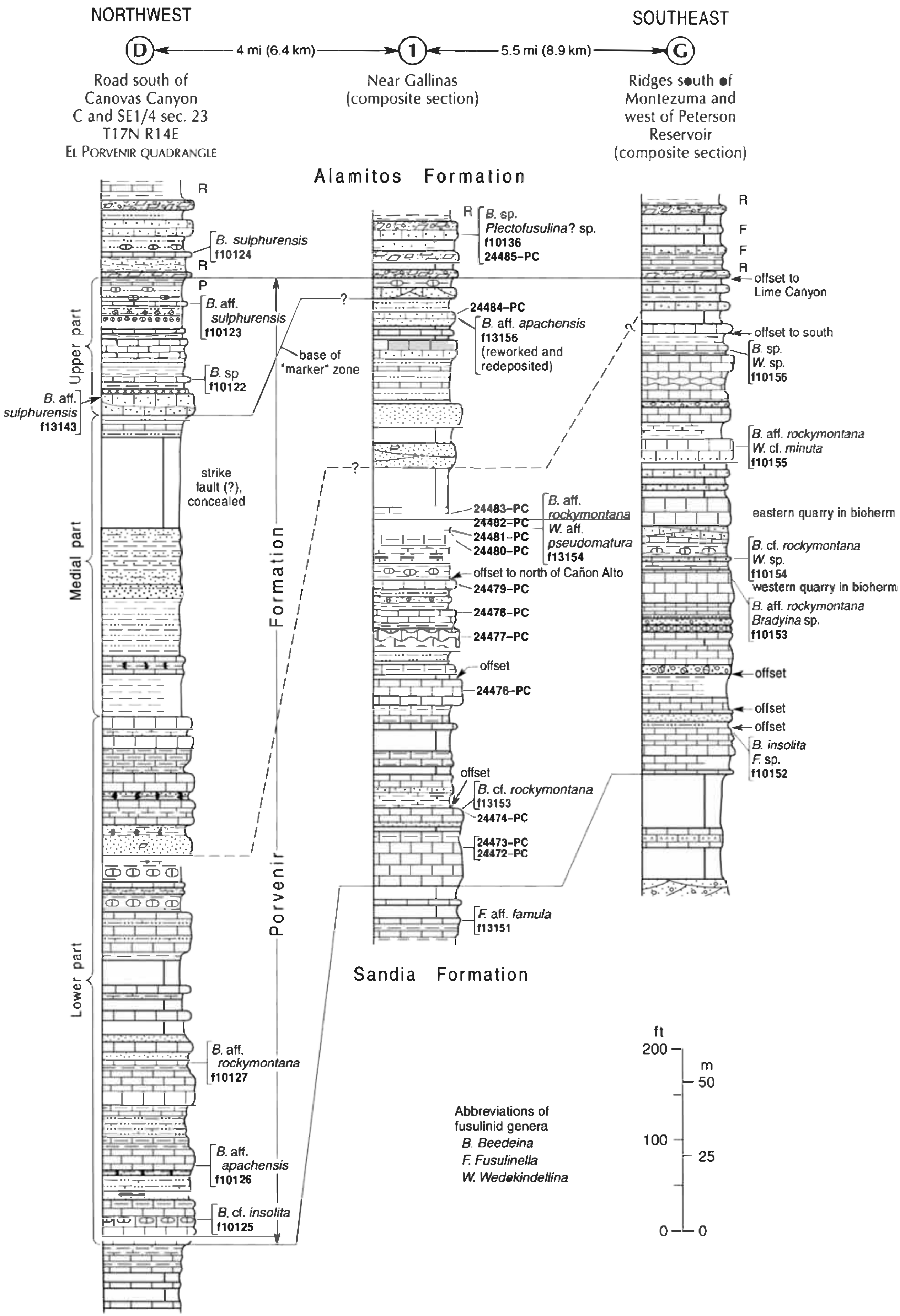
from near the San Miguel–Mora County line southward to the vicinity of locality 1a (Fig. 31) west of Tres Hermanos Creek. However, it is not possible to correlate the lower contact precisely throughout this region, especially in the north where thick feldspathic to arkosic sandstones occur within the interval (Fig. 29). The medial and upper parts of the Porvenir are absent because of unconformity with the overlying Alamitos and Sangre de Cristo Formations in the eastern (sec. G, Fig. 33) and southern (Fig. 32) parts of the area, and in some places in the southwestern part west of Bernal.

The upper part of the Porvenir Formation in the carbonate facies at the type locality (D) consists of a basal crossbedded sandy limestone that is overlain by shale, siltstone, thin fossiliferous limestone, limestone-pebble conglomerate, and nodular limestone. The upper part is about 175 ft (53 m) thick at the type locality. The distinctive basal unit of the upper part contains fragments of crinoid columnals and other fossil debris that do not appear to have been transported far, but much of the unit is crossbedded calcarenite that is composed of well-rounded, fine to coarse calcite sand containing angular coarse quartz sand and granules. This unit is designated, informally, as a "marker" zone. The marker zone, ranging in thickness from 10 to 70 ft (3 to 21 m), is present in all three facies throughout much of the central part of the area from near the Mora–San Miguel County line southward to Tres Hermanos Creek southwest of Tecolote. The marker zone is recognizable not only by its lithology, but also because the stratigraphically lowest occurrence of the late Desmoinesian fusulinid *Beedeina sulphurensis* is within or just below it. A few hundred feet south of the type locality, the "marker" zone grades laterally into highly calcareous coarse-grained sandstone as it does at a few other places but, generally, the zone is crossbedded calcarenite that contains angular quartz sand and granules.

In the Gallinas Creek area, the carbonate facies of the Porvenir Formation thins eastward toward the Tecolote uplift (Fig. 33) because the upper and medial parts of the Porvenir are beveled by the Alamitos Formation. Part of the thinning might be the result also of local unconformity at the base of the marker zone, because sandy calcarenite, possibly equivalent to the marker, lies on the lower part of the Porvenir at locality 1. However, we did not find fusulinids in these calcarenite beds at locality 1, and the identification of the marker is questionable there. North of Montezuma the lower part of the carbonate facies of the Porvenir is preserved from Cenozoic erosion on La Sierrita dome. There, it is lithologically similar to the Porvenir at locality G. Along the east front of the mountains the Porvenir is partly to completely cut out by the Montezuma fault northward past Cañon Bonito (Fig. 32; Plate 1).

At the east front of the mountains, at locality G, a short distance south of Montezuma, the Porvenir is about 550 ft (168 m) thick and correlates entirely with the lower part of the carbonate facies at the type locality. The lower part of the Porvenir thins southward because of unconformity with the Alamitos Formation and the Sangre de Cristo Formation (Fig. 32).

About 2.6 mi (4.2 km) northwest of Agua Zarca on New Mexico State Road 283 (Plate 1), ledge-forming limestones and interbedded thin shales of the lower part of the carbon-



NORTHWEST
SOUTHEAST
D
4 mi (6.4 km)
1
5.5 mi (8.9 km)
G
Road south of Canovas Canyon C and SE1/4 sec. 23 T17N R14E El Porvenir quadrangle
Near Gallinas (composite section)
Ridges south of Montezuma and west of Peterson Reservoir (composite section)
Alamitos Formation
Porvenir Formation
Sandia Formation
Upper part
Medial part
Lower part
R
P
F
B. sulphurensis f10124
B. aff. sulphurensis f10123
B. sp f10122
B. aff. sulphurensis f13143
base of "marker" zone
strike fault (?), concealed
B. aff. rockymontana f10127
B. aff. apachensis f10126
B. cf. insolita f10125
B. sp. Plectofusulina? sp. f10136 24485-PC
24484-PC
B. aff. apachensis f13156 (reworked and redeposited)
24483-PC
24482-PC
24481-PC
24480-PC
B. aff. rockymontana W. aff. pseudomatura f13154
offset to north of Cañon Alto
24479-PC
24478-PC
24477-PC
offset
24476-PC
offset
B. cf. rockymontana f13153
24474-PC
24473-PC
24472-PC
F. aff. famula f13151
offset to Lime Canyon
offset to south
B. sp. W. sp. f10156
B. aff. rockymontana W. cf. minuta f10155
eastern quarry in bioherm
B. cf. rockymontana W. sp. f10154
western quarry in bioherm
B. aff. rockymontana Bradyina sp. f10153
offset
offset
offset
B. insolita F. sp. f10152
Abbreviations of fusulinid genera
B. Beedeina
F. Fusulinella
W. Wedekindellina
ft
200
100
0
m
50
25
0

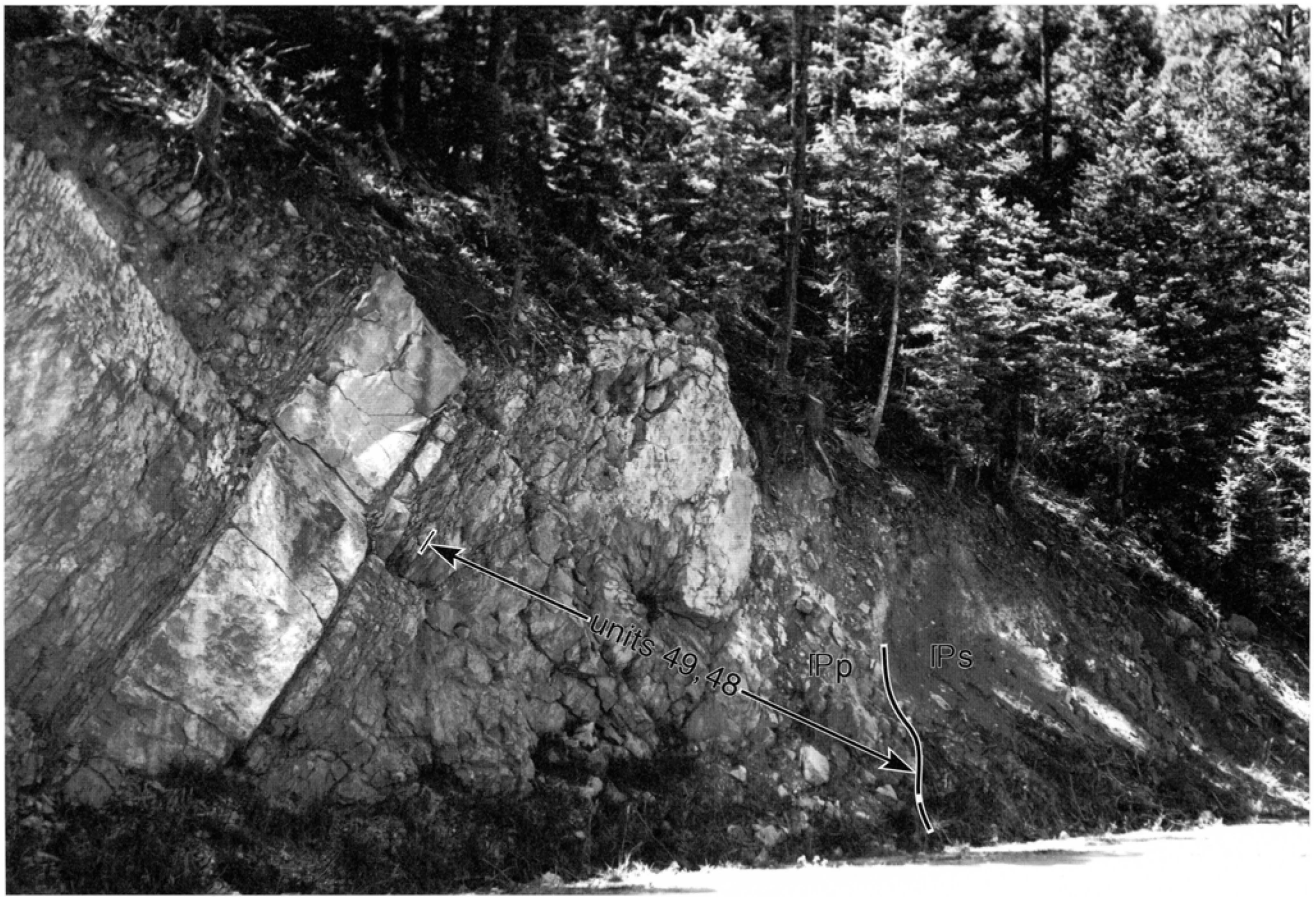


FIGURE 34—Limestones of basal part of Porvenir Formation (IPp) at its type locality (D) along U.S. Forest Service Johnson Mesa road. Units 49, 48 are about 18 ft (5.5 m) thick. Thick, calcareous, clayey shale and interbedded thin limestones of upper part of Sandia Formation (IPs) are exposed poorly on slope at right.

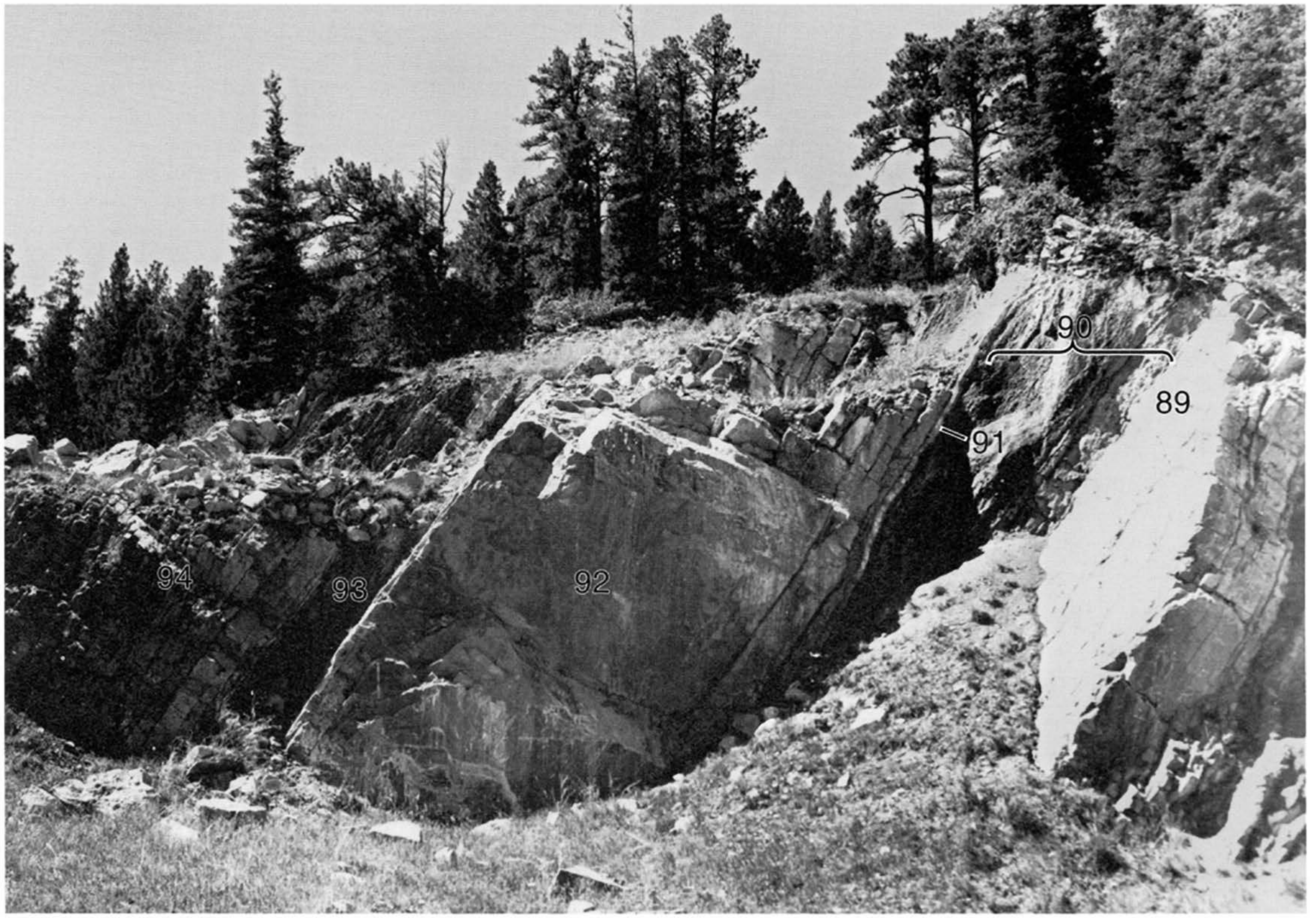
ate facies of the Porvenir are exposed. The basal thin limestones contain the fusulinids *Beedeina* sp. and *Fusulinella* cf. *F. famula* (f10308), indicating correlation with the basal part of the Porvenir elsewhere in the area. The Porvenir is only about 220 ft (67 m) thick and, about 3.5 mi (5.6 km) northwest of Agua Zarca, it is overlain unconformably by feldspathic sandstone and calcareous sandstone of the Alamitos Formation (Plate 1). Farther west, west of the north end of Ojitos Frios anticline, the Porvenir thickens westward beneath the Alamitos. At outcrops on New Mexico State Road 283, at the top of the bluffs just east of Cañon Mesteño, the marker zone containing *Beedeina sulphurensis* (f10309) crops out just below the Alamitos and just above calcareous dark-gray shale of the medial part of the Porvenir. Traced southward from there, the Porvenir is beveled gently down to shales of the medial part by the Alamitos Formation.

Along the west side of Tecolote Creek southeast of its confluence with San Pablo Creek (Plate 1), the Sangre de Cristo Formation bevels gently southeastward down to the lower part of the Porvenir, and the rocks that crop out southward past Ojitos Frios are limestones, shale, and minor sandstones, almost entirely of the lower part of the carbonate facies. About 1 mi (1.6 km) northwest of Ojitos Frios, on the cliff above the west side of Tecolote Creek, a thick unit of coarse-grained calcareous sandstone is present locally at the top of the Porvenir. Similar thick sandstone occurs also at the top of the Porvenir about 2 mi (3.2 km) north–northeast of Ojitos Frios. These sandstones probably were derived locally from the Tecolote uplift and might be equivalent to part of the medial unit or to the marker zone.

In the southwestern part of the area, on the west limb of the Chapelle syncline, the carbonate facies of the Porvenir Formation consists of thin to thick limestones, shale, and minor amounts of sandstone lithologically generally similar to the type locality. At Cabo Lucero Creek and Falls Creek all three parts of the Porvenir are present. Farther south at Santillanes Creek and San Pablo Creek only the lower part, about 500 ft (152 m) thick, is present unconformably beneath the Sangre de Cristo Formation. Still farther south, at localities 1a and 1b (Fig. 31) west of Tres Hermanos Creek, all three parts of the Porvenir are present. The basal part contains *Beedeina* aff. *arizonensis* (f10335) and the marker zone contains *Beedeina sulphurensis* (f10337).

Near the southern margin of the area, on both limbs of the Serafina monocline, thick limestones, shales, and thin sandstones represent only the lower part of the carbonate facies of the Porvenir Formation. *Beedeina rockymontana* (f10311), representative of upper horizons in the lower part, was found in a quarry on the Bernal–Blanchard road about 1 mi (1.6 km) west of Bernal in sandy bioclastic limestone estimated to be about 100 ft (30 m) below the top of the lower part of the Porvenir. Higher limestone and shale beds

FIGURE 33—Stratigraphic sections of the Porvenir Formation, Gallinas Creek area. Locality D is the type section. Lithologic symbols are explained in Figure 9. Localities of measurement and line of sections are shown in Figure 31.


90
89
91
94
93
92

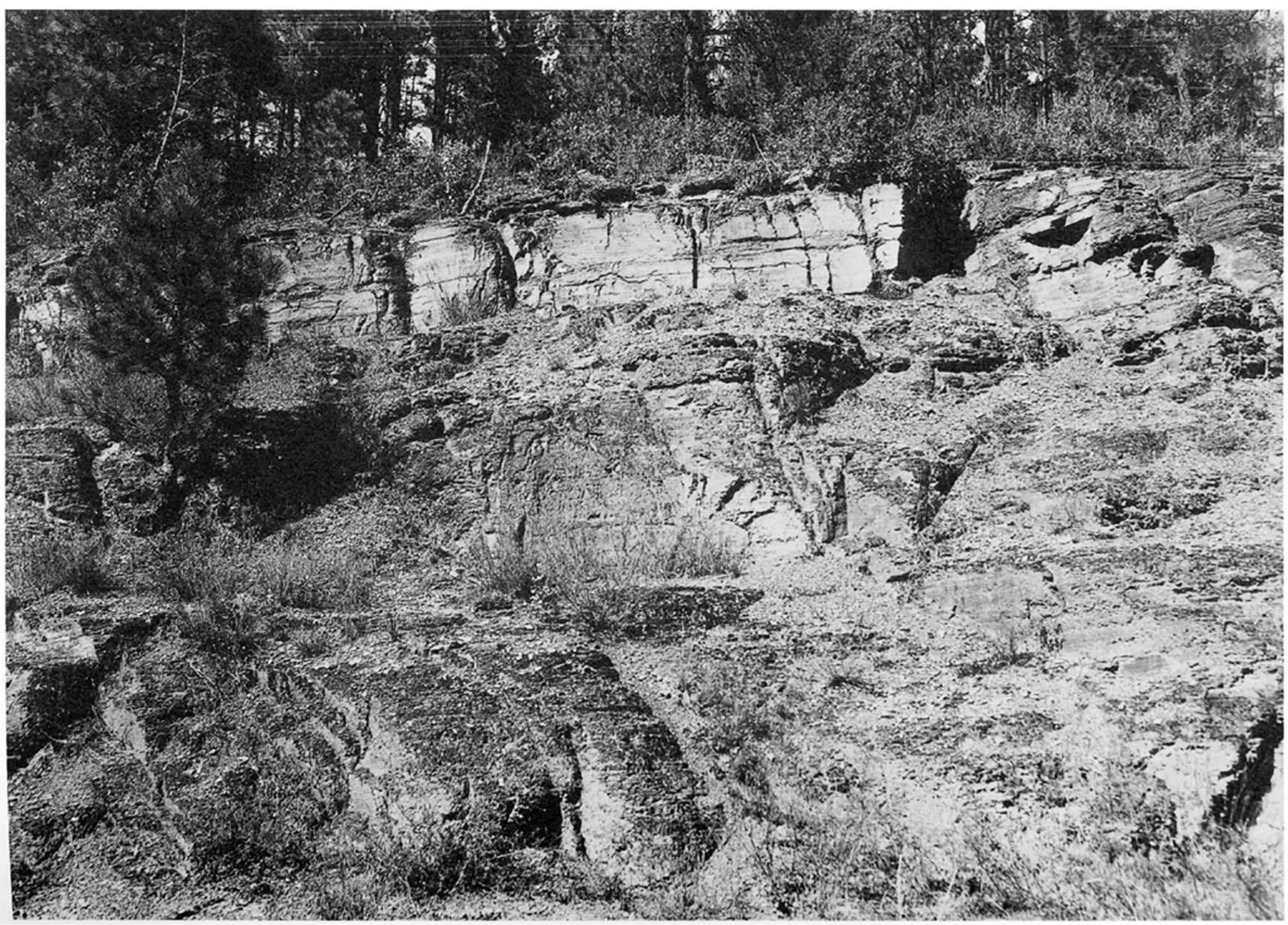


FIGURE 35—Limestone and carbonaceous shale of the lower part of the Porvenir Formation at its type locality (units 94–89 of type section, D). Massive bioclastic limestone (unit 92) in center is about 25 ft (7.6 m) thick, is mainly structureless internally, and may be the core of a small bioherm. Notch-forming beds stratigraphically below (to right of) the limestone are 0.5 ft thick, medium- to coarse-grained sandstone (unit 91) underlain by highly carbonaceous to coaly dark-gray shale that grades downward into yellow-weathering claystone (unit 90).

FIGURE 37—Bed (delineated) of low, biohermal mounds in lower part of Porvenir Formation just south of Ojitos Frios. Limestones contain colonies of *Chaetetes* and phylloid and filamentous algae. Mounds are 1–3 ft (0.3–1 m) high.

of the Porvenir are poorly exposed and are locally concealed south of the quarry and the railroad where the Sangre de Cristo Formation lies unconformably on the lower part of the Porvenir.

Limestone petrology—The limestones of the carbonate facies are texturally and structurally diverse, almost bewilderingly so. Shaly bedded limestone and interlayered shale and thin lenticular limestone are common. Nodular limestones and shale containing limestone nodules also are common. Thin, micritic limestones occur throughout the section, but most of the limestones are bioclastic, ranging from very fine to coarse grained; coquinas of crinoid columnals, brachiopods, and even fusulinid tests occur here and there. Coarse, crinoidal limestones are especially common north of Blanchard in the southern part of the area.

A common type of limestone is highly fossiliferous and well-bedded but massive weathering and ledge forming. Parallel, but undulatory, bedding commonly is caused in part by local low (generally 1–3-inch) mounds of *Chaetetes* and at some places by *Syringopora* or by algal-bound mounds of crinoidal and other debris. The calcareous material in these rocks accumulated mainly because of upward-building and entrapment of fine bioclastic debris by sedentary organisms. These rocks are classified as biostromes; at some places they are broadly lenticular biostromal banks.

Conspicuously mounded limestones are common in the lower part of the Porvenir Formation. These range from beds only a few inches to a few feet thick (Fig. 37) to distinct bioherms 20–30 ft (6–9 m) thick. The low-mounded rocks commonly contain *Chaetetes* and algal remains and, at places, fine to coarse crinoidal and other fossil debris. Mounded phylloid-algal limestones and interspersed cross-bedded, sandy, clastic limestones are well exposed at places east and north of Blanchard.

A small, complex bioherm is well exposed in a quarry in eastward-dipping beds of the lower part of the Porvenir at locality G on the ridge south of the Montezuma powerhouse (Fig. 38). This quarry was mapped by plane table to study the stratigraphic details of the bioherm and its overlying rocks. The bioherm can be traced south of the quarry, but because of poor exposures its southern limit was not deter-

FIGURE 36—Calcareous gray shale and thin-bedded limestone in medial part of Porvenir Formation, east limb of Las Gallinas syncline, north side of Gallinas Creek. Highest ledge in outcrop is thin-bedded limestone. Exposure is roadcut on New Mexico Highway 65 about 2,300 ft (0.7 km) west of bridge across Porvenir Creek. Outcrop is about 25 ft (7.5 m) high.

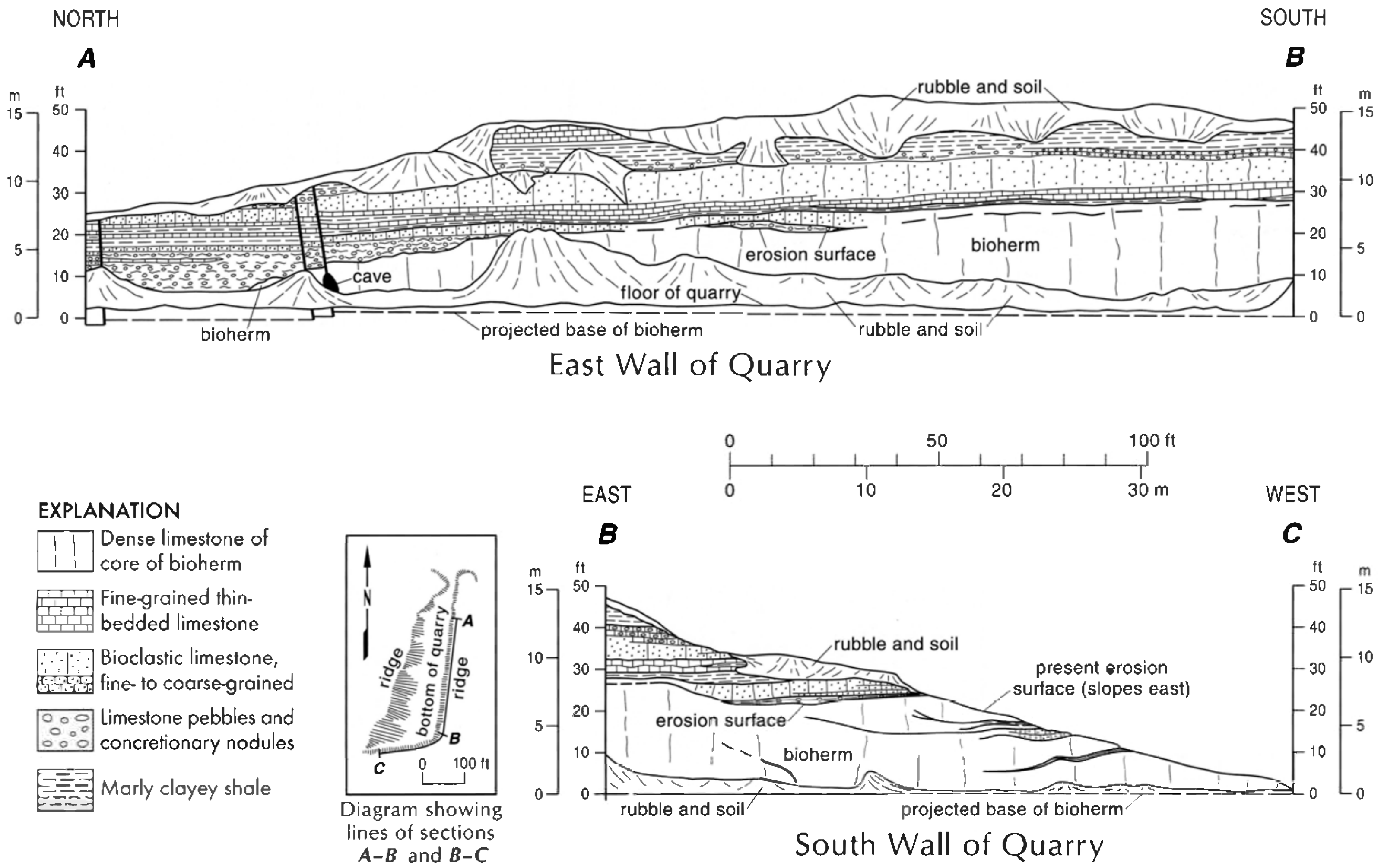


FIGURE 38—Drawing of bioherm exposed in quarry at locality G on ridge about 700 ft south of powerhouse at Montezuma. Base of bioherm is about 190 ft (58 m) stratigraphically above base of the Porvenir Formation. Beds dip southeast 35–40°. Planes of sections are rotated to positions where base of bioherm is horizontal.

mined. The depositional sequence that includes this bioherm begins with a thin quartzose sandstone exposed on the ridge west of the quarry (see sec. G, Fig. 33). This sandstone is mainly fine grained but contains coarse grains and small quartz and limestone pebbles. The sandstone is overlain by thin micaceous siltstone that in turn is overlain by coquinas of coarse crinoid fragments, brachiopod fragments and complete shells, and micaceous, sponge-spicule-bearing limestone. These units contain phylloid algae. Bedding is undulatory to low-mounded and lenticular. These sub-bioherm rocks are units 42 through 46 in descriptive section G (p. 217–218) and are exposed on the sloping west floor of the quarry and on the ridge to the west.

The core of the bioherm (Fig. 38) is mainly dense, massive limestone almost 30 ft (9 m) in maximum thickness. The core thins northward and its northernmost exposures appear to have been eroded and slightly brecciated, probably by wave action, prior to the deposition of overlying beds. An undulatory erosional surface can be traced across the east and south walls of the quarry at the top of the core rock and below a bed of bioclastic limestone. At places, this contact is partly obscured by recrystallization, but its trace is mainly apparent. Most of the core is structureless, but in the south wall of the quarry several sloping bedding planes and attendant thin beds of finely bioclastic limestone indicate spatially and temporally varying centers of growth. Part of the core rock is composed of mainly articulated brachiopod shells, crinoid columnals, a few horn corals, clumps of *Chaetetes* and syringoporid corals, bryozoans, echinoid debris, a few siliceous sponge spicules, gastropod shells, foraminifers, worm tubes, and filamentous and phylloid algae. The calcareous alga *Eugonophyllum johnsonii* was identified as occurring at this locality by Konishi and Wray (1961, p. 662). Toomey (1980, p. 255) identified phylloid-algal plates assigned to *Ivanovia tenuissima* Khvorova as being common to abundant in the core rock of the bioherm. Although many of the fossils are broken, they show little evidence of abrasion. Many fossils are randomly oriented, suggesting disturbance by wave or current action and, probably, bioturbation prior to cementation.

The matrix comprises 40–70 percent of the rock. Polished sections show that much of the matrix is composed of varying proportions of fine to very fine grained fossil fragments and pellets and micritic calcite. Texturally, parts of the matrix are very fine grained, finely banded, sinuous bodies that appear to represent lime mud that "oozed" around the larger fossils. Some fine-banding may represent encrusting algae. Insoluble residues are less than 5 percent by weight and consist of quartz sand, glauconite grains, siliceous-sponge spicules, lacy chert, and a small fraction of light-gray clay. The limestone appears to be almost entirely lacking in dolomite.

Much of the matrix is recrystallized. Patches as much as 0.8 inch (20 mm) across are clear sparry calcite that is in optical continuity with some of the enclosed fossils. Other patches are fine- to coarse-grained, sucrose, white to light-brown, crystalline calcite. Reticulating stringers of ocherous yellow silica are common in microfractures; in places lacy or spongy networks of silica replace part of the matrix and some of the small fossils.

A complex sequence of beds occurs above the core. On the north flank, bedded marly clay containing rudely bedded limestone pebbles and concretionary nodules lies unconformably on the core. Many of the nodules are articulated brachiopods surrounded by accreted algal? calcite. Zaphrentid corals and large crinoid columnals are common also. Pebbles of dense gray limestone similar to the matrix of the biohermal core range up to 2.5 inch (6.4 cm) diameter. The stratigraphic relations (sec. *A–B*, Fig. 38) suggest that the pebbles and some of the fossils were swept off the bioherm by wave or current action and deposited in mud accumulating on its flank in a late, shallow-water stage of its development, probably during and after the time when the unconformity developed at the top of the core.

The highest beds of the bioherm and the overlying beds are coarse bioclastic (mainly crinoidal) limestone that contains some quartz and glauconite sand grains. Fusulinids are common in these beds and some thin beds are composed primarily of unbroken and well preserved fusulinid tests.

Another similar, but smaller and stratigraphically higher bioherm, is exposed in a large quarry about 200 ft (60 m) east of the locality of Figure 38. Other similar rocks that may be bioherms have been observed at other places in the southern carbonate facies (for example, Fig. 35), but exposures generally are poor or discontinuous, and the details cannot be observed as well as in the two quarries just south of Montezuma.

Toomey (1980) has studied the petrography and paleontology of the western bioherm (Fig. 38) near Montezuma and classified it as a phylloid-algal mound complex. His observations of the structure and stratigraphy of the bioherm agree generally with those presented here. However, he suggested (p. 253) that the westernmost exposures in the south wall of the quarry (*C*, Fig. 38) represent the western end of the complex and mark an open, seaward-facing side on a shelf bordering a basin (p. 264). Although the preserved part of the core is thickest in the southeastern side of the quarry (*B*, Fig. 38), there is no way to determine where the western limits of the core may have been originally because the east-tilted rocks are beveled and eroded away along the east-sloping present-day land surface. Additionally, the east-sloping bedding in the westernmost exposures (sec. *B–C*) indicate that there was more than one center of growth during development of the core and, west of the present quarry, it might have been as thick as, or thicker than, it is in the quarry. Rocks equivalent to the Montezuma bioherm have been eroded from areas immediately to the west on the crest of the Cenozoic Creston anticline. However, on the west limb of the anticline at locality 1 (Fig. 33) and at the type locality of the Porvenir (sec. D), rocks in approximately the same stratigraphic position as the Montezuma bioherm are biostromal limestones, indicating that shelf-depositional environments continued westward from Montezuma.

Toomey (1980) also suggested (p. 253) that the northeast part of the present quarry (*A*, Fig. 38) was "in a more shelfward location." The northern flank of the core was eroded prior to the deposition of the overlying marly shale and nodules, suggesting that wave or current action was rigorous at least temporarily on its north flank. This does not necessarily imply a more shelfward position than the other parts of the bioherm, in our opinion. Biostromal and, probably biohermal, limestone occurs in the lower part of the Porvenir about 0.5 mi (0.8 km) north of Montezuma, indicating similar depositional conditions in that direction. To the east, the Montezuma bioherm is overlain by stratigraphically higher rocks of the Porvenir, and there is no way to determine its extent in that direction.

Inasmuch as the lower part of the Porvenir is lithologically generally similar throughout the Gallinas Creek area and at the well that penetrated it in the adjacent part of the Las Vegas Basin (no. 2, Fig. 18), we know of no specific evidence that would show that distinct shelf margins existed in the vicinity of Montezuma in early or middle Desmoinesian time. The Tecolote uplift subsided a little slower than areas to the north and northwest, but our stratigraphic data indicate that it was tectonically uplifted mainly after the deposition of the lower part of the Porvenir.

Shaly facies

In the belt of hogbacks southeast of Hermit Peak, the Porvenir Formation thickens northward from the type locality. This thickening is accomplished mainly by a northward increase in the proportion of shale in the lower part of the formation. In the hogbacks northeast of Hermit Peak the Porvenir is completely represented at Sapello River and at Manuelitas Creek (sec. H, Fig. 39) where it is 1,614 ft (492 m) thick. At these places, ledge-forming limestones at the base of the formation contain *Beedeina arizonensis*, (f10338, f10139) of early Desmoinesian age and the upper part contains *Beedeina sulphurensis* (f10142) of late Desmoinesian age, indicating that the age span of the thickened formation is the same as at the type locality. The medial shaly part is recognizable, although its base may be stratigraphically higher than at the type locality. The upper part also is present although, at Sapello River, the marker zone either was not deposited or is represented by sandstone. At locality H, the lower part of the Porvenir contains several coarse-grained to conglomeratic sandstones that contain traces of weathered yellowish-gray feldspar. Near the top of the lower part, two pebbly, arkosic sandstones contain chalky-weathered feldspar clasts that are as large as 0.25 inch (0.3 cm) diameter.

The rocks of the Porvenir Formation northeast of Hermit Peak at Sapello River and Manuelitas Creek are classified as the eastern part of the shaly facies, but some of the limestones are similar to those of the carbonate facies, and the feldspathic and arkosic conglomeratic sandstones are similar to those of the northern facies. Thus, the Porvenir in this area is transitional between all three facies.

To the west, at Beaver Creek, about 1,000 ft (305 m) of the shaly facies of the Porvenir was preserved from Cenozoic erosion (loc. 2, Fig. 39). The lower 300 ft (90 m) consists of thin, gray limestone and interbedded siltstone, calcareous shale, and shaly limestone that commonly weather to platy rubble. The remainder of the section is mainly gray shale and calcareous shale that contains stratigraphically widely spaced thin to thick limestones and a few thin, sheet-like sandstones. To the north, in the Beaver Creek syncline and in the Sparks syncline between Maestas and Sparks Creeks, only the lower 250–400 ft (75–120 m) of the Porvenir is preserved. The lithology is generally similar to the section at Beaver Creek, but the proportion of shale is probably greater than at Beaver Creek.

Fusulinids were not found at the base of the Porvenir at Beaver Creek, but, farther north in the Beaver Creek and Sparks synclines, *Beedeina arizonensis* and *Fusulinella* aff. *F. famula* (f10312) occur near the base on the ridge north of Sapello River. North and south of Maestas Creek (f10313, f10339) and on the ridge north of Sparks Creek (f10314) *B. arizonensis* occurs near the base of the formation (Baltz and O'Neill, 1986). These early Desmoinesian fossils confirm the lithologic correlation of the shaly facies of the Porvenir in these isolated outcrops with the Porvenir elsewhere in the area.

The limestones of the shaly facies are similar to the gray, bioclastic limestones in the southern carbonate facies, but they do not commonly form thick, massive units as they do farther south. Algal limestones and biostromal limestones are present, but bioherms are uncommon. However, on the west limb of the Beaver Creek syncline just north of the ridge crest north of Daily Creek, and on the east limb of the Sparks syncline just north of Sparks Creek, biohermal mounds as much as 15 ft (4.5 m) high are present locally near the base of the formation. These mounds were eroded partly and are overlain by local limestone-pebble to boulder-conglomerate and coarse-grained sandstone. These lithologies and stratigraphic relations are similar to those of the basal part of the Porvenir in the sandstone-shale-limestone facies northwest and north of Manuelitas where biohermal mounds occur and where an intraformational unconformity occurs in the lower part of the formation.

An outlier of rocks in the trough of the Sparks syncline north of Gascon (Plate 1; Fig. 28) probably is an erosional remnant of the shaly facies of the Porvenir. This remnant is about 400 ft (120 m) thick. The basal part, about 80 ft (25 m) thick, is oolitic limestone, thin-bedded sandy limestone, shale, and, a sandstone that locally contains abundant pebbles and cobbles of gray limestone. Stratigraphically higher rocks are mainly gray shale that contains thin gray limestones and thin coarse-grained sandstones. Near the middle is a ledge-forming unit of thin-bedded gray limestone about 10 ft (3 m) thick. These rocks are correlated with the lower part of the Porvenir because of stratigraphic position and general lithologic similarity to outcrops of these rocks to the south and southeast, but no fusulinids were found to confirm the correlation.

Sutherland and Harlow (1973, p. 6–7) reported that the percentage of shale increases northward in the Desmoinesian part of their La Pasada Formation in the high part of the mountains east of Truchas Peaks and mainly west of the area of the present report (Plate 1). According to Sutherland and Harlow (1973, p. 116–117) fossiliferous Desmoinesian rocks, about 365 ft (110 m) thick, are present in the eroded upper part of their La Pasada Formation on the ridges near the head of Rio Valdez in the northwest corner of the area of Plate 1 of the present report. They described these rocks as being mainly shales that contain thin limestones and a few thin sandstones. These Desmoinesian rocks apparently belong to the shaly facies of the Porvenir, which suggests that the Paleozoic Rociada structural and depositional basin extended northwestward across this area in at least part of Desmoinesian time. Because the Desmoinesian rocks have not been mapped in the northwesternmost part of the area they are shown on Plate 1 and in Figure 28 only in their general location, described by Sutherland and Harlow (1973).

In the belt of hogbacks east of Rociada, the Porvenir thins northeastward from locality H, and thick feldspathic sandstones appear in the lower and upper parts of the formation as it grades into the northern sandstone-shale-limestone facies. The marker zone can be recognized at places in these hogbacks to the vicinity of the Mora–San Miguel County line where it either wedges out or grades into coarse sandstone. In the subsurface of the Cenozoic Las Dispensas syncline east of locality H, the Porvenir thins depositionally onto the Paleozoic Manuelitas saddle (Plate 4) and grades laterally into the northern sandstone-shale-limestone facies (Fig. 30 and sec. E, Fig. 39).

Northern sandstone-shale-limestone facies

General description—In the central part of the area, at about Cañon Bonito (Fig. 28), thick, coarse-grained quartzose and feldspathic sandstones occur near the middle of the Porvenir Formation. The relative proportion of sandstone and conglomeratic sandstone throughout most of the formation increases northward, as does the feldspar content and the thickness of many sandstone beds. Northwest of Sapello, sandstones and conglomeratic sandstones are major constituents of the Porvenir Formation, about equal in proportion to shales, but limestones are minor constituents of all but the lower 200–250 ft (60–75 m) of the formation (secs. E and 3, Fig. 39). The lower 200–250 ft (60–75 m) of the formation as far north as Cerro de la Cruz, near Manuelitas, is mainly thick, ledge-forming, biostromal limestones and interbedded gray shales of the southern carbonate facies. Farther north, a basal limestone zone persists but much of this lower interval becomes predominantly shale that contains interbedded thin to thick limestones and minor amounts of sandstone that are considered to be the lower shale-limestone unit of the northern facies (secs. E and 3, Fig. 39). The Porvenir Formation in the eastern part of the mountains maintains this general character northward past the area of this report, although from about La Cañada del Guajalote north past Mora River, the lower shale-limestone unit is thin because of intraformational unconformities (Fig. 29).

Baltz and Myers (1984) designated a composite stratigraphic section at Cañon del Horno (sec. E, Fig. 39 of the present report) as the principal reference section of the northern sandstone-shale-limestone facies of the Porvenir Formation. A description of the reference section and a geologic map of the reference locality northwest of Manuelitas (Fig. 83) are included near the end of the present report. A description of the Porvenir and a geologic map of the Mora River area (sec. K, Fig. 89) also are included near the end of the report as an additional reference section and reference locality of the northern facies of the Porvenir. The basal part of the northern facies in the lower Manuelitas Creek–Sapello area contains *Beedeina arizonensis* and other early Desmoinesian fusulinids (f10340, f10341, and f10283), and the upper part contains the late Desmoinesian *Beedeina sulphurensis* (f10292), confirming the stratal equivalence of the northern facies to the other facies of the Porvenir.

Lower Manuelitas Creek–Sapello—The basal part of the northern sandstone-shale-limestone facies near Manuelitas is a mainly persistent zone of limestone, as much as 50 ft (15 m) thick, that contains low mounds of filamentous- and phylloid-algal limestone and small, low bioherms. Rocks of this kind are well developed at locality E1 (Fig. 39) and elsewhere nearby (Fig. 40). Two small isolated circular outcrops of the Porvenir, shown on Plate 1 northeast of New Mexico Highway 94 about 1.5 mi (2.4 km) northwest of Manuelitas, are large biohermal mounds, one of which is about 60 ft (18 m) in diameter and 32 ft (9.8 m) high (Fig. 41). Similar large mounds occur near the base of the Porvenir near the east front of the mountains 1.5–2 mi (2.4–3.2 km) northeast of Manuelitas.

The basal limestone zone is as much as 40 ft (12 m) thick near Cañon de Duran northwest of Manuelitas and on the flanks of the Padilla anticline (Plate 1) northeast of Manuelitas. At most places at least part of the zone is thin-bedded filamentous- or phylloid-algal limestone, but other parts are thin, parallel-bedded, sparsely fossiliferous, fine-grained limestone. At places some of the limestone is partly or entirely replaced by gray to white chert in which stromatolitic banding is still apparent. A thin sandstone containing limestone pebbles occurs within the basal zone east of Cañon de Duran. This sandstone thickens northeastward and cuts downward through the underlying limestone so that about 1.2 mi (2 km) north of Manuelitas it cuts completely through the basal part of the Porvenir to rest unconformably on gray shale of the Sandia Formation. Traced northeastward, the sandstone thins, and, near the north end of Cerro de la Cruz anticline, it is again a thin limestone-pebble-bearing sandstone within the Porvenir.

South of locality E, along the county road southwest of the confluence of Cañon del Rocio and Manuelitas Creek, the basal limestone zone is absent locally, and stratigraphically higher coarse-grained sandstone of the Porvenir lies unconformably on dark-gray shale of the upper part of the Sandia Formation. South and east of Manuelitas Creek, on the west slopes of Cerro de la Cruz, limestones are present at the base of the Porvenir, as they are southward past Sapello River.

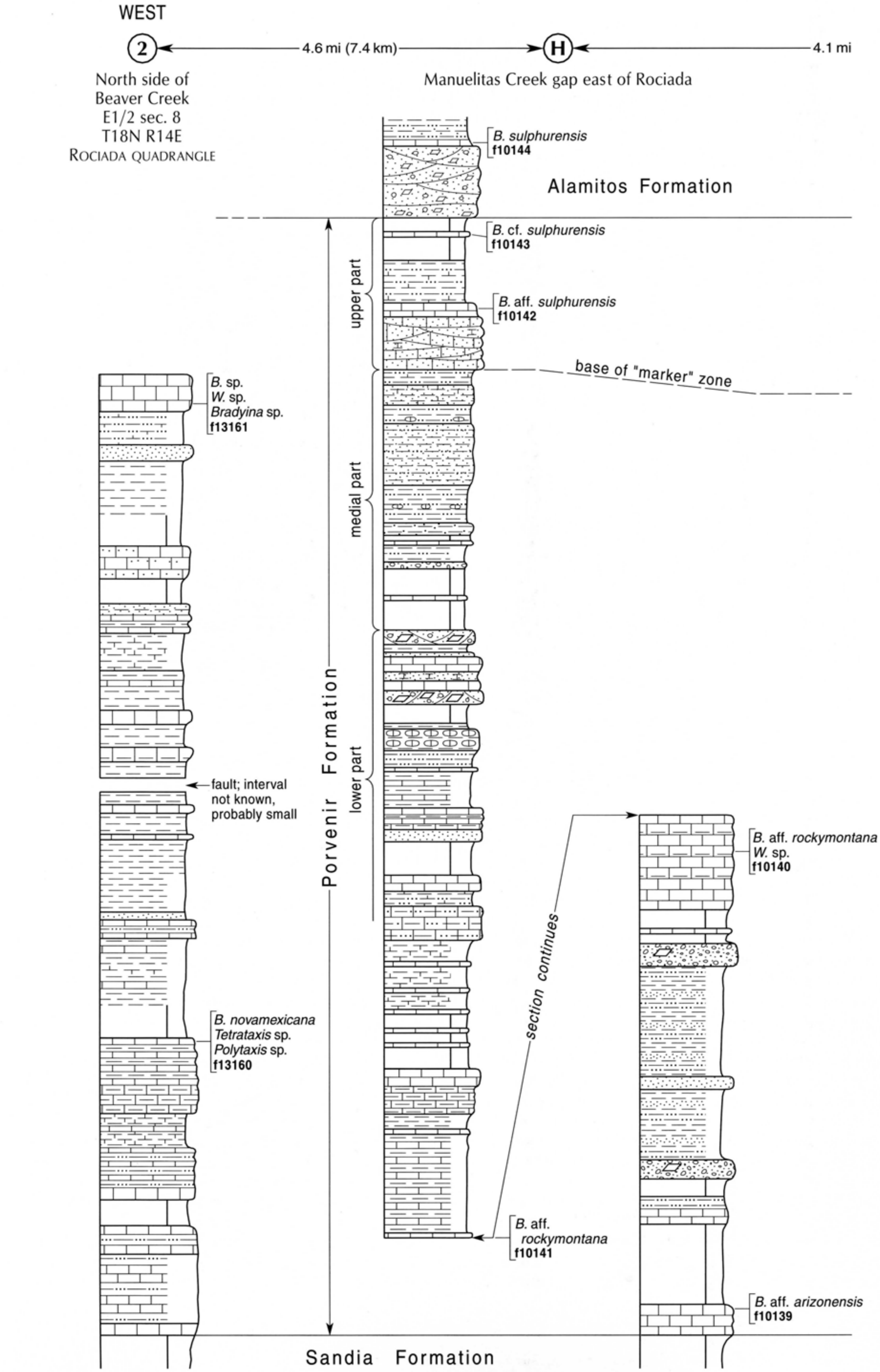
Above the basal zone north of Manuelitas Creek, the lower shale-limestone unit of the northern facies (loc. E1, Fig. 39) is about 170 ft (52 m) thick, and is composed of dark-gray shale that contains some thin sandstones and gray limestones, some of which are remarkably parallel bedded, fine-grained, and sparingly fossiliferous. Limestone beds of this kind are exposed just east of Cañon de Duran. Other limestones at places in this unit are stromatolitic. An outcrop of low stromatolitic mounds and intermound breccias of algal-mat fragments occurs near the top of the lower shale-limestone unit on the ridge about 1,000 ft (300 m) east of the axis of Woods anticline (Plate 1) about 1,300 ft (400 m) south of the Mora County line (Figs. 42, 43). Shale that formerly lay on these beds has been erosionally stripped, leaving the scattered mounds in growth position in an area of about half an acre.

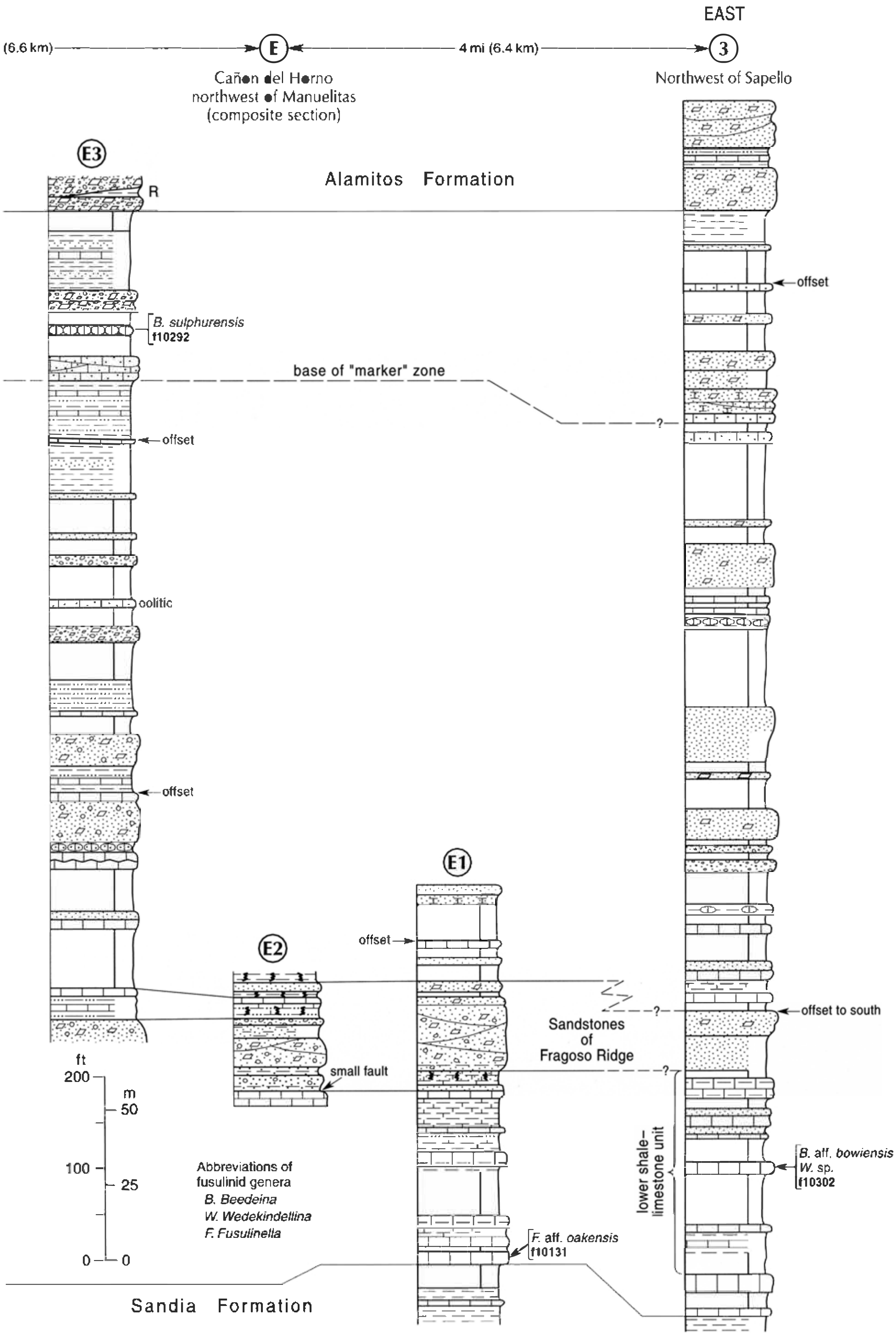
Stratigraphically above the lower shale-limestone unit is a sequence of coarse-grained to conglomeratic, feldspathic sandstones that was called, informally, the sandstones of Fragoso Ridge by Baltz and Myers (1984). At locality E1 these sandstones are almost 100 ft (30 m) thick. They are subparallel to crossbedded, and consist mainly of very coarse to granule size, subangular to subrounded, irregularly shaped clasts and subangular to subrounded pebbles some of which are as much as 0.5 inch (1.3 cm) diameter (Figs. 44, 45). In the lower part of the unit about 20 percent of the clasts in all grain sizes is yellow, weathered feldspar; higher beds are also feldspathic, but less so than those of the lower half. Most beds are at least slightly micaceous, and thin lenses of finer grained shaly micaceous sandstone are interbedded at places. Northeast of locality E1, these sandstones rise structurally and topographically on the west flank of the Woods anticline (Plate 1) and form the caprock of Fragoso Ridge south of Rito Cebolla. At the northwest corner of the ridge along section F (Fig. 46) the unit is a little more than 210 ft (64 m) thick. This northward thickening occurs probably because shaly and sandy intervals above the sandstones at locality E1 grade northward into sandstone and shaly sandstone (Fig. 29).

On the east limb of Cerro de la Cruz anticline northwest of Sapello (Plate 1) feldspathic sandstone correlative with the sandstones of Fragoso Ridge occurs at locality 3 (Fig. 39) and probably at least as far south as exposures just north of Sapello River where calcareous sandstones occur in the lower part of the carbonate facies of the Porvenir Formation. Northeast of locality 3, on the east limb of the Padilla anticline, the sandstones of Fragoso Ridge are present in the hogback belt, and they are well exposed in the syncline west of the Padilla anticline about 0.5 mi (0.8 km) south of the Mora County line. The sandstones are exposed in the hogbacks at the east margin of the mountains from the county line north to a little south of Rito Cebolla where this part of the Porvenir is cut out by the Sapello fault.

On the west limb of Cerro de la Cruz anticline the sandstones of Fragoso Ridge thin southwestward to past the upper part of Sanguijuela Arroyo where thin, probably correlative, sandstones are interbedded with shale and limestone of the carbonate facies. In the western belt of hogbacks just west and northeast of Tierra Monte (Plate 1), coarse-grained sandstones and interbedded shale that probably are correlative with the sandstones of Fragoso Ridge occur in the lower part of the Porvenir, but they thin southwestward toward Rociada into the shaly facies of the forma-

FIGURE 39—Stratigraphic sections of the Porvenir Formation, Beaver Creek–Manuelitas Creek–Sapello area. Localities of measurement and line are shown in Figure 31. Lithologic symbols are explained in Figure 9. Section 2 and section H are representative of the shaly facies. Section E is the principal reference section for the northern sandstone-shale-limestone facies.


WEST
2
4.6 mi (7.4 km)
H
4.1 mi
North side of
Beaver Creek
E1/2 sec. 8
T18N R14E
Rociada quadrangle
Manuelitas Creek gap east of Rociada
B. sulphurensis
f10144
Alamitos Formation
B. cf. sulphurensis
f10143
B. aff. sulphurensis
f10142
upper part
base of "marker" zone
medial part
lower part
Porvenir Formation
B. sp.
W. sp.
Bradyina sp.
f13161
fault; interval
not known,
probably small
B. aff. rockymontana
W. sp.
f10140
section continues
B. novamexicana
Tetrataxis sp.
Polytaxis sp.
f13160
B. aff.
rockymontana
f10141
B. aff. arizonensis
f10139
Sandia Formation


EAST
(6.6 km)
E
4 mi (6.4 km)
3
Cañon del Horno
northwest of Manuelitas
(composite section)
Northwest of Sapello
E3
Alamitos Formation
R
offset
B. sulphurensis
f10292
base of "marker" zone
?
offset
oolitic
offset
E1
E2
offset
offset to south
Sandstones
of
Fragoso Ridge
small fault
ft
200
m
50
100
25
0
0
Abbreviations of
fusulinid genera
B. Beedeina
W. Wedekindellina
F. Fusulinella
lower shale–
limestone unit
B. aff. bowiensis
W. sp.
f10302
F. aff. oakensis
f10131
Sandia Formation

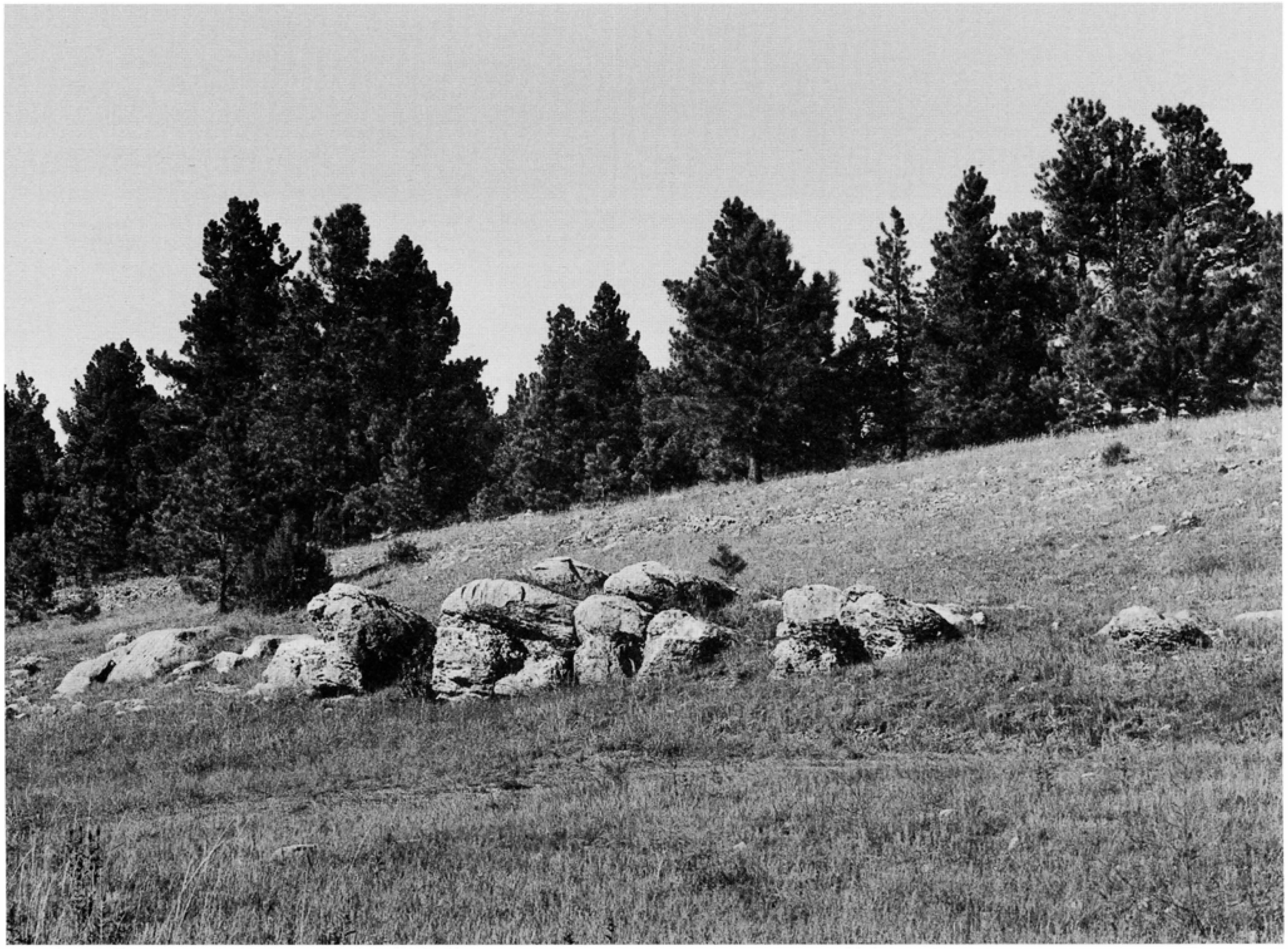


FIGURE 40—Low, biohermal-limestone mounds near base of northern sandstone-shale-limestone facies of Porvenir Formation. Outcrops are on north side of Cañon del Rocio near its mouth northwest of Manuelitas.

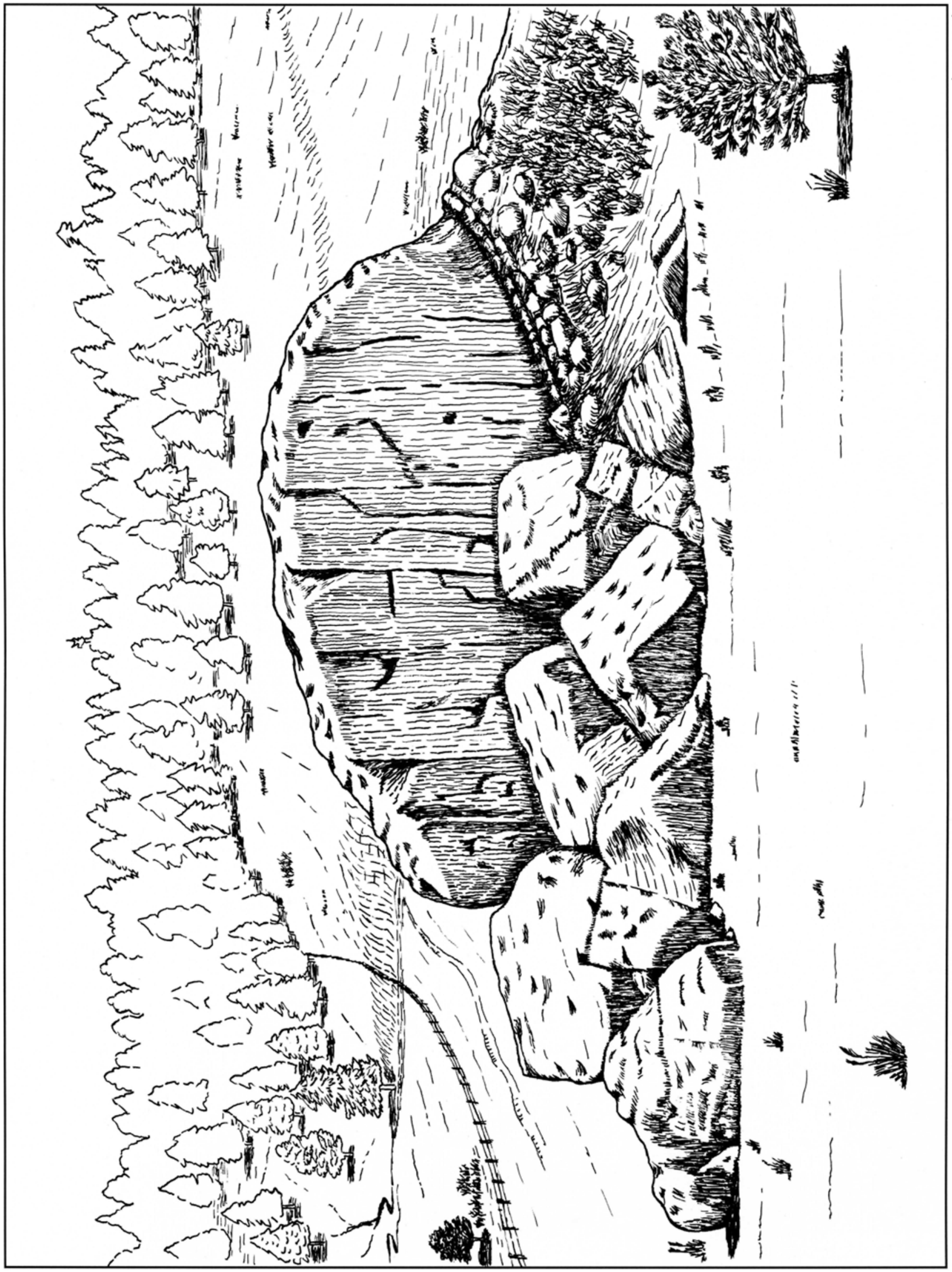
tion where their identification becomes uncertain. Several feldspathic conglomeratic sandstones in the lower part of the shaly facies at locality H east of Rociada probably are equivalent to parts of the sandstones of Fragoso Ridge (Fig. 30).

In the Lower Manuelitas Creek–Sapello area, the part of the Porvenir Formation between the sandstones of Fragoso Ridge and the marker zone is silty to sandy, gray to light-olive-gray-weathering shale that contains thin to thick feldspathic and quartzose sandstones and conglomerates. Some of the sandstones are calcareous. Thin gray limestone, sandy limestone, and some nodular limestones form subordinate amounts of the interval (locs. E3, 3, Fig. 39). The rocks of this stratigraphic interval are laterally equivalent to some of the lower part and to the medial part of the southern carbonate facies of the Porvenir (Fig. 29). West of Cerro de la Cruz anticline sandstones of this stratigraphic interval persist into the carbonate facies as far south as the upper part of Cañon Bonito (Fig. 28). Near the eastern front of the mountains also, the sandstones thin southward and become relatively less conspicuous at about Sapello River as they grade into the carbonate facies south of Las Tusas. North of Manuelitas Creek, thick feldspathic sandstones and thin limestones interbedded in gray shale occur in the upper half of the Porvenir northward past the area of this report.

The marker zone of the upper part of the Porvenir is present in much of the Lower Manuelitas Creek–Sapello area. It is coarsely bioclastic limestone that contains medium to coarse sand and granules of angular quartz, and it is commonly crossbedded and cross-laminated. It is present west of Cañoncito on Manuelitas Creek and at locality E3. It was traced northwestward from locality E3 past New Mexico Highway 94 where it forms a well-exposed west-dipping ridge. The marker zone was identified also in the hogbacks north of Tierra Monte almost to the San Miguel–Mora County line.

On the east limb of Cerro de la Cruz anticline the marker zone was identified in outcrops about 1,200 ft (365 m) west of the junction of New Mexico Highways 94 and 266. Here, the marker is thicker, more coarsely bioclastic, and sandier

FIGURE 41—Sketch of partly slumped, circular, biohermal mound near base of Porvenir Formation east of San Isidro Cemetery and church near mouth of Cañon de Duran 1.5 mi (2.4 km) northwest of Manuelitas. Bioherm is stratigraphically equivalent to thin-bedded basal limestones of the Porvenir at break in slope at north side of valley in the background. Light-gray shaly siltstone, exposed on brushy slope just east (right) of mound, is upper part of Sandia Formation. Thin-bedded substratum of bioherm is coarse crinoidal limestone containing horn corals and brachiopod fragments that grades upward into fine-grained algal limestone, thin shale, and nodular algal limestone. The bioherm is about 32 ft (9.8 m) high. The lower 2–3 ft (0.6–0.9 m) is brachiopod-bearing undulatory-bedded limestone. Upper part is dark-gray carbonaceous limestone that is nearly all recrystallized and whose primary structures are mostly obliterated. Fragments of banded algal limestone occur in the upper part, suggesting that at least part of the mound originally was a stromatolite.



Drawing by E. H. Baltz

FIGURE 43—Breccia of algal-mat fragments from lower shale-limestone unit of Porvenir Formation at locality of Figure 42. Slab is 6 inches (15 cm) wide. Many of the thin fragments are concave and appear to have been produced by desiccation followed by fragmentation by waves or currents. Photograph by H. E. Malde.

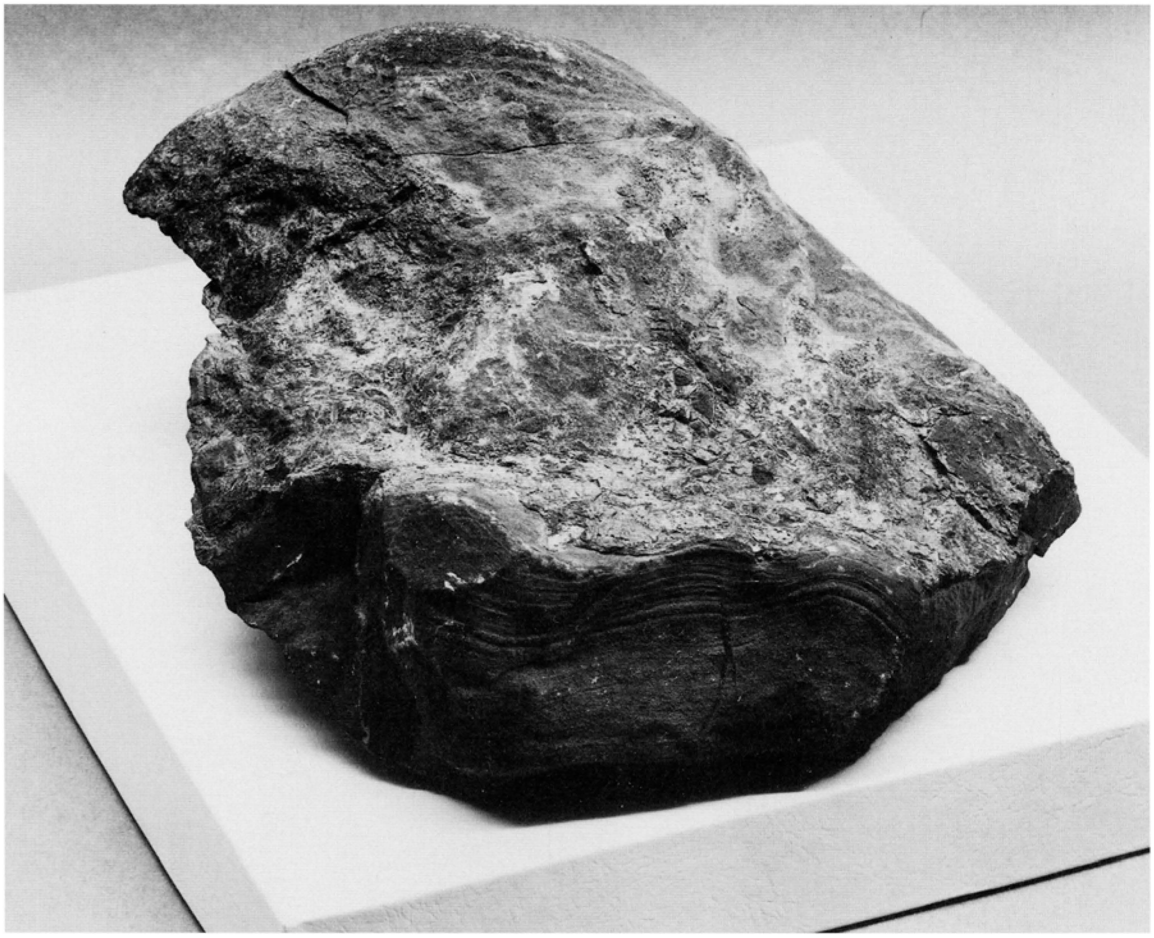


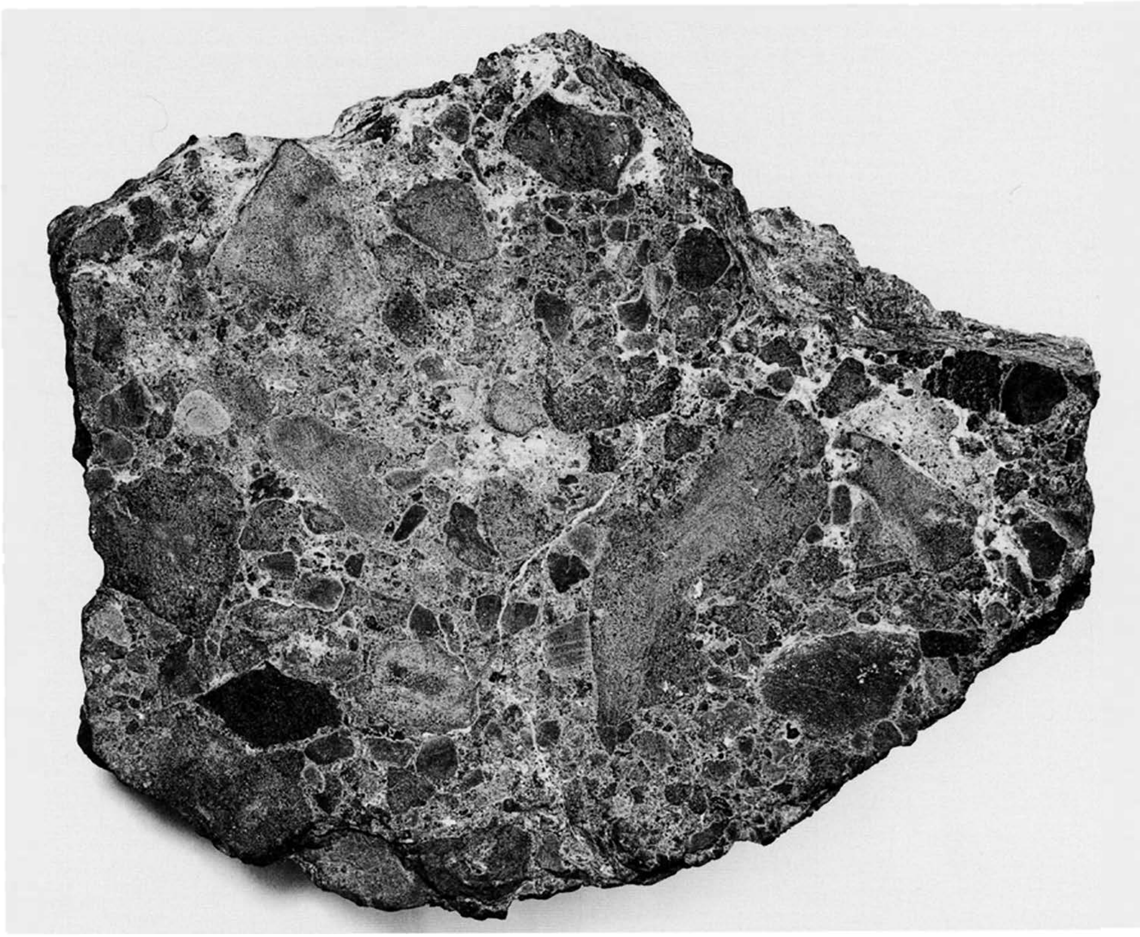
FIGURE 42—Small stromatolitic mound from lower part of Porvenir Formation south of Mora–San Miguel County line, 3 mi (4.8 km) north-northeast of Manuelitas. Concentrically banded mound (top of picture) is about 6 inches (15 cm) high. Stratigraphic position of the stromatolitic rocks is near the top of the lower shale-limestone unit, not far below base of the sandstones of Fragoso Ridge. Photograph by H. E. Malde.

than it is to the west, and it contains abundant shells of thick-walled brachiopods some of which are unbroken. The inclined bedding, coarseness, and thick-walled fossils suggest that it is a beach or nearshore deposit. In sporadic outcrops to the north the unit becomes sandier; it is tentatively correlated with crossbedded, calcareous, slightly feldspathic sandstone and sandy limestone at locality 3 (Fig. 39). North of there, along the east front of the mountains, the marker was not recognized, although about 3 mi north of Rito Cebolla *Beedeina sulphurensis* (f10290) was found, indicating that the upper part of the Porvenir is present at least that far north. In the Lower Manuelitas Creek–Sapello River area the marker zone may be slightly unconformable on the underlying part of the Porvenir (Fig. 30).

Fragoso Ridge–Rito Cebolla—On the east slope of Fragoso Ridge (Plate 1; Fig. 88), the ledge-forming basal limestone zone of the Porvenir Formation is fairly well exposed and was traced around the southwestern, southern, and eastern margins of the erosional amphitheater that occupies the crestal part of the Woods anticline near the Mora County line south of Rito Cebolla (Plate 1). At these outcrops the limestones generally are thin bedded and highly fossiliferous. At places, they contain banded, low-mounded, stromatolitic limestone, parts of which are replaced by light-gray, banded chert. At most places on the eastern and northern slopes of Fragoso Ridge the basal limestone zone is concealed by Quaternary colluvium or is poorly exposed. It was observed on the eastern flank of Fragoso Ridge at locality C (Fig. 22) and near the northwest end of Fragoso Ridge (Fig. 84) at and near locality F (Fig. 46). The overlying lower shale-limestone unit is mainly concealed on the east- and north-facing slopes of Fragoso Ridge, but a few outcrops show that it is similar to the unit farther south.

At locality F the basal limestone unit is at least 20 ft thick and is lithologically complex. The lower part at locality F is stromatolitic limestone that has been replaced largely by gray to white chert in which the algal banding can still be seen. This is overlain by bioclastic limestones containing interbeds of oolite and some angular pebbles of limestone as large as 0.5 inch (1.3 cm) diameter. Fusulinids, including

FIGURE 44—West-dipping, coarse-grained to pebbly, feldspathic sandstone near base of sandstones of Fragoso Ridge. Locality E1, roadcuts at north side of New Mexico Highway 94 about 1.7 mi (2.7 km) northwest of Manuelitas. Crossbedding is sinusoidal and generally is inclined southwest (left).



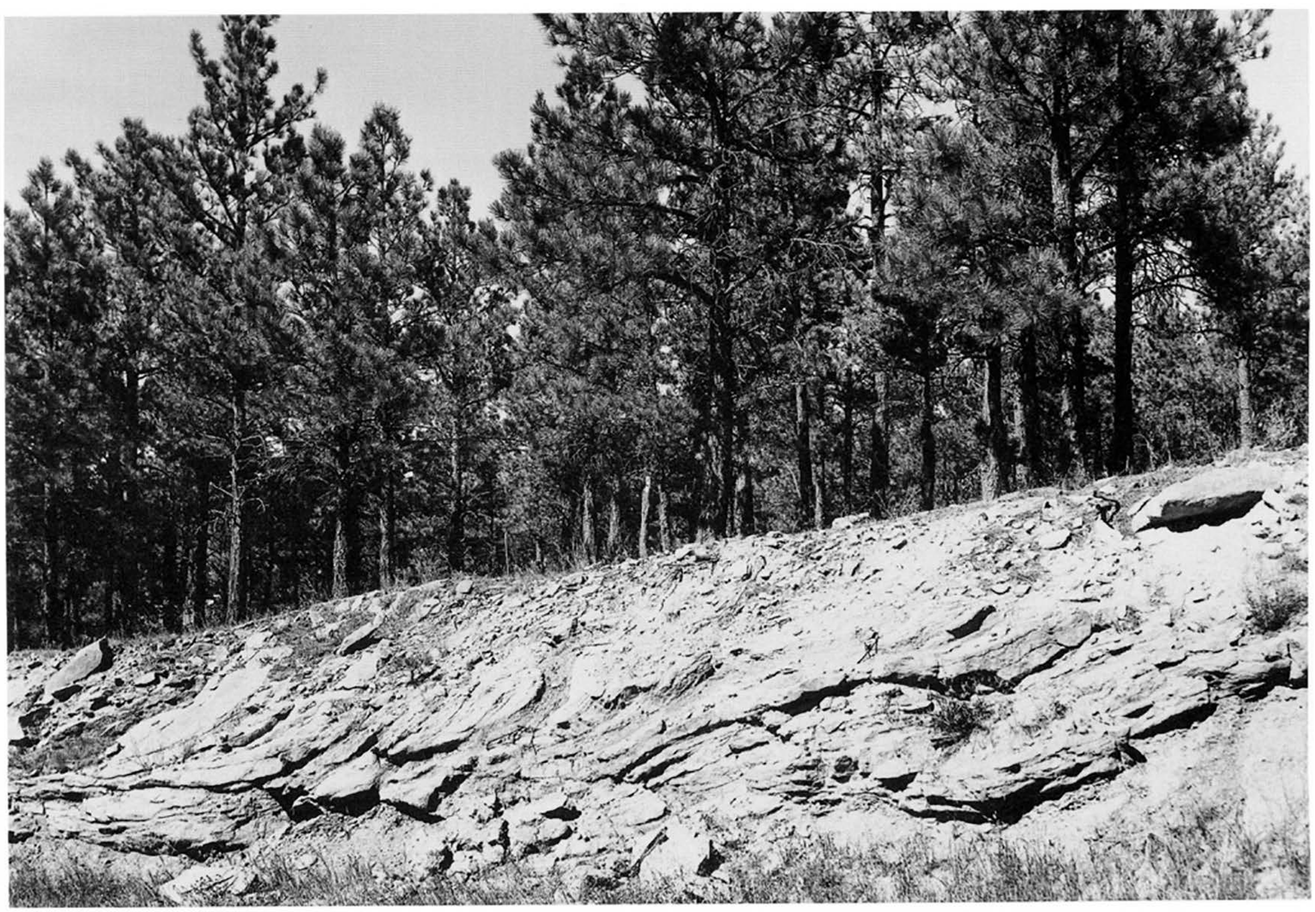


FIGURE 45—Close view of sandstone near base of sandstones of Fragoso Ridge at locality of Figure 44. Knife is 4.5 inches (11.4 cm) long. Lower part of knife is on shaly, micaceous, carbonaceous sandstone. Rock above is cemented grus of very coarse sand and granules that contains pebbles as large as 0.5 inch (1.3 cm) diameter. Most clasts are irregularly shaped and subangular. About 20 percent of clasts in all sizes is yellowish gray, weathered feldspar.

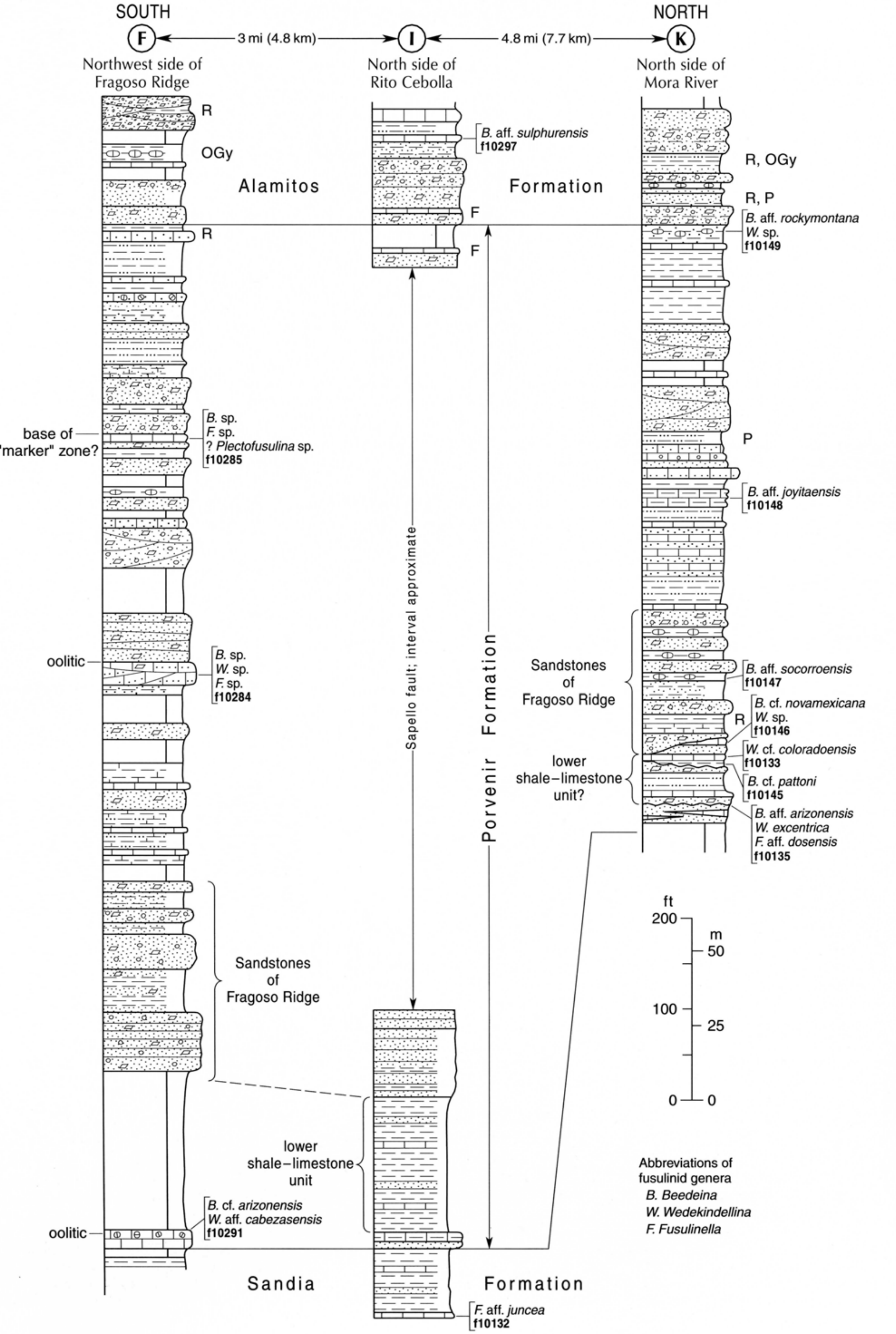
Beedeina arizonensis (f10291), occur in the bioclastic beds, indicating their correlation with the basal part of the Porvenir elsewhere.

Fragoso Ridge is capped by the basal part, as much as 70 ft (20 m) thick, of the sandstones of Fragoso Ridge, and stratigraphically higher parts of the unit crop out on the dip slopes southwest of the crest of the ridge. At locality F, the unit is 210 ft (64 m) thick and consists of coarse-grained to conglomeratic, feldspathic, micaceous sandstone with thin interbeds of fine- to coarse-grained, micaceous sandstone and a minor amount of thin shale and shaly sandstone. The sandstones of Fragoso Ridge were traced southeastward from the ridge across the crest of the Woods anticline, just south of the Mora–San Miguel County line, into the hogback ridges near the eastern front of the mountains where they are overlain by upper parts of the Porvenir. The entire Porvenir is cut out locally by the Sapello fault south of Rito Cebolla (Plate 1; Fig. 88).

Above the sandstones of Fragoso Ridge at locality F, the Porvenir consists of gray shale and interspersed thin gray limestones and fine-grained to conglomeratic, mainly feldspathic and micaceous sandstones. Some of the conglomeratic sandstones in the upper half are highly feldspathic, containing yellowish-gray to pink feldspar. Subround to subangular feldspar clasts constitute 10–25 percent of these rocks and commonly range in size up to pebbles 0.25 inch (0.6 cm) in diameter. Shales in the lower part of this interval are mainly gray calcareous claystone, but higher in the section they are mainly light olive gray silty shales. Some shale contains marine fossils or fossiliferous limestone interbeds.

The limestones in the interval above the sandstones of Fragoso Ridge at locality F are predominantly silty to sandy and coarsely bioclastic; some beds are coquinas of fragmented brachiopods, bryozoans, and other fossils. Near the middle of the formation is a crossbedded, sandy, bioclastic, and oolitic limestone. This limestone contains algal debris, brachiopods, a trace of crinoid columnals, and many fusulinids. Lenses of angular quartz granules are interbedded. The unit is similar to the marker zone but seems to be stratigraphically too low to correlate with the marker. The fusulinids are abraded, many have accretionary calcite layers around them and probably are reworked. The faunal association, including *Beedeina* sp. and *Fusulinella* sp. (f10284), indicates very early Desmoinesian age, which does not accord with the stratigraphic position of the fossils. Fusulinids from the upper part of the unit (f10285) are abraded and *Fusulinella*

FIGURE 46—Stratigraphic sections of the Porvenir Formation, Fragoso Ridge–Rito Cebolla–Mora River area. Localities of measurement and line of sections are shown in Figure 31. Lithologic symbols are explained in Figure 9. Lowest fusulinid collection (f10135) shown with stratigraphic section K was obtained from sandy bioclastic limestone on ridge southwest of Mora River about 600 ft (180 m) south of locality K. This limestone is absent by unconformity at locality K, but it is present again farther north.



SOUTH
F
3 mi (4.8 km)
I
4.8 mi (7.7 km)
NORTH
K
Northwest side of Fragoso Ridge
North side of Rito Cebolla
North side of Mora River
R
OGy
Alamitos
Formation
B. aff. sulphurensis
f10297
F
F
R
R, OGy
R, P
B. aff. rockymontana
W. sp.
f10149
base of "marker" zone?
B. sp.
F. sp.
? Plectofusulina sp.
f10285
P
B. aff. joyitaensis
f10148
Sapello fault; interval approximate
Porvenir Formation
oolitic
B. sp.
W. sp.
F. sp.
f10284
Sandstones of Fragoso Ridge
B. aff. socorroensis
f10147
B. cf. novamexicana
W. sp.
f10146
R
W. cf. coloradoensis
f10133
lower shale–limestone unit?
B. cf. pattoni
f10145
B. aff. arizonensis
W. excentrica
F. aff. dosensis
f10135
ft
200
100
0
m
50
25
0
Sandstones of Fragoso Ridge
lower shale–limestone unit
Abbreviations of fusulinid genera
B. Beedeina
W. Wedekindellina
F. Fusulinella
oolitic
B. cf. arizonensis
W. aff. cabezasensis
f10291
Sandia
Formation
F. aff. juncea
f10132

sp. occurs with an undetermined species of *Beedeina* whose morphology suggests a mid-Desmoinesian age. The presence of the abraded tests of *Fusulinella* well above their expected stratigraphic position suggests that they were eroded from a nearby uplifted area where the basal part of the Porvenir or the uppermost part of the Sandia was exposed during the deposition of upper parts of the Porvenir at locality F.

The rocks of the upper 160 ft (49 m) of the Porvenir Formation at locality F are similar to those of the upper part of the Porvenir above the marker zone farther south, but we did not find fusulinids in this interval to confirm a lithologic correlation. A tentative correlation of the rocks at locality F with the marker and overlying rocks farther south is based mainly on stratigraphic position (Fig. 29).

At the front of the mountains immediately north of Rito Cebolla at locality I (Fig. 46) the basal zone of the Porvenir Formation is a steeply dipping unit of sandstone, thin limestone, and thin shaly limestone that forms a low ridge west of the poorly exposed lower shale-limestone unit. The basal zone can be traced along sporadic outcrops about 2,500 ft (760 m) northward from locality I to where it and the lower shale-limestone unit are cut out by the Sapello fault (Fig. 88), which throws the middle or lower part of the Sandia Formation against stratigraphically high parts of the Porvenir. At locality I the poorly exposed lower part of the sandstones of Fragoso Ridge apparently is thrown against the uppermost part of the Porvenir by a branch of the Sapello fault (Plate 1; Fig. 88), but farther north the sandstones of Fragoso Ridge and stratigraphically higher feldspathic sandstones and interbedded shales and thin limestones crop out in prominent hogback ridges whose beds range in dip from vertical to overturned. The lithology is generally similar to that at locality F. About 2 mi (3.2 km) north of Rito Cebolla the Porvenir is cut out completely by the Sapello fault, which locally throws the Sandia Formation against the Alamitos Formation. North of there, overturned feldspathic sandstone, shale, and thin limestone of the upper half of the Porvenir are exposed again east of the Sapello fault. *Beedeina sulphurensis* (f10290) was found in the upper part of the formation about 3 mi (4.8 km) north of Rito Cebolla, confirming the stratigraphic position of the upper part.

Mora River and northern part of area—In the eastern part of the mountains, from about La Cañada del Guajalote northward past Mora River (Plate 1; Fig. 89), the lower part of the Porvenir is a laterally and vertically heterogeneous assemblage of fine-grained to conglomeratic sandstone and micritic, coarsely bioclastic, and oolitic limestone. The basal part of the Porvenir at most places is a 20–30-ft (6–9-m) thick unit of gray, fine to very fine grained calcareous sandstone that contains alternating interbeds of gray silty limestone (sec. L, Fig. 26; sec. K, Fig. 46). The sandstone and limestone beds are 1–12 inches (2.5–30 cm) thick, parallel bedded, and sparingly fossiliferous; many limestone beds are lenticular. Locally, as about 800 ft (245 m) north of Mora River, some of the limestones are as much as 1 ft (0.3 m) thick and highly fossiliferous. This unit commonly weathers to a slabby, notched slope. It appears to be conformable with the underlying Sandia Formation.

The lower part of the Porvenir, above the basal unit, is a distinctive gray, sandy, bioclastic, and locally oolitic limestone, 15–30 ft (4.5–9 m) thick, that is present sporadically from just south of La Cañada del Guajalote northward past the area of this report. The limestone commonly consists mainly of coarse grained to very coarse grained crinoid debris; fusulinids, including *Beedeina arizonensis* (f10135, f10293), are abundant. The limestone generally is very sandy and at places, such as the ridge just south of Mora River and elsewhere to the north, it grades laterally into coarse-grained calcareous sandstone, which grades laterally back into limestone. The bioclastic limestone is not present immediately north of Mora River at locality K where it has been cut out because of channeling by overlying sandstone, but it is present on the ridge (sec. L, Fig. 26) about 1,500 ft (455 m) north of Mora River where it is conspicuously oolitic and crossbedded. North of there for a short distance, an intraformational unconformity causes a stratigraphically higher sandstone to cut out the lower part of the Porvenir, but the basal unit and the sandy bioclastic limestone both are present at locality J7 (Fig. 26) on the drainage divide between Mora River and Cañon del Agua where the limestone contains *Fusulinella* aff. *F. dosensis* and *Wedekindellina* sp. (f10137). The fusulinids confirm the early Desmoinesian age of the lower part of the Porvenir near Mora River and its correlation with the basal part of the Porvenir farther south.

From Cañon del Agua northeastward about 1 mi (1.6 km), the basal beds of the Porvenir are absent and a sandstone bed above the intra-Porvenir unconformity lies directly on the Sandia. The stratigraphic position of the sandstone of the Porvenir is confirmed generally by the occurrence of *Beedeina* cf. *B. rockymontana* (f10304) of middle Desmoinesian age a short distance above its top about 2,000 ft (600 m) north of Cañon del Agua (Fig. 89). Farther north, both the basal fine-grained sandstone and limestone unit and the overlying bioclastic limestone again are present at the base of the Porvenir and, about 7,000 ft (2.1 km) northeast of Cañon del Agua, *Beedeina* aff. *B. arizonensis* (f10305) is present near the base. As previously mentioned, sandy oolitic limestone containing the same fusulinid (f10303) is present at the base of the Porvenir at an outcrop south of the creek and road west of Los Cisneros about 5 mi (8 km) north of the area of this report, which suggests that a unit of this general lithology was widespread at the time the basal beds of the Porvenir were deposited.

At exposures along New Mexico Highway 518 just north of Mora river (sec. K, Fig. 46) the part of the Porvenir that lies on the basal fine-grained sandstone and limestone unit consists of olive-gray shale with interbedded feldspathic to arkosic coarse-grained to conglomeratic sandstone and thin silty gray limestone (Fig. 47). These rocks probably are equivalent to the lower shale-limestone unit of the Porvenir of areas to the south. However, the unit at Mora River is only about 55–75 ft (17–23 m) thick because of several intraformational unconformities, one of which is slightly angular (Fig. 48). Tracing of individual beds northward from the roadcuts at Mora River indicates that an unconformity at the base of a sandstone within the lower part of the unit is the previously described unconformity that cuts out the underlying basal parts of the Porvenir to northeast of Cañon del Agua. The lower shale-limestone unit can be recognized at places nearly to the north edge of the area of this report, although to the north it seems to be mainly cut out by another stratigraphically higher intraformational unconformity at the base of the overlying sandstones of Fragoso Ridge.

The sandstones of Fragoso Ridge at Mora River (sec. K) are partly ridge-forming, feldspathic, granule and pebble conglomerates that are lithologically similar to those of the unit farther south, except that at Mora River they are not as thick and massive and they contain a little more interbedded shale than farther south. Most of the sand is coarse to very coarse and is angular to subangular; quartz pebbles as large as 0.75 inch (1.9 cm) across are common. Feldspar content ranges from 5–20 percent. Many feldspar clasts are pink, fresh-appearing, and angular. Feldspar pebbles range in diameter up to 0.5 inch (1.3 cm). Most of the conglomerates and sandstones are crossbedded, but some sandstones are fine- to medium-grained, micaceous, and have thin subpar-

FIGURE 47—Lower part of Porvenir Formation, New Mexico Highway 518 at locality K, north of Mora River about 3.5 mi (5.5 km) southeast of Mora. Upper part of basal sandstone-limestone unit (unit 212 of stratigraphic section K) is poorly exposed on slope at lower left. The overlying bioclastic-oolitic limestone of areas to north and south is absent from these outcrops. Thin, coarse-grained sandstone, sandy limestone, and shale (units 213–218 of section K) underlie low ledges. Ledge-forming sandstone at upper right is unit 219 of section K. These rocks, above the basal sandstone-limestone unit, probably are equivalent to parts of the lower shale-limestone unit of the Porvenir in the Manuelitas Creek–Rito Cebolla area (Figs. 39, 46). Tree at left on outcrop of unit 212 is about 15 ft (4.6 m) high.

allel bedding. Shales in this interval generally are olive-gray, silty, and contain limestone nodules, some of which are fillings of fossil burrows, a few of which are lined with fusulinid tests (Fig. 2 on Plate 11). The upper part of the lowest shale in the sandstones of Fragoso Ridge at locality K weathers to a distinctive purplish-red; southward to a little south of La Cañada del Guajalote reddish-brown to maroon-weathering shale occurs in the lower part of the sandstones of Fragoso Ridge, but shale of this color was not observed anywhere else in the Porvenir south of there or north of locality K.

North of Mora River the sandstones of Fragoso Ridge persist and form hogbacks past the northern boundary of the area (Plate 1) of this report. Near the northern boundary the unit is mostly crossbedded, feldspathic conglomerates that form a prominent hogback ridge. North of the area the continuity of the sandstones of Fragoso Ridge is not established certainly. However, about 5.2 mi (8.4 km) north of the area of this report, thick, conglomeratic sandstones occur in the hogback ridge at and north of the road about 2,800 ft (850 m) west of Los Cisneros cemetery (USGS Lucero quadrangle). These rocks, west of the base of locality 4, Plate 3, probably are equivalent to the sandstones of Fragoso Ridge. The sandstones are very coarse grained to pebbly, highly micaceous, and feldspathic; they are composed mainly of quartzite granules and pebbles but contain potassium and plagioclase feldspar granules and pebbles as large as 0.5 inch (1.3 cm) across. Interbedded shale is highly micaceous.

The higher part of the Porvenir Formation, above the sandstones of Fragoso Ridge at Mora River (sec. K, Fig. 46), is a stratigraphic succession similar to the succession of the lower part. The base of the upper succession is a thin limestone that is overlain by silty clayey shale. The shale grades upward into a unit of thin-bedded fine-grained calcareous sandstone that contains thin, lenticular, silty, gray limestone beds that are sparingly fossiliferous. This unit is similar to the basal fine-grained sandstone and limestone unit of the Porvenir. The upper fine-grained sandstone-limestone unit is overlain by shale and interbedded thin brachiopod-crinoid coquinas that, in turn, are overlain by bioclastic sandy limestones, some of which grade laterally into calcareous very coarse-grained to conglomeratic sandstones. These beds are overlain by ridge-forming, thick, coarse-grained feldspathic sandstones and interbedded thin shale and limestones that are similar to the sandstones of Fragoso Ridge. The highest part of the Porvenir at Mora River is mostly gray clayey shale and silty shale that contains a few thin beds of gray finely bioclastic limestone and weathers to slopes and strike valleys.

The upper sequence of the Porvenir, above the sandstones of Fragoso Ridge, persists to the northern edge of the area of this report, but the details of its stratigraphy were not studied during mapping north of Cañon del Agua. The upper sequence at Mora River correlates with part of the rocks above the sandstones of Fragoso Ridge in the Manuelitas Creek and Rito Cebolla areas. However, the

FIGURE 48—Lower part of Porvenir Formation, New Mexico Highway 518 at locality K, north of Mora River. About 200 ft (60 m) east of view of Figure 47. Thick sandstone at lower left is unit 219 of section K. Local unconformity that is slightly angular (arrows) occurs in thin shale just below base of thin limestone (unit 223, section K) in middle of outcrop. Beds below the unconformity in right side of view dip east more steeply than beds above. Channel sandstone in upper middle left (unit 225, section K) thickens westward (left) by cutting out underlying beds. Left of the view the sandstone forms a prominent ledge and is sharply folded. This sandstone is correlated, tentatively, with the lower part of the sandstones of Fragoso Ridge.

occurrence of the middle Desmoinesian fusulinid *Beedeina rockymontana* (f10149) at the top of the Porvenir at Mora River indicates that beds equivalent to the upper Desmoinesian marker zone and highest part of the Porvenir are not present at Mora River, probably because of unconformity with the overlying Alamitos Formation.

In the subsurface northeast of Mora River, at the Amoco "A" and "B" no. 1 Salman Ranch Wells, the Porvenir Formation (Plate 3) is generally similar to the Porvenir cropping out from Mora River northward. The lower 70 ft (20 m), approximately, at the wells consists of gray, fine to very fine grained sandstone, highly calcareous gray siltstone, and some limestones, all similar to the basal part at Mora River. The overlying fine- to coarse-grained sandstones at the wells contain white to pink feldspar and are interbedded with gray to reddish-gray calcareous shales and thin limestones. These rocks probably correlate with the sandstones of Fragoso Ridge. The section above the sandstones at the wells is similar to the upper part of the Porvenir at Mora River. In general, the sandstones above the basal part of the Porvenir at the wells seem to be somewhat finer grained than at the outcrops.

Vertical repetition of lithologies

In the southern carbonate facies, the lower part of the Porvenir Formation contains complex sequences of rocks that are repeated vertically in the section. However, because of locally poor or discontinuous exposures, it is difficult to determine if the repetitions of various lithologies occur in orderly sequences, laterally or vertically.

An area north of Gallinas Creek near the village of Gallinas (Figs. 49, 50) affords an opportunity to examine some of the details of lithologic repetition in the lower part of the carbonate facies of the Porvenir. Good outcrops exist in roadcuts, steep arroyos, and gullies; several key beds crop out well enough to be traced for about a mile (1.6 km).

Figure 50 was constructed from detailed sections and from observations between sections during lateral tracing of

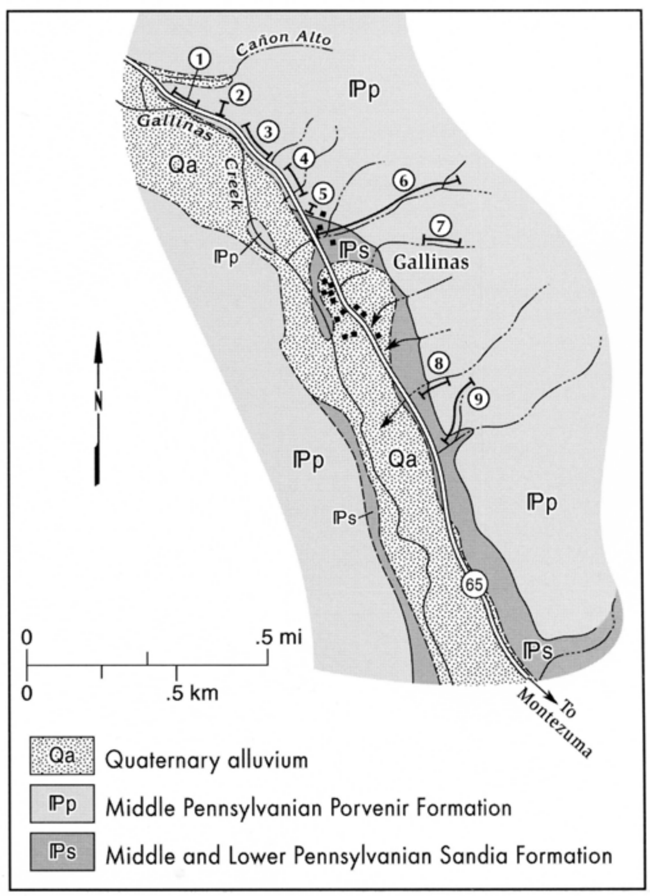


FIGURE 49—Map of vicinity of Gallinas village northwest of Montezuma showing location of stratigraphic sections for interpretive correlation diagram (Fig. 50).

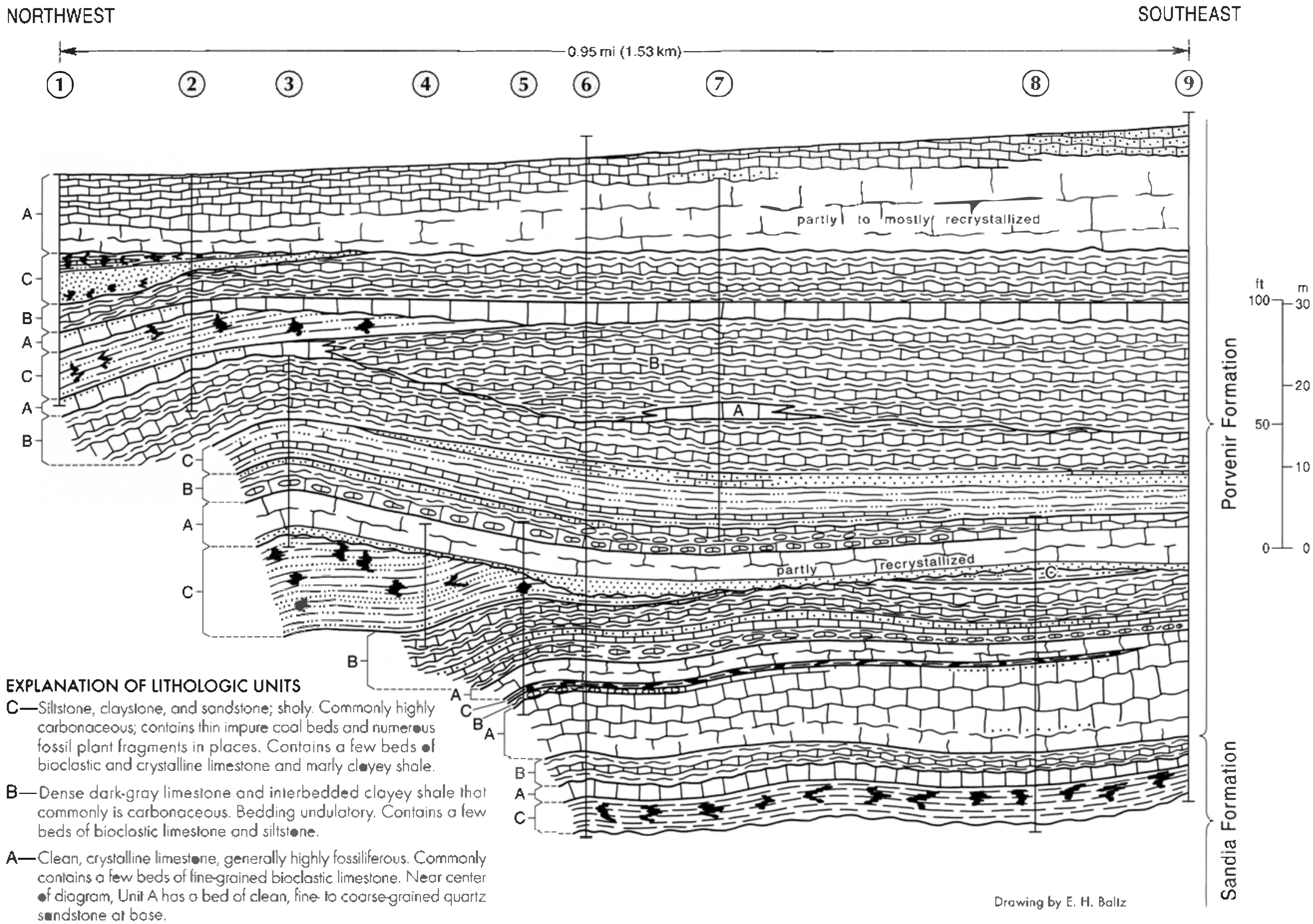


FIGURE 50—Interpretive correlation diagram of lower part of the Porvenir Formation near Gallinas showing vertical repetitions of lithologies. Localities of sections are shown in Figure 49. Lithologic symbols are explained in Fig. 9. Actual measured sections indicated by vertical lines. Section 9 is lower part of composite section 1 (Fig. 33) of the Porvenir.

FIGURE 51—Limestone of unit A of Porvenir Formation. North side of New Mexico Highway 65 northwest of Gallinas at top of section 1, Figure 50. Middle part of limestone is partly recrystallized. Ledge is about 30 ft (9 m) high. At lower right, limestone lies on thin carbonaceous shale and interbedded thin limestone of unit C.

units near Gallinas. The diagram shows that several units of distinctly different lithologies occur in mainly orderly successions. Erosional and slightly angular unconformities occur at several horizons, associated with gentle folds. The amplitudes of the folds are exaggerated greatly because of the exaggeration of the vertical scale of the diagram; in proper context, they are no more than minor wrinkles with structural relief of only 30–40 ft (9–12 m) in about 0.5 mi (0.8 km). The erosional unconformities are partly inferred because some units thin and disappear between measured sections. However, some of the unconformities were apparent in outcrops where sharp undulatory contacts or channeling was observed directly. The unconformity within the thick B unit at the top of section 3 was well exposed on the hillside, and the unconformity between units B and A in the lower part of section 2 was observed in outcrops near the highway west of Gallinas.

The angular unconformity between units C and A at section 4 and in the upper part of section 5, also was observed in outcrops near the highway west of Gallinas (Fig. 53). This unconformity at section 4 was traced eastward to section 9 where the A unit above the unconformity contains the middle Desmoinesian fusulinid *Beedeina* cf. *rockymontana* at a position about 70 ft (21 m) above the base of the Porvenir Formation (loc. 1, Fig. 33). To the west and east in the Gallinas Creek area, the lowest occurrence of this fusulinid is a little more than 200 ft (60 m) above the base of the Porvenir (secs. D and G, Fig. 33). This suggests that the unconformity at Gallinas may cut out as much as 130 ft (40 m) of the lower part of the Porvenir on a broad anticline. The presence of unconformities within the lower part of the Porvenir in this area is consistent with the previously described unconformities in the lower part of the Porvenir in the shaly facies near Daily and Sparks Creeks, and in the lower part of the northern sandstone-shale-facies north of Manuelitas and near Mora River.

The units labeled A in Figure 50 are biostromal limestones. They generally contain abundant broken and complete brachiopods, crinoid columnals, bryozoans, horn corals, *Chaetetes* clumps, and other fossils. Algal fossils are common also. The matrix is finely bioclastic and micritic limestone. Beds are generally several inches to 1 ft (30 cm) thick; bedding is undulatory with local small mounds abundant. Commonly the rocks are recrystallized so that part of the bedding and internal structure is obscured. The upper parts of most of these units consist of thin undulatory beds of fine- to medium-grained bioclastic material that is slightly marly at places. Fusulinids are common in some of the bioclastic beds. In general, the lithology of the biostromal units is similar to that of the bioherm south of Montezuma, but the biostromes are bedded throughout and lack massive cores (Fig. 51).

The biostromal limestones generally have sharp contacts with underlying rocks. Most of the basal contacts are disconformities or slightly angular unconformities. One of the units (A in the lower part of section 3) lies conformably on a fine- to coarse-grained quartz sandstone that channels slightly into underlying rocks. The upper contacts of the biostromal rocks seem to be mainly conformable with and locally gradational into overlying rocks.

FIGURE 52—Dark-gray shale and interbeddd lenticular fine-grained limestone (light colored) of Porvenir Formation, roadcut on New Mexico Highway 65 west of Gallinas. Shale and limestone is unit B in lower part of section 2, Figure 50; exposed part is about 15 ft (4.6 m) thick. Ledge-forming limestone (lowest unit A of section 2) at top of roadcut is unconformable on unit B and, to the northwest (left), cuts out the upper 3 ft (1 m) of unit B.

The units labeled B in Figure 50 consist of thin dark-gray shales and interbedded thin limestones (Fig. 52). Proportions of limestone to shale vary laterally in some of the units but, generally, about 50 percent of the rocks is calcareous, slightly carbonaceous clayey shale. Beds are mainly from 2 inches to 2 ft (5 to 60 cm) thick. The limestones are mainly composed of silt-size to fine-grained calcite clasts, but some are micritic. Some limestones have faint banding that suggests stromatolitic structures, and some are carbonaceous, yielding macerated very fine carbonaceous fragments as insoluble residue. Fossils are sparse although a few brachiopods and gastropods occur at places. Bedding is undulatory, and the limestones thicken and thin rapidly along the outcrop. Most limestone is lenticular, ranging from flat discs 1–2 ft (30–60 cm) across to thin lenses as much as 30 ft (9 m) long. The undulatory bedding is a depositional feature of the limestones because the intervening shales thicken and thin in response to the topography of the tops of limestone beds. The tops of the B units seem to be conformable with overlying carbonaceous quartz siltstone and shale where units B and C are in contact although, locally, in the upper parts of sections 1 and 2, a unit C sandstone channels into the underlying unit B.

The units labeled C in Figure 50 are mostly shaly quartz siltstone containing interbedded clayey shale and fine- to medium-grained quartz sandstones (Fig. 53). The sandstones form stringers and lenses from 1 inch to 1 ft (2.5 to 30 cm) thick that grade laterally and vertically into siltstone. The sandstones and siltstones are slightly micaceous. A westward-thickening channel sandstone occurs in the highest C unit at sections 1 and 2. This quartz sandstone ranges from fine grained to granule grained, generally coarsening upward. Several C units contain a few thin bioclastic limestones and some marly shale. The C units are characterized by being mainly highly carbonaceous. Very thin coaly layers are present, and recognizable fragments of carbonized twigs and leaves are common in some beds. Marine fossils are rare, but small brachiopods and gastropods occur in a few beds, for example, in the upper C unit at section 1.

The general order of deposition of the repeated lithologies seems to have been A, B, C, where all three units are preserved completely between bounding disconformities or unconformities. In the lower part of section 7 (Fig. 50), a B unit overlies a C unit, but the two are separated by a lens of medium- to granule-grained quartz sandstone with lenses of calcareous sandstone that contain brachiopods and crinoid columnals. These thin calcareous sand beds may represent an aborted unit A. The sequence A, B, C is considered to be a hemicycle. The hemicycles are mostly or entirely marine, although most of the sediments of the C units were derived from terrigenous sources.

Lithologic sequences similar to those near Gallinas have been observed at outcrops of the Porvenir at other places in the southern carbonate facies, but much of the detail is obscure because of poor exposures. Without a considerable amount of additional study it is impossible to determine whether the individual hemicycles of Figure 50 are local or of greater extent. It is apparent from Figure 50 that detailed interpretations of individual sections or isolated outcrops could lead to incorrect interpretations of vertical successions

FIGURE 53—Gray, carbonaceous, shaly siltstone, of Porvenir Formation forming slope in roadcut on New Mexico Highway 65 northwest of Gallinas. Shaly siltstone is unit C in section 4, Figure 50. Unit is overlain with angular unconformity by very thin sandstone and limestone of unit A, lower part of which forms irregular ledge about 7 ft (2 m) high at top of cut. Unit C dips west (left) more steeply than unit A and thickens westward. Unit C thins southeastward (right) and wedges out east of section 5, Figure 50.

when the lateral stratigraphic variations and correlations cannot be determined with relative certainty.

The hemicycles of the carbonate facies, as observed at Gallinas (Fig. 50), suggest a primarily tectonic control of sedimentation on the northwest flank of the Paleozoic Tecolote uplift. This is indicated by the small folds and attendant unconformities and by the regional evidence of an active tectonic setting of the Pecos shelf during deposition of the Porvenir Formation. A general scheme that might explain the repetition of lithologies is as follows:

1. Rapid depression of the basin, attended by slight wrinkling and folding, inundating widespread areas of shallow-water bank deposits. Transgression of the deeper sea allowed wave and current action to scour the tops of pre-existing deposits and to create minor unconformities and disconformities.
2. Continuing slow subsidence during which biostromal limestone (units A) and bioherms developed but, as subsidence continued, areas of organic upbuilding migrated toward shallower water.
3. Deposition in quieter, deeper water of organic muds and calcisiltite (units B) winnowed or eroded from biostromal and biohermal limestone developing elsewhere in shallower water.
4. Temporary cessation of subsidence. Infilling and upbuilding by highly carbonaceous terrigenous sediments (units C) derived from marshes, estuaries, or lagoons near islands or low uplifts nearby. These sediments could have been swept out periodically by storms or they might represent prograding deposits of sluggish coastal-plain or island-margin streams.

It does not seem necessary that every hemicycle, or part of one, at every locality in the carbonate facies began with a regional tectonic pulsation, because the local topography of the bottom, developed by slight folding and by buildups of bioherms or other banks, could have controlled the direction of distributive currents and provided shallow, local, restricted, depositional basins. This might have caused one sequence to be deposited at one locality while another sequence was deposited nearby. Some of the thinner sequences of units B and C might be no more than the results of storms or seasons of storms. Nevertheless, the overall repetitions of lithologies of the carbonate facies of the Porvenir must have been ultimately the result of repeated episodes of subsidence of the Pecos shelf during which filling by sediments was generally able to keep pace with subsidence. Other hemicyclic sequences occur in the carbonate facies of the Porvenir south of Montezuma. One of these sequences at the Montezuma bioherm was described previously. The general succession of sequences at Montezuma also requires repeated episodes of subsidence followed by upbuilding to shallow water levels during the overall depression of the basin.

Other kinds of repetitive lithologic sequences occur in the northern sandstone-shale-limestone facies of the Porvenir. The sandstones of Fragoso Ridge at locality F near Rito Cebolla exhibit both upward-coarsening and upward-fining sequences. Interbedded shale, limestone, sandy limestone, and arkose in the upper part of the formation in the Manuelitas Creek–Rito Cebolla area also show repetitions of lithologies, but we have not studied these rocks in detail.

At Mora River, the lower part of the Porvenir and the rocks just above the sandstones of Fragoso Ridge each are very fine grained sandstone and limestone deposited in quiet marine water. These are succeeded upward by sandy and oolitic limestones in turn succeeded upward by feldspathic sandstone and conglomerate, parts of which were deposited in very shallow marine and nonmarine environments. The highest part of the Porvenir is predominantly marine shale. Therefore, the section at Mora River may exhibit two hemicycles and the lower part of a third. These hemicycles seem to represent recurrent episodes of rapid subsidence followed by infilling and upbuilding to shallow-water conditions by progradational deposits near a source of coarse, terrigenous, clastic sediments. However, the orderly sequence was interrupted by slight local uplift and erosion prior to deposition of the partly nonmarine sandstones of Fragoso Ridge.

The vertical repetitions of lithologies throughout the Porvenir Formation probably were primarily the results of recurrent tectonic activity of the local basins and intrabasinal uplifts, as well as the major uplifts that are marginal to the entire Pennsylvanian basin. Our data are not sufficient to determine whether, or to what extent, the repetitions were influenced by other more widespread causes, such as climate changes or world-wide eustatic changes of sea level that have been proposed, for example, by Wanless and Patterson (1951).

Contact with overlying rocks

In most of the area the Porvenir Formation is overlain by the Alamitos Formation. In the central part of the area, on the west limb of the Cenozoic Las Gallinas syncline from about Cabo Lucero Creek north, the contact generally is structurally conformable, although local scouring and channeling occurred at the base of the Alamitos. At many places the marker zone is present in the upper part of the Porvenir, but the interval between it and the base of the Alamitos thickens and thins somewhat, suggesting at least local disconformity. The hiatus at the contact probably is small because the late Desmoinesian fusulinid *Beedeina sulphurensis* occurs in the lower part of the Alamitos as well as in the upper part of the Porvenir.

Northeast of Hermit Peak, on both limbs of the Cenozoic Las Dispensas syncline, and on the east limb of Cerro de la Cruz anticline between Sapello River and Manuelitas Creek, the contact is similar to that farther south, maintaining about the same stratigraphic interval above the marker zone. *Beedeina sulphurensis* occurs above and below the contact here as it does farther south.

These places, where all or nearly all of the Porvenir Formation is present, are parts of the Paleozoic San Geronimo and Rociada Basins and Manuelitas saddle (Plate 4). Elsewhere in the area, the contacts of the Porvenir and overlying rocks are mainly low-angle unconformities on the Paleozoic uplifts and their flanks.

Southwestern part of area—On the west limb of the Cenozoic Chapelle syncline, thin remnants of the Alamitos lying on the Porvenir were observed at a few places (Plate 1). At Cabo Lucero Creek and near the northwest corner of T14N R15E (loc. 1b, Fig. 31), the marker zone of the Porvenir is present beneath the Alamitos, but, farther south, at Dead Horse Canyon the lower part of the Porvenir is overlain unconformably by the Alamitos. West of Bernal the lower part of the Porvenir, containing middle Desmoinesian fusulinids, is overlain by a thin remnant of the Alamitos, which contains Missourian fusulinids indicating unconformity between the formations. At most places on the west limb of the Chapelle syncline the Porvenir Formation is overlain unconformably by the Sangre de Cristo Formation. At locality 1a and at Falls Creek (Fig. 31), the Sangre de Cristo lies on the upper part of the Porvenir, but elsewhere in this part of the area and west of Bernal, the Sangre de Cristo lies unconformably mainly on the lower part of the Porvenir. (See Fig. 58.) All these relations show that the Bernal uplift (Plate 4) was active in late Desmoinesian time after deposition of the Porvenir and, again, after deposition of the Alamitos.

Southeastern part of the area—On both flanks of the Cenozoic Ojitos Frios anticline (Plate 1) the Porvenir is overlain by coarse-grained to pebbly feldspathic sandstone and limy sandstone of the Alamitos Formation. At Cañon Mesteño along New Mexico Highway 283 the medial and upper parts of the Porvenir are present and the marker zone contains *Beedeina sulphurensis*. However, the Porvenir thins eastward from Cañon Mesteño and, a short distance east of La Reunion syncline, only the lower part of the Porvenir, about 220 ft (67 m) thick along Highway 283, is present beneath limy sandstone of the Alamitos. Therefore, the contact is locally an angular unconformity on the west flank of the Tecolote uplift. The Porvenir is, similarly, very thin farther southeast. These and other data show that the Tecolote uplift (Plate 4) was active prior to late Desmoinesian deposition of the Alamitos.

Along Tecolote Creek, west of the Cenozoic Ojitos Frios anticline, the Sangre de Cristo Formation cuts out the Alamitos and, southward, progressively cuts out the upper third to half of the Porvenir. South of Ojitos Frios, along the axis of the anticline, the Alamitos again is present unconformably on the lower part of the Porvenir. Southward, the Alamitos bevels down to Mississippian rocks, and, in turn is overlapped by the Sangre de Cristo, which lies on Precambrian rocks. Along the east side of Tecolote Creek just south of Ojitos Frios the contact of the Porvenir and Sangre de Cristo Formations is, at places, a sharp angular unconformity because the Porvenir is folded sharply into small anticlines and synclines whose axes trend northwest. These folds, however, appear to be Late Pennsylvanian because the Alamitos Formation north and south of Ojitos Frios also is folded beneath the unconformity.

About 1 mi (1.6 km) west and southwest of Agua Zarca only the lowermost part of the Porvenir is present, ranging from 0–175 ft (0–53 m) thick. It is overlapped southward by the Alamitos, which lies on Precambrian rocks and contains beds of pebbly arkose that indicate the southern part of the Tecolote uplift also was active in late Desmoinesian after deposition of the Porvenir and during deposition of the Alamitos.

East-central part of area—On the east flank of the Cenozoic Creston anticline north of Agua Zarca, the lower part of the Porvenir is 0–300 ft (0–90 m) thick and is overlain unconformably by thin remnants of the Alamitos Formation at places from Agua Zarca Creek to south of Montezuma (Fig. 32); elsewhere in this part of the area the Porvenir, and locally the Sandia Formation, are overlain unconformably by the Sangre de Cristo Formation. From Montezuma to north of Cañon Bonito the Porvenir is faulted against Permian to Triassic rocks and locally is cut out completely by the Montezuma fault. Only the lower part of the Porvenir is exposed here. Along the eastern front of the mountains north of Cañon Bonito the contact with the Alamitos is poorly exposed but probably is unconformable because the Porvenir is only about 600 ft (180 m) thick and only the lower part of the carbonate facies seems to be present. North of La Sierrita dome, a short distance south of Las Tusas, limestone-pebble conglomerate occurs in the lower part of the Alamitos, indicating an unconformable relationship. The relationships from Agua Zarca north to Las Tusas show that the northern part of Tecolote uplift was active in middle to late Desmoinesian. From the vicinity of Sapello River to north of Manuelitas Creek, where the northern facies of the Porvenir is as much as 1,200 ft (366 m) thick, the marker zone and upper part of the Porvenir are present, and the contact with the Alamitos is at least structurally conformable on the Paleozoic Manuelitas saddle.

On the west flank of the Cenozoic Creston anticline and La Sierrita dome west and northwest of Gallinas the upper and middle parts of the Porvenir are missing locally because of angular unconformity with the Alamitos Formation (Fig. 33), but, from the vicinity of Cañon Bonito northward the marker zone and overlying beds are present beneath the Alamitos. All these described relations show that the northern part of the Tecolote uplift was active after deposition of the Porvenir, or, perhaps, during deposition of its upper part, but before deposition of the Alamitos. The Tecolote uplift of Desmoinesian time (Plate 4) seems to coincide generally with the broad structural block of the Cenozoic Creston anticline and La Sierrita dome, although data are not available to determine where the eastern limb of the Paleozoic uplift lies in the subsurface of the western margin of the Las Vegas Basin.

Northeastern part of area—Along the eastern front of the mountains north of Manuelitas Creek, the Alamitos and upper part of the Porvenir are cut out at places by the Sapello fault on the east flank of the Padilla anticline (Plate 1). Farther north near the San Miguel–Mora County line both formations are present west of the fault, but exposures are so poor in the vertical to overturned beds that little can be discerned about the contact. Near Rito Cebolla the Porvenir is in fault contact with the Sangre de Cristo Formation (Plate 1), but, northwest of Buena Vista, *Beedeina sulphurensis* (f10290) was found in the upper part of the Porvenir, indicating that the upper part is present beneath the Alamitos, and the contact may be conformable.

At Mora River the Porvenir is only about 680 ft (207 m) thick, and it continues to thin northward. At Mora River the highest beds of the Porvenir contain *Beedeina rockymontana* (f10149), indicating that the late Desmoinesian upper part is missing by unconformity on the western margin of the Rainsville trough. In some places, the contact can be seen to be a slightly channeled surface at the base of arkoses of the Alamitos.

Age and fossils

Fusulinid zonation and associations—The general zonation of fusulinids of the Porvenir Formation is shown in Figure 54. Near the base, the Porvenir at places contains *Beedeina insolita* (Thompson), 1948 shown on Plate 6. South of Montezuma (sec. G, Fig. 33), *B. insolita* (f10152) is associated with *Fusulinella* sp. At about the same stratigraphic position *Beedeina arizonensis* (Ross and Sabins) 1965 is common (Plates 8, 11) at many places, and north of upper Sapello River *Beedeina* aff. *B. arizonensis* and *Fusulinella* aff. *F. famula* Thompson (f10312) occur together. *Beedeina hayensis* (Ross and Sabins) 1965 (f10283), another early Desmoinesian form, occurs near the base of the Porvenir north of lower Sapello River. *Wedekindellina excentrica* Dunbar and Henbest, 1942 is associated with *B.* aff. *arizonensis* (f10135, Plate 11) and *Fusulinella* aff. *F. dosensis* at Mora River (sec. K, Fig. 46), and *Wedekindellina*? sp. (Plate 12) is associated with *Fusulinella* aff. *F. dosensis* (f10137) north of Mora River. All these associations indicate that the lower part of the Porvenir is early Desmoinesian.

The rocks that are stratigraphically above the highest occurrence of *Beedeina arizonensis*, but still are in the lower part of the Porvenir, contain a succession or grouping of fusulinids that is relatively distinct. The general ascending order is *Beedeina* aff. *B. apachensis* (Ross and Sabins), 1965 shown on Plate 9; *B.* cf. *B. pattoni* (Needham), 1937 shown on Plate 11; *B.* cf. *B. novamexicana* (Needham), 1937 shown on Plate 10; and *B.* aff. *B. socorroensis* (Needham), 1937 shown on Plate 10. This succession (except *B. apachensis*) is demonstrated best in stratigraphic section K (Fig. 46) at Mora River, where it occurs just below and within the stratigraphic interval of the sandstones of Fragoso Ridge. Several species of *Wedekindellina* (Plates 10, 11) are associated with the *Beedeina* faunas at section K.

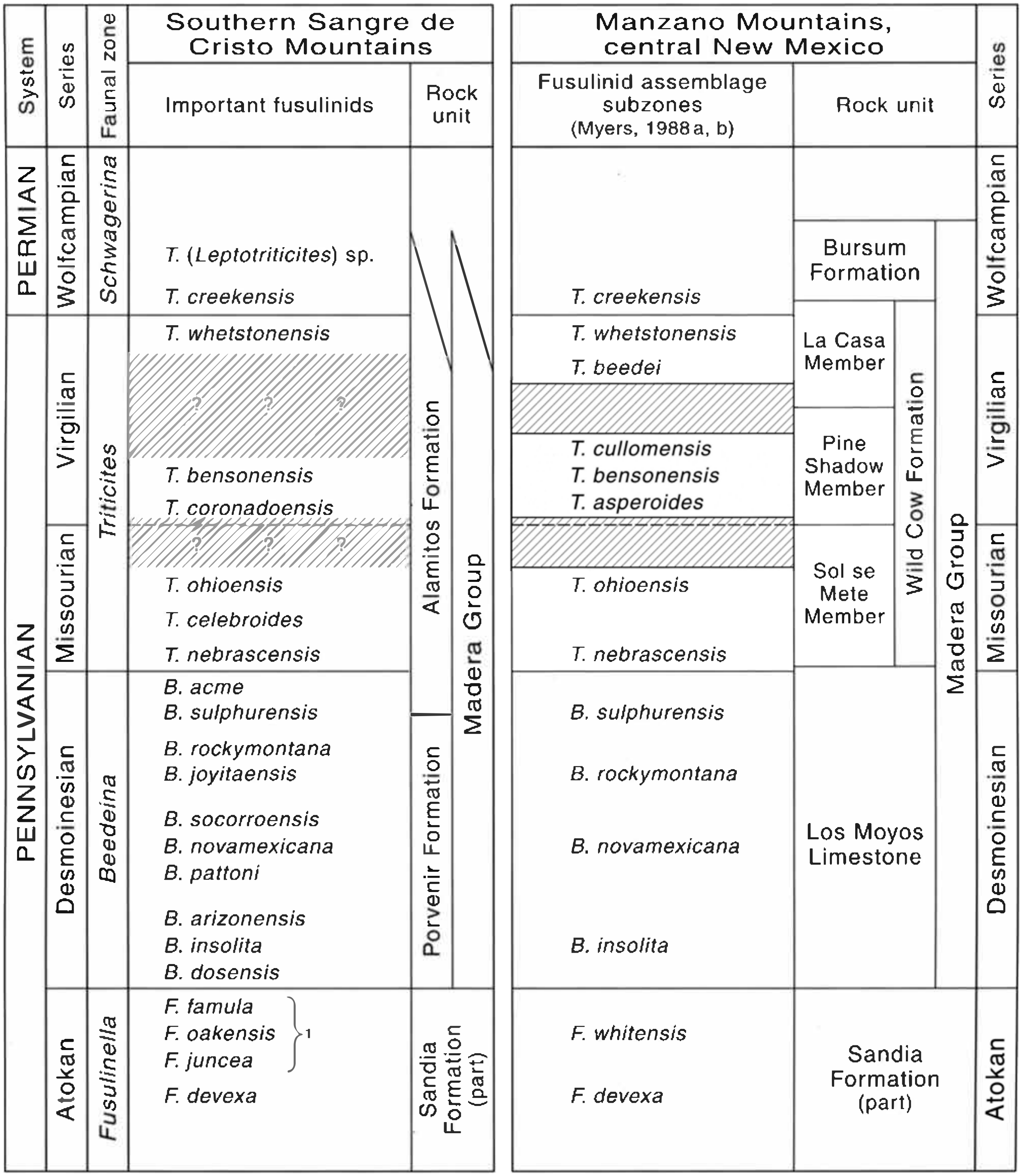
About the lower third to lower half of the Porvenir, above the rocks in which *Beedeina novamexicana* and associated forms occur, is characterized by *Beedeina* aff. *B. rockymontana* (Roth and Skinner), 1930, illustrated on Plate 8. *Beedeina* aff. *B. joyitaensis* Stewart 1970, also found in this interval above the sandstones of Fragoso Ridge at section K (Fig. 47) at Mora River, is illustrated on Plate 10. Associated with *B. rockymontana* are *Wedekindellina* sp. (Plate 12) and rare specimens of *Frumentella*? sp. (Plates 6, 8). Toomey (1980, p. 263) reported *B. novamexicana*, *Frumentella* sp., and *Wedekindellina minuta* in crinoidal grainstone above the bioherm exposed in the western quarry south of Montezuma at section G of the present report. We found *B. rockymontana* in these beds (f10154) and also, stratigraphically a little lower (f10153), in the core rock of the bioherm (Plate 6). These relations suggest that the ranges of these species of *Beedeina* overlap slightly.

The upper part of the Porvenir, from a position just below the base of the lithologic marker zone to the top of the formation, is characterized by *Beedeina sulphurensis* (Ross and Sabins), 1965. This species, illustrated on Plates 8 and 9, is common at many localities and was found throughout the mapped area where beds of this part of the Porvenir are present. This late Desmoinesian species ranges upward into the lower part of the Alamitos Formation where it is also common.

Regional fusulinid-faunal correlations—The succession of fusulinids of the Porvenir Formation and underlying and overlying rocks in the southeastern Sangre de Cristo Mountains is compared in Figure 54 with fusulinid successions in the Manzano Mountains of central New Mexico in the type region of the Madera Group. The faunal zonation of fusulinids of the Pennsylvanian and Lower Permian rocks of the Manzano Mountains and the adjacent Los Pinos Mountains was determined during detailed mapping and biostratigraphic studies of these ranges by Myers and McKay (1976) and Myers et al. (1986). Most of the following data and interpretations are summarized from Myers (1988a, 1988b), where they are discussed in greater detail.

The Los Moyos Limestone, the lower part of the Madera Group in the Manzano Mountains, is shown by its fusulinids to be generally equivalent in age to the Porvenir Formation, although the uppermost part of the Los Moyos is slightly younger than the Porvenir (Fig. 54). The Los Moyos has four fusulinid-faunal subzones that span the Desmoinesian, and these same four subzones can be identified in the Porvenir. Correlatives of these subzones have been recognized in the Midcontinent and elsewhere in the Western United States.

The oldest subzone assemblage of *Beedeina insolita* of the Los Moyos is approximately equivalent to Ross and Sabin's (1965) assemblage subzone of *B. hayensis*, which includes *B. hayensis*, *B. arizonensis*, *B. portalensis*, and *Fusulinella famula* in southeastern Arizona. *B. insolita* originally was described from the top of the rocks that were called the Derry Series by Thompson (1948, p. 96–97) in south-central New Mexico. It is not known if representatives of this assemblage subzone occur in the Midcontinent region.



[1] Species that are primarily late Atokan but whose ranges, at places, extend upward into the basal part of the Porvenir Formation where they are associated with *B. insolita* and *B. arizonensis*

FIGURE 54—Important fusulinids from southeastern Sangre de Cristo Mountains, and assemblage subzones in Manzano Mountains, New Mexico. *T.–Triticites; B.–Beedeina; F.–Fusulinella*. Patterned area indicates faunal hiatus; queried where uncertain.

The next youngest subzone assemblage of the Los Moyos is that of *Beedeina novamexicana*. In this assemblage, *B. novamexicana* is associated with various slender species of *Wedekindellina* and probably is equivalent to the *W. euthysepta* assemblage subzone of Ross and Sabins (1965) in southeastern Arizona. The subzone of *B. novamexicana* contains forms similar to those of the fauna from the *Wedekindellina* zone of Dunbar and Henbest (1942, fig. 2) from the Stonefort Limestone Member of the Spoon Formation of southern Illinois.

The assemblage subzone of *Beedeina rockymontana* of the Los Moyos probably is equivalent to the *B. girtyi* subzone of Ross and Sabins (1965). *B. rockymontana* originally was described from the McCoy Formation at McCoy in western Colorado by Roth and Skinner (1930). It has been reported from the Youghall Formation on the flanks of the Uinta Mountains in eastern Utah by Thompson (1945, p. 62–63). *B. rockymontana* seemingly marks a widespread and distinctive biostratigraphic zone in the Western United States (Ross and Tyrrell, 1965, p. 627).

The assemblage subzone of *Beedeina sulphurensis* of the upper part of the Los Moyos contains fusulinids that are typical of those found in the upper beds of the Desmoinesian Series in the Midcontinent and Southwestern United States. Its fauna is similar to that illustrated by Dunbar and Henbest (1942) from the upper part of the McLeansboro Group of southern Illinois and resembles the fauna figured by Thompson (1934) from the upper part of the Desmoinesian Series of Iowa. The *B. sulphurensis* fauna is similar to the faunas figured by Myers (1960) and by Stewart (1958) from the Capps Limestone Lentil of Plummer and Moore (1921) in central and north-central Texas, and it is equivalent to the *B. eximia* subzone of Ross and Sabins (1965) in southeastern Arizona.

The lower part of the Porvenir Formation correlates with the predominantly carbonate upper part of the La Pasada Formation of Sutherland (1963) at its type locality north of Pecos in the southwestern part of the Sangre de Cristo Mountains. Beds 89–96 of Sutherland's type section of the La Pasada (1963, p. 59) are lithologically similar to the Sandia Formation and contain *Fusulinella* cf. *F. devexa* and *F.* cf. *F. famula* (zone I of Sutherland and Harlow, 1973, p. 10), both of which occur in the upper part of the Sandia Formation in the southeastern part of the mountains. Beds 97 and above of the La Pasada are similar lithologically to the carbonate facies of the Porvenir and contain *Beedeina* and *Wedekindellina* (zones II–IV of Sutherland and Harlow, 1973, p. 10) similar to those of the lower 500 ft (180 m) of the Porvenir.

Megafossils—Megafossils were collected from the Porvenir, mainly in the Gallinas Creek area, to obtain a general sample of the fauna of the formation in the southeastern part of the Sangre de Cristo Mountains. Most of the collections were made from the highly fossiliferous limestones of the lower part of the formation, but several collections were made also from the medial and upper parts. The identified genera and species are listed on Plate 5 and are calibrated with fusulinid occurrences throughout the Porvenir in the Gallinas Creek area. The collections represent only part of the total fauna and do not contain, for example, some of the brachiopods reported by Sutherland and Harlow (1973) from their extensive collections from Desmoinesian rocks of the southwestern part of the mountains. Several brachiopods not in our collections were reported by Toomey (1980, p. 257–259) from the Montezuma bioherm in the rocks from which we obtained fusulinid collections f10153 and f10154 (Plate 5). These brachiopods are *Antiquatonia hermosana* (Girty), *Cleiothyridina pecosii* (Marcou), *Hustedia mormoni* (Marcou), *Linoproductus planiventralis* Hoare, and *Orbiculoidea* sp. The evidence of Desmoinesian age presented by all the brachiopods is consistent with the age indicated by the fusulinids.

Stevenson (1881, p. 304) reported several collections of brachiopods and a few pelecypods from the lower part of rocks now assigned to the Sandia Formation on Rito Cebolla northwest of the village of Cebolla (now called Ledoux) and from the rocks now assigned to the Sandia, Porvenir, and Alamitos Formations on Manuelitas Creek (Stevenson, 1881, p. 306–310) at the locality of section H of the present report. Evaluation of his collections was not within the scope of the present investigation, but they are mentioned because of their historical interest and because these fossils led to the correct deduction that the rocks were equivalent to the "Upper Coal-measure" division of the Carboniferous (White, 1881).

Paleotectonic and sedimentational interpretations

Early Desmoinesian—At the beginning of Desmoinesian time the area of this report was submerged beneath a widespread shallow sea in which biostromal, biohermal, and bioclastic limestones and shale were accumulating. These deposits represent a short-lived period of regional tectonic quiescence after the filling of the basin by the Sandia Formation, and they occur in several places that were, at other times, recurrently positive. In the western part of the Sangre de Cristo Mountains, lower Desmoinesian biostromal and bioclastic limestones containing *Beedeina arizonensis* (f10316) and equivalent to the basal part of the Porvenir occur in the Pecos River area and near Lamy on the Cañoncito uplift (Fig. 4). Clastic limestones also equivalent to the basal Porvenir and containing *Beedeina portalensis* (f10315) occur unconformably on the (Morrowan) lower part of the Sandia Formation at Rio Nambe north of Santa Fe on what probably was the west flank of the Cañoncito uplift. According to Casey (1980b, p. 29–32, 77–81), shallow-water marine carbonates and conglomeratic fan deltas were deposited in the western part of the Taos trough in Atokan to earliest Desmoinesian time, and primarily shallow-marine carbonate rocks were deposited in the eastern part in early Desmoinesian.

In the area of this report the Tecolote, Bernal, and Hermit Peak uplifts (Plate 4) were not active in earliest Desmoinesian as indicated by the presence of lowest Desmoinesian rocks at the base of the carbonate facies on the uplifts as well as in the adjacent basins. The lower Desmoinesian biostromal limestones, local bioherms, and thin calcareous shales of the carbonate facies were deposited on the broad, slowly subsiding southern shelf (Fig. 4) in shallow water mainly within the photic zone, as shown by the common occurrence of filamentous and phylloid algae. Some of the bioherms built up to depths shallow enough to be partly eroded by waves or strong currents, and some bioherms are overlain by thin carbonaceous to coaly shale, suggesting local subaerial conditions. Here and there, thin beds of fine to coarse quartz sand were deposited.

To the north, on the Manuelitas saddle and in the Rociada Basin, the basal part of the Porvenir Formation also was deposited on a shelf. Thin-bedded biostromal to sparsely fossiliferous limestones, and local algal-bioherm mounds accumulated in a shallow subtidal environment. Stromatolitic limestones that contain algal-mat breccias, limestone pebbles, and some quartz sand and granules were deposited in the shallow subtidal to tidal zone, as were the coarsely bioclastic to oolitic limestone and coarse sandstone near the base of the Porvenir in the northern part of the area.

Not long after the beginning of the Desmoinesian, local tectonic activity began to influence deposition of the Porvenir Formation as shown by (1) the small folds and unconformities in the lower part of the carbonate facies on the northwest flank of the Tecolote uplift at Gallinas; (2) the eroded bioherms, the limestone pebble and limestone cobble conglomerates, and the feldspathic, conglomeratic sandstone, all near the base of the shaly facies north of Daily and Sparks Creeks and north of Gascon; (3) limestone-pebble conglomerate and feldspathic channel sandstone near the base of the northern facies west and north of Manuelitas; and (4) erosional and slightly angular unconformities and feldspathic coarse-grained sandstones and conglomerates in the lower part of the northern facies at and north of Mora River. In the area of the northern facies, parts of the basal limestones of the Porvenir Formation were briefly and locally eroded by shallow-marine currents and subaerial streams that were strong enough to transport coarse to pebbly sand from northerly source areas. After this episode the region subsided episodically and shallow-water limestone and shale continued to accumulate as the lower part of the carbonate facies. The lower part of the shaly facies and the lower shale-limestone unit of the northern facies accumulated mainly in deepening water.

Middle Desmoinesian—Beginning with deposition of the sandstones of Fragoso Ridge, in about middle Desmoinesian time, northerly sources produced sheets of coarse to conglomeratic, micaceous, and feldspathic to arkosic sand. The marine and nonmarine sandstones of Fragoso Ridge were deposited as a complex-fan apron near an uplifted source of coarse clastics. These clastic sediments were spread across the Manuelitas saddle, but they lens out southwestward on the east flank of the deepening Rociada Basin in which the shaly facies was being deposited, and they lens out southward into the carbonate facies (Figs. 28–30). In the subsurface of the southern part of the Las Vegas Basin these clastic sediments die out southeastward from Sapello before reaching the carbonate facies at the J. D. Hancock no. 1 Sedberry well (Fig. 18).

North of Sapello River, for many miles, the subsurface extent of the sandstones of Fragoso Ridge is unknown but, in the Rainsville trough at the Amoco "A" and "B" wells (Plate 3), they are mainly fine to medium grained, indicating eastward fining from the outcrops between Mora River and Los Cisneros.

The subsurface probable eastward fining of the sandstones of Fragoso Ridge indicates sources to the west. However, the remnants of the shaly facies of the Porvenir in the Rociada Basin show that those sources were not west of the present El Oro Mountains. Short distances of sediment transport are indicated by the coarseness and relative angularity of the clasts in some beds at the surface, especially the feldspars, which are common in granule and small-pebble sizes and which locally range up to 0.5 inch (1.3 cm) diameter. The locally poor mineralogic sorting and grus-like character of some beds (Figs. 4, 45) also suggest short distances of transport. The Precambrian micaceous schists, quartzofeldspathic gneisses (Fig. 5), and abundant pegmatites (Baltz and O'Neill, 1984) of the El Oro Mountains are lithologically appropriate to have been the sources in the area of this report. Farther north, Precambrian micaceous quartzites, quartzofeldspathic gneiss, and pegmatites of the eastern part of the Rincon Range could have been the sources of the abundant quartzite clasts, mica, and feldspars of the conglomeratic sandstones in the lower part of the Porvenir that crop out west of Los Cisneros.

At locality C south of Rito Cebolla, about 50 ft (15 m) above the base of the sandstones of Fragoso Ridge, a 17-ft (5-m) thick bed of feldspathic conglomerate contains numerous limestone pebbles, some as large as 2 inch (5 cm) diameter, indicating a source terrane that was partly sedimentary rocks. At the northwest side of Fragoso Ridge (sec. F, Fig. 46) the middle and upper parts of the Porvenir contain reworked abraded fusulinids (*Fusulinella* sp.) whose normal stratigraphic position is near the base of the Porvenir or the top of the Sandia Formation. This suggests that the lower part of the Porvenir or the upper part of the Sandia was being eroded from a nearby area while higher parts of the Porvenir were being deposited at locality F. Therefore, in middle and late Desmoinesian time clastics of the Porvenir on the Manuelitas saddle may have been derived from uplifted conglomeratic sandstones of the Sandia as well as the Precambrian rocks on the southern margin of the El Oro–Rincon uplift in a manner similar to that illustrated in section C, Figure 27.

The thinning of the Porvenir Formation northward from the vicinity of Rito Cebolla (Fig. 46) provides other evidence of Desmoinesian uplift of sedimentary rocks on the east flank of the El Oro–Rincon uplift. The thinning resulted from uplifting in the area east of Mora during deposition of the early Desmoinesian lower part of the formation, before the deposition of the sandstones of Fragoso Ridge, and after the deposition of the middle Desmoinesian upper part of the formation. The interpretation of the shape of the uplift (Plate 4) is tentative because all the thickness data are in the northerly trending line of hogbacks from Rito Cebolla north. The rocks beneath the slightly angular intraformational unconformity (Fig. 48) in the lower part of the Porvenir at locality K at Mora River are tilted east more steeply than the overlying rocks. This is meager evidence because of the small area of the outcrop but, taken in the context of the other erosional unconformities within the lower part of the Porvenir from Mora River north, the angular unconformity may indicate uplift to the west.

In middle Desmoinesian, the medial part (Figs. 29, 30) of the Porvenir Formation was deposited in the deepening San Geronimo and Rociada Basins and the Manuelitas shelf. Some of the shale and limestone, particularly to the south, was deposited in relatively deep unagitated water, but most of the sediments are sublittoral deposits of shaly silt and fine-grained sand. On the Manuelitas saddle, rocks generally equivalent to the medial part contain feldspathic to arkosic conglomeratic sandstones that were spread southward and eastward from the recurrently active El Oro–Rincon uplift as low, mainly marine fans.

The medial part of the Porvenir is absent from the Tecolote uplift and from the Bernal uplift and most of its eastern flanks, at least partly because of late Desmoinesian uplift. On the northwest flank of the Tecolote uplift (loc. 1, Fig. 33) sandy limestone near the top of the Porvenir contains abraded specimens of the fusulinid *Beedeina* aff. *B. apachensis* (f13156) whose normal stratigraphic position is in the lower part of the Porvenir (sec. D, Fig. 33), indicating elevation, erosion, and reworking of older sediments at places on the Tecolote uplift during middle to late Desmoinesian deposition of the medial and upper parts in the flanking basins. To the south, in the canyon east of Cañon Mesteño about 2.3 mi (3.7 km) east-southeast of San Geronimo, shale of the medial part contains sandstones and sandy, bioclastic limestone whose northward-inclined crossbeds indicate derivation of sediments from the direction of the southern part of the Tecolote uplift. The occurrence of thick, coarse-grained, calcareous sandstones above the lower part of the Porvenir at a number of locations northwest and north-northeast of Ojitos Frios also indicate an emergent source of terrigenous sediments on the southern part of the Tecolote uplift probably in middle Desmoinesian. Therefore, some of the southward erosional beveling of the Porvenir on the Tecolote uplift (Fig. 32) probably occurred relatively rapidly in the latter part of middle Desmoinesian time.

Late Desmoinesian—The late Desmoinesian upper part of the Porvenir Formation, including the marker zone, is present generally in the San Geronimo and Rociada Basins and on part of the Manuelitas saddle. The marker zone at the base of the upper part seems to represent a short period of widespread, nearly uniform, shallow sublittoral conditions of deposition in the San Geronimo and Rociada Basins in late Desmoinesian time. In the southern part of the area the marker zone is mainly crossbedded, medium-grained, well-rounded calcite sand containing medium to coarse subangular to angular quartz sand, but it becomes coarser northward. On the Manuelitas saddle the directions of inclination of crossbeds in the marker zone at many places indicate southerly and southwesterly sediment transport. The marker zone appears to be slightly unconformable with underlying rocks on the eastern part of the Manuelitas saddle west of Sapello (Fig. 30), where a beach probably was present and where the marker grades northward into mainly calcareous sandstone and feldspathic granule and pebble gravel (loc. 3, Fig. 30). This nearshore facies probably trended northwestward toward the northwest part of Fragoso Ridge (loc. F, Fig. 29).

The late Desmoinesian upper part of the Porvenir Formation, including the marker zone, is absent, probably because of nondeposition, from the Bernal uplift and most of its eastern flank, from the Tecolote uplift, and from the east flank of the El Oro–Rincon uplift near Mora River. By the beginning of late Desmoinesian, the uplifts were mainly emergent and had attained structural relief of probably 500–600 ft (150–180 m) relative to the adjacent basins. The Hermit Peak uplift also may have been active in late Desmoinesian, as suggested by younger lithologic variations of the Alamitos Formation. However, we have no direct evidence of this activity in the Porvenir Formation except for limestone-pebble conglomerate in the upper part at locality D (Fig. 33) that might have been derived from the vicinity of Hermit Peak or farther south.

Alamitos Formation

Definition

The Alamitos Formation was named by Sutherland (1963, p. 36–38) and includes the interbedded arkose, shale, and marine limestone of Middle and Late Pennsylvanian age that overlie his La Pasada Formation in the southwestern part of the Sangre de Cristo Mountains in New Mexico. The Alamitos Formation is overlain by the Sangre de Cristo Formation, which consists of red beds and arkosic sandstone and conglomerate that are almost entirely nonmarine. Two measured sections were designated by Sutherland as type sections of the Alamitos Formation because near Pecos, New Mexico, no single section exposes the entire formation. His section 97, which includes the lower part, was measured on a ridge west of Pecos River northwest of Pecos. His section 96, which includes the upper part, was measured in Alamitos Canyon northwest of Pecos. The total thickness of the Alamitos Formation at the type sections is approximately 1,275 ft (390 m).

At the type sections about 50 percent of the Alamitos is reported to be arkosic sandstone and conglomerate, about 21 percent is fossiliferous limestone and sandy limestone, and about 29 percent is shale and siltstone. In some sandstone beds 30 to almost 60 percent of the clasts are mainly unweathered potassium feldspar (Sutherland, 1963, p. 36). Sutherland (1963, p. 38) reported that shales of the lower part are mainly gray, but that red shales occur in the middle and upper parts of the Alamitos Canyon section (96), and red to green shales occur at other places. Red shale occurs also near the base of the formation at the position of unit 6 of Sutherland's section 97 west of the Pecos Valley. (See also, Brill, 1952, p. 846–849.) Sutherland (1963) reported that, at the type sections, 65 percent of the lower two-thirds of the formation is sandstone and conglomerate, and that 40 percent of the upper third is dominantly carbonate rocks. However, he pointed out that these general divisions are not consistent laterally, and that all lithologies show marked lateral and vertical variations. The type Alamitos was deposited in and near fluctuating shallow seas adjacent to an uplifted source of very coarse terrigenous clastics, presumably the Brazos uplift (the southern extension of the Uncompahgre highland of Sutherland, 1963, p. 41–44).

Sutherland (1963, p. 36–37) placed the basal contact of the Alamitos Formation at a lithologic change from limestone of the La Pasada to arkosic sandstone of the Alamitos where 30–40 percent of the clasts are feldspar. The contact with the overlying Sangre de Cristo Formation at the type locality is gradational and was placed arbitrarily at the top of the highest "well-developed" limestone by Sutherland (1963, p. 38). This limestone is a prominent unit at section 96, but sandy limestone and limy sandstone beds that bear marine fossils occur also in slightly higher rocks that were assigned to the lower part of the Sangre de Cristo by Sutherland at this section. The presence of marine beds above the type Alamitos does not contradict Sutherland's observations or his local arbitrary assignment of the upper contact, but it illustrates part of a problem of assigning, mapping, and correlating the contact of the Alamitos and Sangre de Cristo Formations on a regional basis where lateral and vertical transitions of lithology occur in short distances within the Alamitos.

In the type area the Alamitos Formation is late middle Desmoinesian through Virgilian age (Sutherland and Harlow, 1973, fig. 8). Near the base, in units 9 and 11 of Sutherland's (1963, p. 66) type section 97, we found the middle Desmoinesian fusulinids *Beedeina rockymontana* and *Wedekindellina* sp. (f10317, f10318) that occur in the Porvenir Formation below the marker zone in the southeastern part of the mountains. We were not able to determine whether the fusulinids are indigenous or whether they were reworked from older rocks during erosion that produced a possible local unconformity at the base of the Alamitos.

In the southeastern part of the Sangre de Cristo Mountains, rocks above the Porvenir Formation that are lithologically similar to the Alamitos Formation at its type locality were assigned to the Alamitos by Baltz and Myers (1984). Although there are variations in thickness and lithologic details between the type locality and the southeastern part of the mountains, the main bulk of the rocks in the southeastern part undoubtedly correlates with the type Alamitos, as shown partly by the mapping of the equivalent arkosic limestone member of the Madera Formation by Read et al. (1944) between Pecos and the southwestern part of the area of Plate 1 of this report. In the southeastern part of the mountains Early Permian (early Wolfcampian) fusulinids occur in the upper part of the Alamitos and late Desmoinesian fusulinids occur in the basal part. Therefore, the deposition of the Alamitos Formation in the southeastern part of the mountains may have begun a little later and at places continued a little longer than in the type area.

The Alamitos Formation in the area of this report (Plate 1) is, generally, the arkosic limestone member of the Madera Limestone mapped by Read et al. (1944) and Northrop et al. (1946). It is the upper member of the Madera Formation mapped by Baltz (1972) and the Alamitos Formation as used by Baltz and Myers (1984) and mapped by Baltz and O'Neill (1984, 1986).

Distribution and thickness

The Alamitos Formation is present in much of the area (Plate 1) except in topographically high parts where it was removed by Cenozoic erosion and, locally, where it is absent because of nondeposition or erosion in Late Pennsylvanian and Early Permian time (Fig. 55). The thickness of the Alamitos in the mountains and in the subsurface of the Las Vegas Basin is shown by isopachs on Plate 4C.

San Jose Basin and Bernal uplift—In the southwestern part of the area, north of San Jose, the position of the 400-ft(122-m) isopach (Plate 4C) is estimated from cross sections. Tentative correlations of the Alamitos Formation with arkose, red and greenish-gray shale, and limestone at wells southwest of San Jose indicate that the formation and the total Pennsylvanian section (Fig. 72) thicken southwestward in the subsurface away from the Paleozoic Bernal uplift into the Paleozoic San Jose Basin. The eastward thinning of the Alamitos toward the Bernal uplift is indicated by outcrops in the southern part of the area (Plate 1).

Near the southern margin of the area, between Bernal and Blanchard (Plate 1), the Alamitos Formation is absent from nearly all of the Paleozoic Bernal uplift. Northwest of Blanchard, the lower part of the Sangre de Cristo Formation and the underlying Porvenir Formation are well exposed in roadcuts of Interstate Highway 25 and the parallel access road to the north, but the contact between the two is concealed by a few feet of Quaternary deposits. South of Blanchard the contact of the Sangre de Cristo with the Porvenir is concealed by Quaternary or Tertiary terrace gravel, but parts of both formations are exposed near each other at places. West of Bernal the lower part of the Sangre de Cristo Formation and upper beds of the Porvenir are well exposed on the east limb of the Cenozoic Serafina monocline south of the Atchison, Topeka, and Santa Fe Railway line, but the contact is concealed by Quaternary deposits; the concealed interval is about 25 ft (7.6 m). Although the actual contact of the Sangre de Cristo and Porvenir Formations was not seen at any of these places, nothing was seen in outcrops or float that suggested the presence of the distinctive lithologies of the Alamitos Formation. However, a thin (37 ft; 11 m) and poorly exposed remnant of the Alamitos is present on the east limb of the Cenozoic Serafina monocline west–northwest of Bernal (Plate 1), where the formation is exposed best in the northern part of roadcuts north of Interstate Highway 25 west of the Bernal exit.

San Geronimo Basin—Northwest of Bernal the Alamitos Formation is absent, except for a few thin remnants, from the west limb of the Cenozoic Chapelle syncline (Plate 1), indicating that this was the eastern flank of the Paleozoic Bernal uplift in Late Pennsylvanian and Early Permian time (Plate 4C). In the subsurface of the southern part of the Chapelle syncline the Alamitos Formation is inferred to be present, but thin (Plate 4C), because the formation is present, at least locally, on both flanks of the syncline farther north.

From a little south of the junction of San Pablo and Tecolote Creeks the Alamitos thickens rapidly northwestward into the Paleozoic San Geronimo Basin. The thickness is about 600 ft (180 m) near San Geronimo and 645 ft (197 m) on the west flank of the Cenozoic Las Gallinas syncline near Gallinas Creek (Plate 4C).

In the northern part of the San Geronimo Basin, west of Gallinas, the Alamitos thickens rapidly eastward from the Cañon del Medio anticline into the Medina syncline and thins eastward on the eastern limb of the syncline. An outlier of slightly folded Sangre de Cristo Formation extends across the Medina syncline (Plate 1), indicating angular unconformity with the Alamitos (Baltz, 1972, cross section *F–F'*) and showing that the anticline and syncline are primarily Late Pennsylvanian and Early Permian features. North of these structures the Alamitos thickens northward into the southern part of the Paleozoic Rociada Basin (Plate 4C).

Tecolote uplift and Sierra Grande uplift—On the west flank of the Paleozoic Tecolote uplift (Plate 4C) north and south of Ojitos Frios, the Alamitos is thin because of an intraformational unconformity and is absent locally because of unconformity with the Sangre de Cristo Formation. The Alamitos thickens northward to about 200 ft (60 m) in the Cenozoic La Reunion syncline north of Ojitos Frios (Plate 1), but it is cut out to the east by the Sangre de Cristo Formation, which laps eastward onto Precambrian rocks of the Tecolote uplift.

At the eastern front of the mountains between Agua Zarca and Montezuma, thin remnants of the Alamitos are present unconformably below the Sangre de Cristo Formation at places on the Tecolote uplift (Fig. 32). The thickness and extent of the formation are unknown in the immediately adjacent part of the Las Vegas Basin. The isopachs that show a shallow Paleozoic basin here are an interpretation based on a general correspondence of major Cenozoic and Paleozoic features at outcrop areas. Farther east a thin section of rocks correlated with the Alamitos is present at the Continental no. 1 Leatherwood–Reed well (Fig. 18); but to the southeast at the Phillips no. 1 Leatherwood well the Alamitos is absent, and the Sangre de Cristo Formation lies on Precambrian rocks on the northern flank of the Sierra Grande uplift.

Along the front of the mountains between Montezuma and Cañon Bonito (Plate 1) the thickness is not known because the Alamitos Formation is cut out by the Montezuma fault. However, the formation has thickened to about 600 ft (182 m) a little north of Cañon Bonito, showing the general correspondence of this northern part of the Tecolote uplift and the northward-plunging Cenozoic La Sierrita dome. To the east, the Alamitos has thickened northward also in the subsurface of the Las Vegas Basin (Fig. 18, well 2).

Manuelitas saddle and Rociada Basin—On the Paleozoic Manuelitas saddle (Plate 4C), a little more than half a mile northwest of Sapello, the Alamitos is at least 1,075 ft (328 m) thick in a section measured across a concealed part of the Sapello fault. An estimated minimum of 200 ft (60 m) of section may be missing, as suggested by the unfaulted composite thickness of about 1,270 ft (385 m) farther northwest along Manuelitas Creek. In hogbacks along the eastern front of the mountains near the San Miguel–Mora County line the Alamitos is at least 700 ft (215 m) thick, but it is thrown against the Sangre de Cristo Formation by the Sapello fault (Plate 1), and the actual thickness is not known.

West of the Manuelitas saddle the Alamitos thickens into the northwestward-deepening southern part of the Paleozoic Rociada Basin. At Manuelitas Creek east of Rociada the Alamitos is 1,828 ft (557 m) thick, which is the maximum thickness known in the area of this report. The westward thickening probably is intraformational and not the result of unconformity with the Sangre de Cristo Formation. In the hogbacks northeast of Rociada the Alamitos thins northeastward and, as estimated from poor exposures about 2.5 mi (4 km) northeast of the area of maximum thickness, the Alamitos is about 1,150 ft (350 m) thick. The Alamitos Formation is not preserved in the area north of Rociada, and nothing is known about the northern part of the Rociada Basin of Late Pennsylvanian time.

Northern part of area and Rainsville trough—About 1 mi (1.6 km) north of Rito Cebolla in the hogbacks at the east front of the mountains, the Alamitos is only 100–200 ft (30–60 m) thick. Fusulinid data show that these rocks are the lower (late Desmoinesian) part of the formation. Evidence of faulting was found (Baltz and O'Neill, 1984) at one place, about 2 mi (3.2 km) north of Rito Cebolla, where the Sapello fault cuts out the Alamitos completely. At other places the

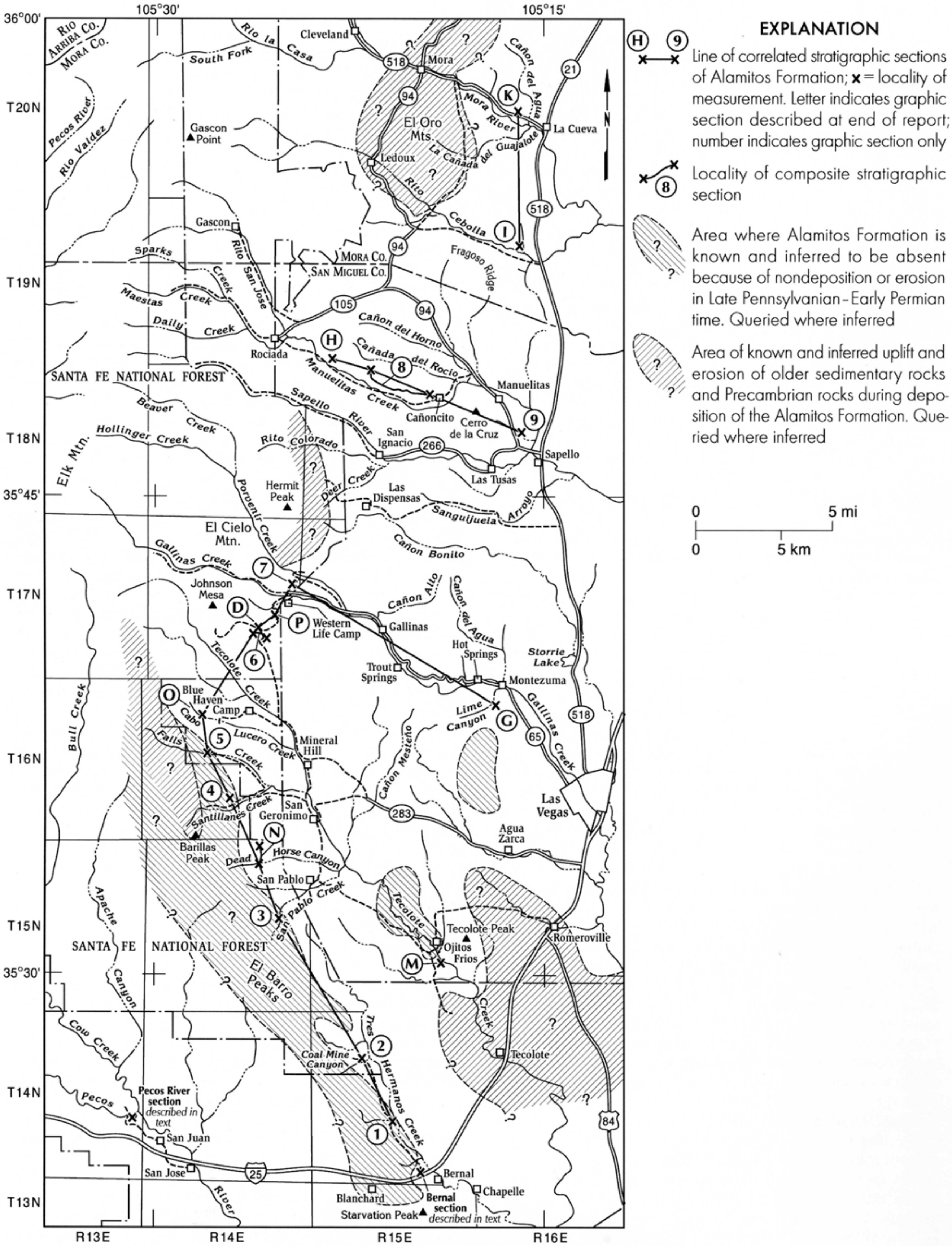


FIGURE 55—Index map of southeastern Sangre de Cristo Mountains showing localities of measurement and lines of correlated stratigraphic sections of the Alamitos Formation and inferred areas of erosion and nondeposition.

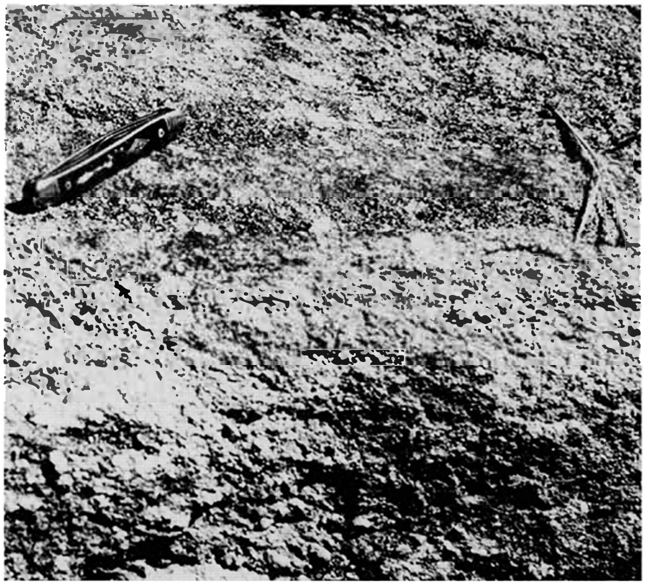


FIGURE 56—Arkose in middle part of Alamitos Formation, north side of Gallinas Creek, near New Mexico Highway 65, west of axis of Las Gallinas syncline. Knife is 3 in. (7.6 cm) long. Rock is grus-like small-pebble conglomerate of angular to subround quartz and feldspar clasts. Light-colored clasts are mostly pink potassium feldspar.

upper and lower contacts can be seen, and the thin Alamitos apparently is overlain unconformably by the Sangre de Cristo Formation.

Not far south of La Cañada del Guajalote, the Alamitos begins to thicken rapidly northward. It is about 1,050 (320 m) thick at Mora River where it is overlain conformably by nonmarine rocks assigned to the Sangre de Cristo Formation. The lower part of the Sangre de Cristo at Mora River contains palynomorphs of probable Pennsylvanian (Virgilian?) age and probably is partly equivalent in age to the upper part of the Alamitos on the Manuelitas saddle. If the temporal position of the upper contact of the Alamitos farther south could be determined in the lower part of the Sangre de Cristo at Mora River, and the Pennsylvanian part of the Sangre de Cristo at Mora River was included with the Alamitos, the Alamitos at Mora River would be at least 500 ft (152 m) thicker than shown by the isopachs on Plate 4C.

In the subsurface Rainsville trough to the east, the Alamitos is about 650 ft (192 m) thick at the Amoco "A" no. 1 Salman Ranch well and about 580 ft (175 m) thick at the Amoco "B" well about 2 mi to the north (Plate 3). The apparent thinning eastward from outcrops to these wells suggests that the area of the Cenozoic Ocate anticline was uplifted slightly during or after deposition of the Alamitos. This interpretation is similar to that for the Sandia and Porvenir Formations and is subject to the same limitation; that is, no other nearby well data exist to show whether the Alamitos thickens eastward off the flank of the Cenozoic anticline.

General lithology

In the southeastern part of the Sangre de Cristo Mountains the Alamitos Formation is composed of complexly interbedded shale, limestone, and feldspathic to arkosic sandstone and granule to pebble conglomerate. The internal stratigraphy is heterogeneous laterally and vertically and, although some generalizations can be made about gross regional variations, the facies are not as well defined as those of the Porvenir Formation. The Alamitos contains both marine and nonmarine rocks and is distinguished from the overlying Sangre de Cristo Formation partly because the Sangre de Cristo, as mapped, does not contain marine rocks except at one locality west of Sapello.

Throughout the area of this report, shale is the most abundant rock type of the Alamitos Formation, but the proportion of shale varies considerably from place to place. Generally, shale constitutes a greater proportion south of the vicinity of Gallinas Creek than it does north of Gallinas Creek. At some sections in the southern part of the area 60 percent or more of the formation is shale; however, to the north where the Alamitos is thicker, no more than 45 percent of some sections is shale. The shale is lithologically diverse; silty to sandy shaly clay is the most abundant type, but calcareous to marly shales containing limestone nodules or interbedded thin limestones and shaly limestones are common, as are units of clayey shale that contain interlayered thin shaly sandstones. Some of the shales are light to dark gray, but olive green and olive gray are the most common colors. Many shale units weather maroon to purplish red. Many shale beds contain marine fossils or fossiliferous limestone interbeds, but some red shales are unfossiliferous and probably were deposited terrestrially.

Thin to thick, fine-grained to conglomeratic, feldspathic to arkosic sandstone is interspersed with other lithologies throughout the Alamitos Formation at all localities. In hand specimens the megascopic feldspar of most beds ranges from 10 to 15 percent, but in some beds the feldspar is 20–30 percent (Fig. 56). To the south most of the feldspar clasts are pink to reddish-pink orthoclase and appear fresh and unweathered, suggesting that they were eroded rapidly from Precambrian terranes, transported relatively short distances, and buried quickly. This is suggested also by the common occurrence of feldspar granules and small pebbles that are irregular-shaped, subangular to subrounded, cleavage fragments. To the north pink feldspar clasts are common, but slightly weathered orange and yellow feldspar and a trace of white feldspar are present also. The yellow and white feldspars are partly plagioclase, probably derived from metamorphic terranes.

Most clasts of the sandstones and conglomerates are light-gray quartz and quartzite, but granite, quartzofeldspathic gneiss, and even amphibolite fragments also are common at places in the northern part of the area. Muscovite is a common minor constituent throughout the area, and some finer grained sandstones are conspicuously micaceous. Pebbles of quartzite and milky-white vein quartz are the main large constituents of the conglomerates. At places, such as in Las Dispensas syncline east and northeast of Hermit Park, large pebbles of gray, reddish-gray, and purplish-gray quartzite are common in some beds. Although many sandstones are conglomeratic, the largest pebbles are rarely more than 2 inch (5 cm) diameter.

Some of the sandstones are fine to medium grained but most are coarse to very coarse grained and often contain granules. Sorting commonly is poor, and fine to medium sand is intermixed with or interlayered with the larger sizes in many beds. Commonly, the clasts of all sizes are irregularly shaped and subangular to subrounded. Bedding is subparallel to inclined planar, and many units are trough-crossbedded. Thickness of the sandstones ranges from a few feet to as much as 120 ft (35 m). Some of the relatively parallel-bedded sandstones and some crossbedded sandstones are marine, as is shown by their fossil content or because they grade laterally in short distances into fossiliferous sandy limestone or shale. Other sandstones are subaerial stream deposits as indicated by large-scale trough crossbedding, scour-and-fill structures, and channeled surfaces at their bases.

The limestones of the Alamitos Formation generally are thinner than many of those of the Porvenir Formation. Most

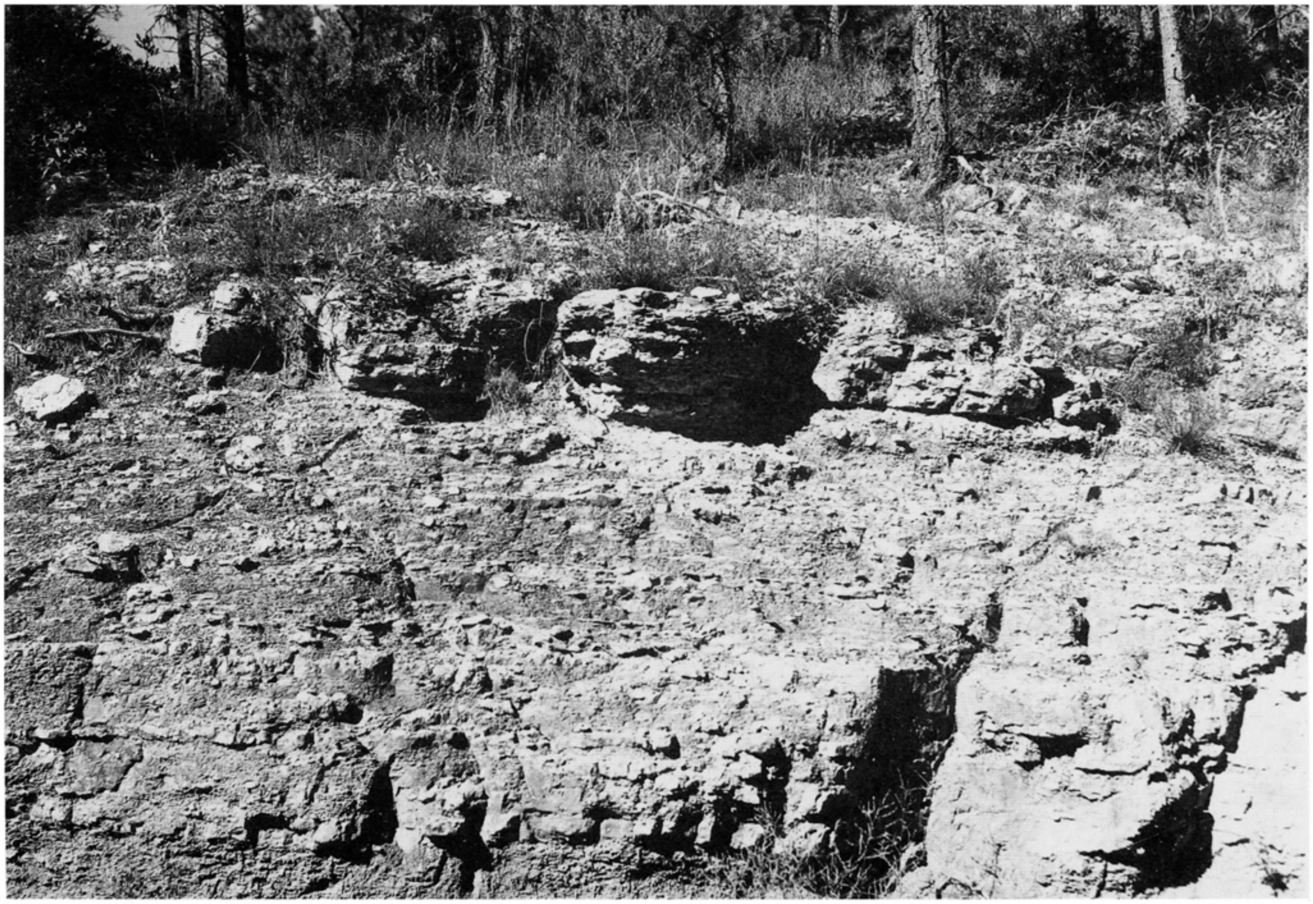


FIGURE 57—Nodular and lenticular limestone (small ledges) and interbedded marly clay shale in upper part of Alamitos Formation, north side of Gallinas Creek in roadcut on New Mexico Highway 65 near axis of Las Gallinas syncline. Ledge at top of cut is limestone, 2–3 ft (0.6–0.9 m) thick.

of the limestones are light gray to light olive gray and are bioclastic, ranging from fine grained to very coarse grained, and at places containing granule- to pebble-size fossil fragments. Some are relatively pure carbonate rocks, but silty to sandy limestones are more common, and at many places limestones grade laterally into calcareous sandstone or into shale. Some limestones contain abundant clasts of pink feldspar as well as quartz clasts. A characteristic lithologic type is nodular to irregularly lenticular limestone interbedded with silty marly shale (Fig. 57). These units usually weather light olive gray. Nearly all the limestones and sandy limestones are fossiliferous, containing brachiopods, pelecypods, abundant crinoid debris, some gastropods and bryozoans, and at places abundant fusulinids. Encrusting and filamentous algae occur, as do small horn corals, but biohermal rocks were not observed in the Alamitos.

Sutherland (1963, p. 36–38) and Sutherland and Harlow (1973, p. 7–8) reported that, in the type area of the Alamitos and elsewhere in the southwestern part of the mountains, an abrupt increase in percentage of feldspar occurs at the contact of the Alamitos and the underlying rocks. Beds of the upper part of the underlying La Pasada Formation to the south (equivalent to the lower part of the Porvenir of this report) and the Flechado Formation to the north are reported to sporadically contain 1–20 percent feldspar; however, feldspar constitutes 30 percent or more of the sandstone of the Alamitos in the southwestern part of the mountains.

In the southeastern part of the mountains, specific feldspar percentage is not a criterion for separating the Alamitos Formation from the underlying Porvenir Formation. In the southern part of the area of this report the basal beds of the Alamitos are conglomerate, sandstone, and locally, sandy limestone. A distinguishing feature of all those beds is that they invariably contain the stratigraphically lowest fresh-appearing, pink feldspar clasts. However, the percentages of feldspar vary laterally from a trace to an estimated 10–15 percent. Although the carbonate facies of the Porvenir locally contains a few slightly feldspathic sandstone beds, the feldspar clasts are weathered and yellowish gray rather than fresh and pink, and the feldspathic rocks of the carbonate facies seldom are stratigraphically near the contact with the Alamitos. The formations are distinguished on other lithologic bases, also. The olive-gray- and red-weathering colors of shale of the Alamitos are distinctly different from the medium- to dark-gray-weathering colors of nearly all the shale of the Porvenir, and the stratigraphically lowest red shale is just above or only a few feet above the basal beds of the Alamitos at most places.

In the northern part of the area, where the Alamitos Formation lies on the northern shale-sandstone-carbonate facies of the Porvenir Formation, the same combinations of criteria are useful to distinguish the contact because in places feldspathic conglomeratic sandstones of the upper part of the Porvenir are similar to some beds of the Alamitos and because percentages of feldspar in individual beds of both formations vary considerably, laterally. The basal part of the Alamitos at almost all places in the northern part of the area is thick (15–80 ft; 4.5–25 m), crossbedded, feldspathic, granule to pebble conglomerate. The feldspar content of the basal conglomerate varies considerably laterally from 5 to 20 percent. At places megascopic feldspar is as much as 30 percent, and the rocks are arkose. Unweathered pink feldspar is invariably present and conspicuous, although at places, weathered yellowish-gray to orange feldspar also is present. The stratigraphically lowest red- to maroon-weathering shale generally is near the base of the Alamitos and, north of Gallinas Creek, the basal conglomeratic sandstones of the Alamitos commonly contain lenticular red shale. At some outcrops shale is not present in the basal conglomerate, but lateral tracing for short distances usually discloses red shale interbeds.

At a few places in the northern part of the area, thin purple-weathering shale occurs near the top of the Porvenir, but the purple hue is distinctive and is of small lateral extent. The local occurrence of red shale in the Porvenir between La Cañada del Guajalote and Mora River has been described previously. The shale is in the interval of the sandstones of Fragoso Ridge, and the fusulinid data confirm that it occurs well below the position of the Alamitos.

The top of the Alamitos Formation in the southeastern part of the mountains is mapped at the top of the highest fossiliferous marine rocks or, locally, at the top of greenish- or reddish-gray shale that contains gray limestone nodules and is slightly above and conformable with the highest fossiliferous marine beds. At places, particularly in Las Dispensas syncline east and northeast of Hermit Peak, the middle and upper parts of the Alamitos contain thick fluviatile arkosic conglomerates interbedded with unfossiliferous red shales. These rocks are lithologically similar to parts of the Sangre de Cristo Formation, and it is difficult to separate the formations in areas of poor exposures. Nevertheless, mapping and tracing of various units (Baltz and O'Neill, 1986) shows that the uppermost part of the Alamitos, above the fluviatile conglomerates and unfossiliferous shales, contains fossiliferous marine limestone, sandy limestone, and greenish-gray to gray shale that are distinct from rocks of the Sangre de Cristo.

Areal stratigraphy and lithology

Southwestern part of area—The Alamitos Formation in the southwestern part of the area, north of San Jose, was examined mainly in reconnaissance. It consists of gray, greenish-gray, and some red shale, fossiliferous limestone and shaly to sandy limestone, and feldspathic to arkosic sandstone, all similar to the Alamitos in the Gallinas Creek area where the formation is relatively thick. The lower contact in the southwestern part of the area, as shown on Plate 1, was adapted mainly from the lower contact of the arkosic limestone member of the Madera Limestone mapped by Read et al. (1944).

The upper part of the Alamitos Formation at places north and west of San Juan was examined in detail to determine its age and its relation to the overlying Sangre de Cristo Formation. Outcrops of the south-dipping upper part of the Alamitos on the east and north sides of a meander loop of Pecos River (Pecos River section, Fig. 55) about 1.2 mi northwest of San Juan near the center of sec. 24 T14N R13E (USGS North San Ysidro quadrangle, just west of the area of Plate 1) are particularly significant because some of the rocks contain Late Pennsylvanian (late Virgilian) fusulinids. The general succession of beds is as follows:

Unit	Lithology	Thickness (ft)	(m)
	Sangre de Cristo Formation (lower part):		
5.	Sandstone, tan, medium- to coarse-grained, arkosic. Forms prominent ledge on south side of Pecos River; north of river, forms several ledges with intervening lenticular red shale interbeds.	30–40	9–12
	Alamitos Formation (upper part):		
4.	Shale, red and green.	10	3
3.	Interbedded lenticular arkosic sandstone, limestone-pebble conglomerate, sandy to oolitic limestone and minor amounts of shale. On east side of the river the lower 1–3 ft (0.3–0.9 m) of the unit is sandy, oolitic, bioclastic limestone that forms small ledges and grades laterally into calcareous fossiliferous sandstone. Unit weathers to ledgy slope. Basal oolitic limestone contains broken and abraded tests of the fusulinid *Triticites bensonesis* Ross and Tyrrell (f10319).	20	6
2.	Shale, greenish-gray with red bands, marly; forms slope.	30	9
1.	Limestone, gray, bioclastic, moderately fossiliferous. Bedding is irregular; beds are 0.5–2 ft (0.15–0.6 m) thick. Forms resistant ledge rising gently northward from river level at east side of meander loop, and resistant ledge above Quaternary alluvium north of river. North of river the unit contains the fusulinids *Triticites* aff. *T. whetstonensis* (f10320) and *Oketaella*? sp.	10+	3+

The underlying main part of the Alamitos Formation was not measured.

Near the southern margin of the area a thin section of the Alamitos Formation is present on the east flank of the Serafina monocline southwest of the concealed termination of the Bernal fault (Plate 1). The best exposure of these rocks is near the top of road cuts at the north side of Interstate Highway 25 about 700–1,000 ft (215–300 m) west of the overpass to Bernal. Here, the lower (western) part of the Alamitos strikes southwesterly, roughly parallel to the road, but stratigraphically higher (eastern) beds wrap around a southerly plunging anticlinal nose and strike in more northerly directions, as does the lower part of the overlying Sangre de Cristo Formation. South of the highway the Alamitos is mainly concealed by Quaternary deposits, but green to red shale and arkose and purplish-gray fossiliferous limestones of the formation crop out sporadically on the piñon- and juniper-covered gentle slopes to the southwest. The contact of the Alamitos and Sangre de Cristo Formations is concealed throughout this area, but it probably is not faulted at the highway. South of the highway the lower part of the Sangre de Cristo strikes westerly as does the Alamitos, and the gentle dip of the Alamitos indicates that it is thin as it is at the highway. Farther south, the Alamitos apparently is absent because of unconformity with the Sangre de Cristo Formation, as was discussed previously.

The outcrops of the Alamitos Formation along Interstate Highway 25 are on the southeast flank of the Paleozoic Bernal uplift and contain early Late Pennsylvanian (Missourian) fusulinids that are significant in determining the history of part of the uplift. A section (Bernal section, Fig. 55) measured in the sloping roadcuts north of the highway is as follows:

Unit	Lithology	Thickness (ft)	(m)
	Sangre de Cristo Formation (basal part):		
11.	Conglomerate, light-gray to tan, feldspathic. Matrix is very coarse sand and granules that are mainly angular to subangular gray quartz; about 15 percent of clasts is pink, angular feldspar. Contains many small pebbles of gray vein quartz and pink feldspar that range up to 0.25 inch (0.6 cm) diameter. Scattered throughout are dark-red and gray quartzite and vein-quartz pebbles as large as 1 inch (2.5 cm) diameter. Forms small ridge; basal several feet of unit concealed.	13	4
	Alamitos Formation:		
10.	Shale, red, silty clay. Forms poorly exposed slope.	20	6.1
9.	Concealed.	4	1.2
8.	Limestone, brown- to purplish-gray-weathering, bioclastic, silty, sandy. Composed mainly of crinoid-columnal fragments, but also contains fragments of bryozoans, brachiopods, and echinoids; many fossil fragments have thick, banded, algal coatings. Forms small platy ledges. Contains the fusulinid *Triticites* cf. *T. ohioensis* (f10322).	1	0.3
7.	Concealed.	5	1.5
6.	Limestone, brown, bioclastic, silty. Composed of fragments of brachiopods, crinoid columnals, and bryozoans. Forms minor ledge that weathers to thin limestone plates that litter the slope. Contains *Triticites* aff. *T. ohioensis* (f10321).	1	0.3
5.	Shale, olive-green; contains interbeds, 1–3 inch (2.5–7.6 cm) thick, of brown, bioclastic limestone. Poorly exposed	3.5	1.1
4.	Sandstone, dull-purple-weathering, feldspathic. Composed of angular to subangular, very coarse sand and granules; most clasts are quartz; about 10 percent of clasts is angular, pink feldspar. Forms small ledge.	1	0.3
3.	Shale, purplish-red, silty clay. Poorly exposed.	2	0.6
	Thickness of Alamitos Formation:	37.5	11.4
	Porvenir Formation (part):		
2.	Limestone, light-gray, nodular. Contains light olive gray shale interbeds; limestone nodules are 0.25–3 inches (0.6–7.6 cm) diameter and are about 60 percent of unit. Poorly exposed in gully near highway culvert.	5	1.5
1.	Limestone, light-buff-weathering, crinoid coquina. Upper 6 inches (15 cm) are oolitic. Weathers to masive, rounded ledge.	10+	5+

About 300 ft (90 m) southwest of the measured section (south of the highway), purplish-gray crinoidal limestone of the Alamitos Formation crops out at places. The limestone contains large, well-preserved tests of *Triticites* aff. *T. celebroides* (f10323) that also is of early Missourian age. Therefore, the thin Alamitos northwest of Bernal is equivalent to about the middle part of the Alamitos of areas farther north and is older than the late Virgilian upper part at Pecos River near San Juan. This indicates middle to late Desmoinesian and Virgilian erosion or nondeposition on the southern part of the Bernal uplift.

South-central part of area—Along the west limb of the Chapelle syncline from Bernal north almost to Cabo Lucero Creek, the Alamitos Formation was found at only two places (Plate 1; Figs. 55, 58) during reconnaissance and local detailed mapping. At most places the Alamitos is missing because of unconformity with the Sangre de Cristo Formation and, where the Alamitos is present, it is only 55–60 ft (16–18 m) thick. At locality 2 (Fig. 58) west of Tres Hermanos Creek, small limestone pebbles occur along with pink feldspar clasts in the basal conglomerate. At locality N (Fig. 58), in the middle branch of Dead Horse Canyon, the basal part of the Alamitos is purplish-gray, coarse-grained, sandy, bioclastic limestone that contains angular to subangular quartz granules and some pink feldspar granules. Above the basal beds at both localities, the Alamitos consists of greenish-gray, olive-gray, and some red to purple shale interbedded with thin sandy fossiliferous limestones and some nodular limestone. The general aspect of these rocks is similar to the Missourian part of the Alamitos at the Bernal section, but we did not find fusulinids in the Alamitos on the west limb of the Chapelle syncline from northwest of Bernal to north of Cabo Lucero Creek. The presence of fusulinid-bearing outcrops of the marker zone of the Porvenir at locality 2 indicates only that the overlying remnants of the Alamitos are late Desmoinesian or younger.

At Dead Horse Canyon (loc. N) and Falls Creek (loc. 5) most of the red shale, arkose, and thin limestone that previously were assigned to the arkosic limestone member of the Madera (the Alamitos of this report) by Read et al. (1944, locs. 26 and 27) are unfossiliferous and are the lower part of the Sangre de Cristo Formation. Dense, light-gray, ledge-forming limestones well above the base of the Sangre de Cristo are unfossiliferous and are similar to other limestones observed elsewhere at several stratigraphic positions well above the base of the Sangre de Cristo. (For example, see Fig. 69.) The Alamitos is absent at Falls Creek.

North of Falls Creek the Alamitos again is present, and it thickens rapidly northward. At Cabo Lucero Creek (loc. O, Fig. 58) the Alamitos Formation is 291 ft (89 m) thick; it contains a thick unit of feldspathic sandstone, and its general aspect is more like that in the Gallinas Creek area (loc. 6, Fig. 58).

Northeast, east, and southeast of the upper part of Cabo Lucero Creek the Alamitos thickens rapidly into the southern part of Las Gallinas syncline (Baltz, 1972). At Tecolote Creek near Blue Haven Camp the lithology and thickness of the entire formation are generally similar to the Alamitos farther north near Gallinas Creek (loc. 6, Fig. 58). Late Pennsylvanian (Virgilian) fusulinids (f10277) occur about 130 ft (40 m) below the top of the Alamitos southeast of Blue Haven Camp, and Early Permian (early Wolfcampian) fusulinids (f13212, f13213) occur near the top at locality 6 and east of the Chapelle syncline north of San Geronimo. These fossil occurrences are discussed in a following part of this report.

Southeastern part of area—East of San Geronimo the west-dipping basal part of the Alamitos is exposed along Cañon Mesteño (Plate 1) where it is a coarse-grained, moderately feldspathic, conglomeratic sandstone that contains pink feldspar and vein-quartz pebbles. Thin red shale occurs near the base where New Mexico Highway 283 crosses Cañon Mesteño and thin red shale is present at the base about 0.5 mi (0.8 km) southwest of the highway. The ledge-forming conglomeratic sandstone is locally as much as 20 ft (6 m) thick, and it thickens and thins in response to a channeled unconformity at its base. The basal sandstone persists southward to the south side of Tecolote Creek where it and overlying greenish-gray to red shale, fossiliferous limestone, and feldspathic sandstones of the Alamitos are beveled and cut out by feldspathic to arkosic conglomerate of the Sangre de Cristo Formation a little more than 1 mi (1.7 km) southeast of the confluence of San Pablo and Tecolote Creeks (Plate 1).

Near the crest of the hill at the east side of Cañon Mesteño, along New Mexico Highway 283, the basal conglomeratic sandstone of the Alamitos Formation grades locally into sandy slightly feldspathic limestone and limy sandstone. Here, the Alamitos lies on the fusulinid-bearing marker zone of the Porvenir exposed in road cuts. To the east, widespread remnants of the basal sandstone of the Alamitos occur on the uplands south and north of the highway (Plate 1) where higher beds mainly have been stripped away by Cenozoic erosion. Although the outcrops are obscured at places by Quaternary pediment deposits, the basal sandstone can be traced eastward to La Reunion syncline. In the easternmost outcrops in this syncline along Highway 283 the sandstone grades into sandy limestone containing pink feldspar that lies unconformably on the lower part of the Porvenir Formation. Remnants of the lower part of the Alamitos, including the basal conglomeratic sandstone, occupy the axial part of La Reunion syncline. The rocks above the basal sandstone are gray and olive-gray shale that contain interbedded sandstone, limy sandstone, and thin gray limestone. The late Desmoinesian fusulinid *Beedeina sulphurensis* (f10324) was found in limestone about 75 ft (23 m) above the base of the Alamitos just east of the syncline axis about 0.9 mi (1.5 km) south of Highway 283. The presence of the fusulinids confirms the lithologic correlation of this part of the Alamitos with the lower part farther north.

On the east flank of La Reunion syncline, about 1 mi (1.6 km) north of the county road to Ojitos Frios, the basal sandstone wedges out northward in a small area. Here, stratigraphically higher limestone and shale of the lower part of the Alamitos Formation can be distinguished from the Porvenir only by stratigraphic position. In the southernmost outcrops of the Alamitos in the syncline, the upper part of the formation is poorly exposed red shale containing interbeds of thin gray and olive-gray shale, limestone nodules, and thin fossiliferous limestone. The base of this upper part of the formation is thin conglomeratic feldspathic sandstone containing limestone pebbles that lies unconformably on the lower part east of the syncline axis about 0.5 mi (0.8 km) north of the county road. Farther east the Alamitos is truncated entirely by the Sangre de Cristo Formation, as it is on the west flank of the syncline west of Tecolote Creek and northwest of Ojitos Frios (Plate 1). West of Tecolote Creek, northwest of Ojitos Frios, a small patch of limestone-pebble conglomerate of the Alamitos is preserved beneath the Sangre de Cristo Formation on the west flank of the Ojitos Frios anticline.

South of Ojitos Frios the Alamitos Formation is exposed on both flanks of the Ojitos Frios anticline and at one place on the crest. On the east flank, at locality M (Fig. 59), the Alamitos is only about 70 ft (21 m) thick. The basal part, tentatively correlated with the (upper Desmoinesian) conglomeratic sandstone at the base farther north, is lenticular coarse-grained to pebbly calcareous sandstone and sandy limestone, about 5 percent of which is sand, granules, and small pebbles of subangular pink feldspar. The basal part is overlain by maroon and olive-gray marly shale, in turn overlain by limestone-pebble conglomerate about 11 ft (3.4 m) thick (Figs. 60, 61) that contains thin lenses of bioclastic limestone. The limestones contain broken, thick-walled brachiopods and fusulinids (f10275) of Early Permian (early Wolfcampian) age. Inasmuch as the Missourian and Virgilian rocks are absent, an intraformational unconformity exists below the limestone conglomerate. The conglomerate is succeeded upward by poorly exposed red marly shale containing limestone nodules and concretions that is about 43 ft (13 m) thick and is overlain unconformably by the Sangre de Cristo Formation. Immediately west of locality M the rocks are concealed by Quaternary pediment deposits, but on the crest of the Ojitos Frios anticline the Porvenir is overlain by poorly exposed red shale that probably is the upper unit of the Alamitos. These relations indicate that all but the uppermost part of the Alamitos wedges out locally on the east flank of the anticline, suggesting a local intraformational angular unconformity.

Southwest of locality M, scattered poor exposures of limestone pebbles on a broad Quaternary pediment might be remnants of the limestone-pebble conglomerate. About 0.4 mi (0.6 km) south of section M, the basal conglomeratic sandstone of the Alamitos is exposed on the crest of the Ojitos Frios anticline and on its west flank. The sandstone is overlain by greenish-gray shale and interbedded thin fossiliferous limestones and thin sandstones that are well exposed along the banks of the lower part of Cañon Pino Real. These beds are overlain by thick red shale equivalent to the upper part of the Alamitos at locality M, but the limestone-pebble conglomerate is absent. The southernmost exposures of the Alamitos on Ojitos Frios anticline are the upper red shale unit that laps onto the Upper Mississippian Tererro Formation and in turn is overlapped by the basal conglomerate of the Sangre de Cristo Formation which farther south lies on Precambrian rocks of the core of the anticline.

The internal stratigraphic relations of the Alamitos Formation in the vicinity of the Cenozoic Ojitos Frios anticline and La Reunion syncline show that the southward thinning of the Alamitos on the west flank of the Paleozoic Tecolote uplift is mainly intraformational and is only partly the result of angular unconformity with the Sangre de Cristo Formation. The upper Desmoinesian part of the Alamitos seems to have been deposited widely, but Missourian and Virgilian rocks apparently are absent from the southeastern part of the area because of erosion or nondeposition. The Lower Permian (lower Wolfcampian) rocks indicate a final partial inundation by shallow seas.

Southeastern front of mountains—Near the east front of the mountains west of Agua Zarca the Alamitos is preserved in a minor synclinal basin whose northwest-trending axis (Plate 1) is concealed beneath Quaternary alluvium along Agua Zarca Creek. The formation is composed of greenish-gray and red shale that contains interbeds of fossiliferous gray limestone, sandy limestone, and limy sandstone. Interbeds of arkosic, very coarse to conglomeratic sandstone also are common in the axial and southwestern part of the syncline. The conglomerates contain pebbles of vein quartz and pebbles of pink feldspar, some of which are as much as 1 inch (2.5 cm) across. The clasts are angular to subangular. The east-dipping upper part of the Alamitos, exposed along New Mexico State Highway 283 about 0.6 mi (0.95 km) west of Agua Zarca, is a red-weathering shale containing abundant limestone nodules. This upper part is similar to the Wolfcampian upper shaly part at locality M south of Ojitos Frios and is overlain by ledge-forming gravelly arkoses of the Sangre de Cristo Formation. However, west of Agua Zarca, the Alamitos is about 200 ft (60 m) thick, which is con-

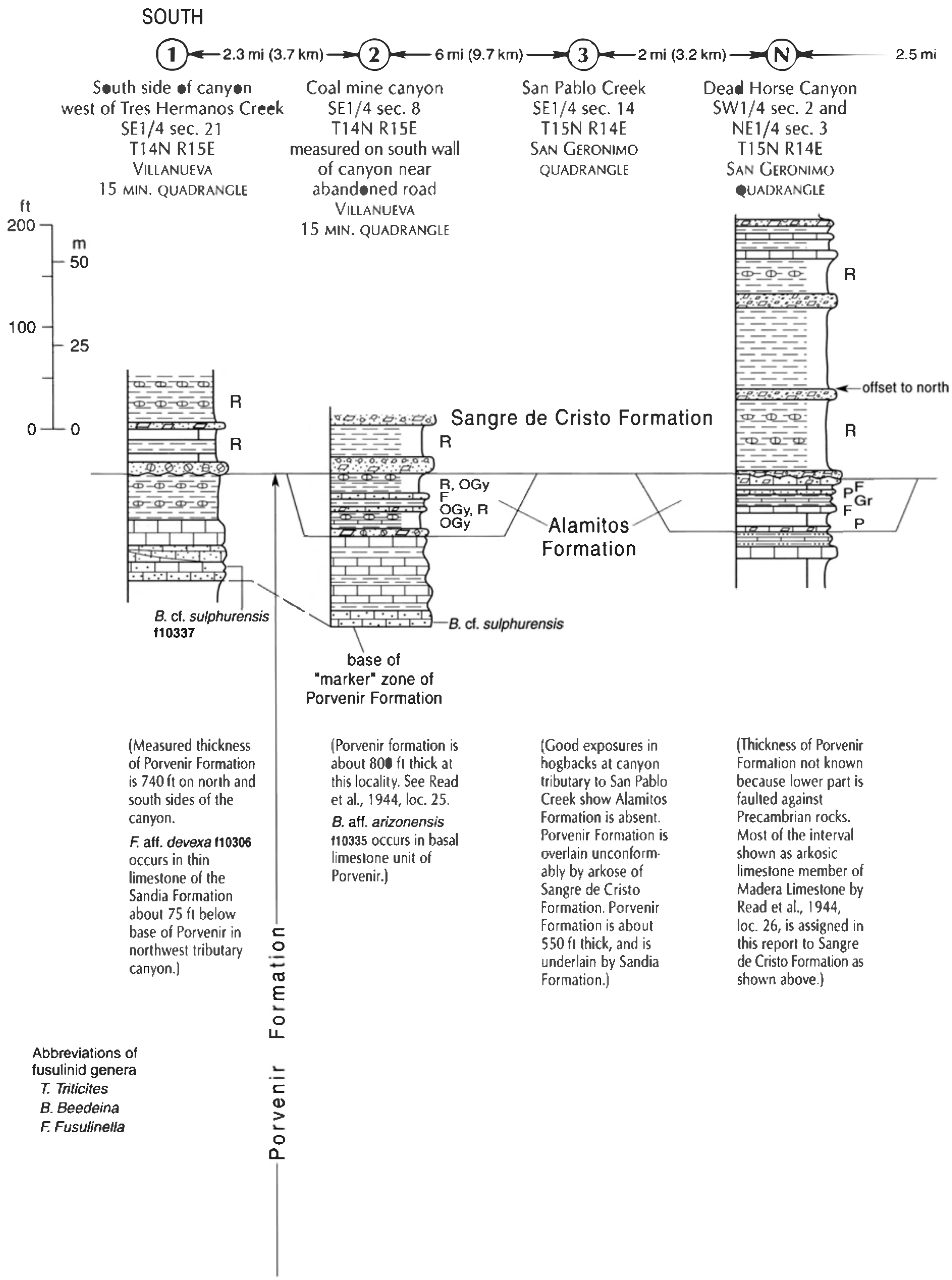
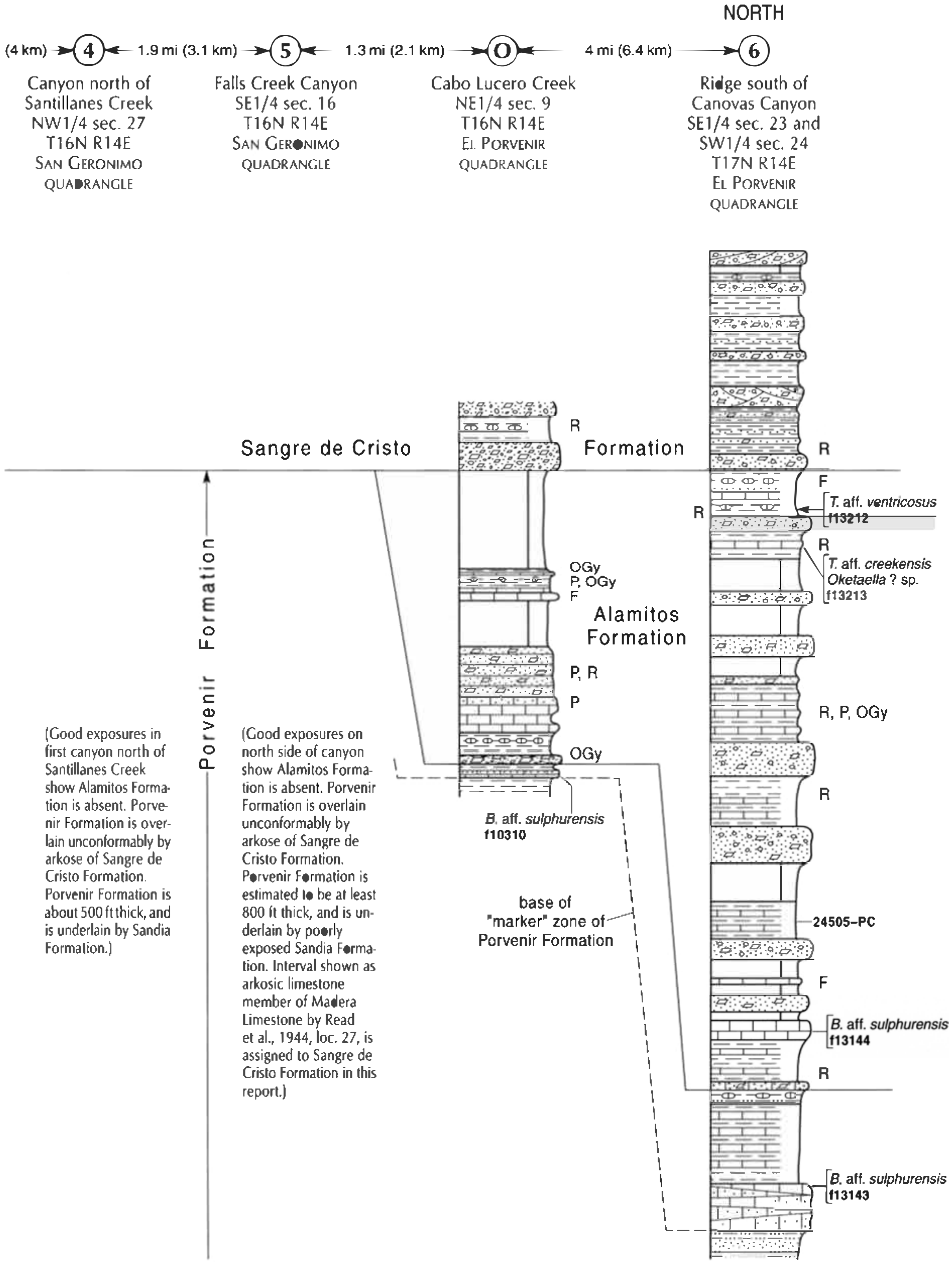


FIGURE 58—Stratigraphic sections of the Alamitos Formation and notes on the Porvenir Formation, Tres Hermanos Creek–Gallinas Creek area. Localities of measurement and line of section are shown in Figure 55. Lithologic symbols are explained in Figure 9.


NORTH
(4 km)
4
1.9 mi (3.1 km)
5
1.3 mi (2.1 km)
O
4 mi (6.4 km)
6
Canyon north of Santillanes Creek NW1/4 sec. 27 T16N R14E San Geronimo quadrangle
Falls Creek Canyon SE1/4 sec. 16 T16N R14E San Geronimo quadrangle
Cabo Lucero Creek NE1/4 sec. 9 T16N R14E El Porvenir quadrangle
Ridge south of Canovas Canyon SE1/4 sec. 23 and SW1/4 sec. 24 T17N R14E El Porvenir quadrangle
Sangre de Cristo Formation
Porvenir Formation
Alamitos Formation
R
F
T. aff. ventricosus f13212
T. aff. creekensis Oketaella ? sp. f13213
OGy
P, OGy
P, R
P
R, P, OGy
B. aff. sulphurensis f10310
base of "marker" zone of Porvenir Formation
24505-PC
B. aff. sulphurensis f13144
B. aff. sulphurensis f13143
(Good exposures in first canyon north of Santillanes Creek show Alamitos Formation is absent. Porvenir Formation is overlain unconformably by arkose of Sangre de Cristo Formation. Porvenir Formation is about 500 ft thick, and is underlain by Sandia Formation.)
(Good exposures on north side of canyon show Alamitos Formation is absent. Porvenir Formation is overlain unconformably by arkose of Sangre de Cristo Formation. Porvenir Formation is estimated to be at least 800 ft thick, and is underlain by poorly exposed Sandia Formation. Interval shown as arkosic limestone member of Madera Limestone by Read et al., 1944, loc. 27, is assigned to Sangre de Cristo Formation in this report.)

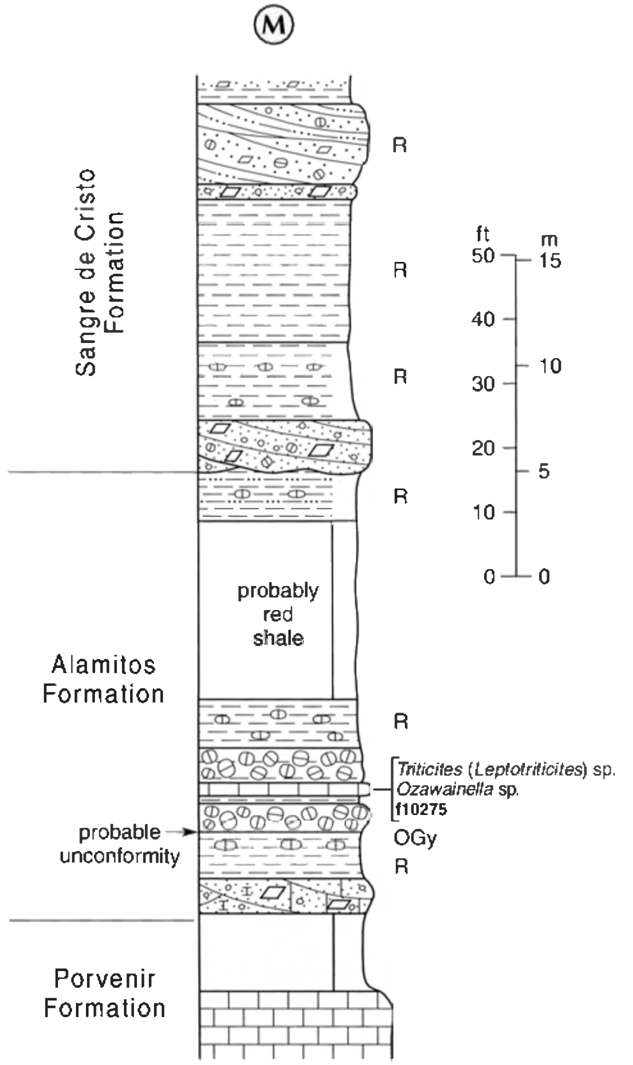


FIGURE 59—Stratigraphic section of Alamitos Formation, locality M, east limb of Ojitos Frios anticline about 0.6 mi (0.95 km) south of Ojitos Frios. Locality of measurement shown in Figure 55. Symbols are explained in Figure 9.

siderably thicker than near Ojitos Frios. About 0.6 mi (0.95 km) west of Agua Zarca and just north of Highway 283, sandy feldspathic limestone in the Alamitos stratigraphically below the upper red shale unit contains abundant *Beedeina sulphurensis* (f10274), indicating that the lower (Desmoinesian) part is present here as it is in La Reunion syncline and locally at locality M.

Along the sharply folded southwest margin of the synclinal basin south of Agua Zarca Creek the Alamitos laps onto Precambrian rocks (Plate 1). North and south of Agua Zarca the Alamitos is overlapped by the Sangre de Cristo Formation, which lies on Precambrian rocks at the south (Fig. 32). Therefore, the northwest-trending basin in which the Alamitos is preserved is a pre-Sangre de Cristo fold on the Tecolote uplift, indicating a structural history similar to that of the area south of Ojitos Frios.

Gallinas Creek—The Alamitos Formation on the west limb of Las Gallinas syncline in the western part of the Gallinas Creek area is as much as 645 ft (197 m) thick (locs. 6, D, P, 7, Fig. 62). It contains fusulinids of late Desmoinesian, Missourian, Virgilian, and Early Permian (early Wolfcampian) ages. More than half the formation is shale, but thick units of coarse-grained to conglomeratic, feldspathic to arkosic sandstone are present throughout, and thin fossiliferous limestones and sandy limestones are common. The basal part is thin, feldspathic, coarse-grained to granule conglomerate, grading laterally into sandy limestone. Both lithologic types contain the stratigraphically lowest fresh, angular to subangular, pink feldspar sand and granules. The feldspar content ranges from 5 to 20 percent. Red shale commonly occurs just above the basal sandstone.

Most of the formation is marine as shown by fossils in the shale and limestone, but some trough-crossbedded, feldspathic, conglomeratic sandstones and nonfossiliferous, red to purple, silty, sandy shales may be fluvial nonmarine sediments. Most of the sandstones seem to be broadly lenticular and some of them may have been deposited as marine, distal parts of subaerial alluvial fans. The clasts of most of these sandstones are coarse grains and granules; some are pebbles ranging up to 0.25 inch (0.6 cm) in diameter; pebbles of vein quartz that are 1–2 inch (2.5–5 cm) in diameter are scattered through some beds. Feldspar content varies laterally in most beds, but the general range is 10–15 percent; as much as 30 percent of some beds is fresh-appearing, pink and tan potassium feldspar that ranges from medium grains to 0.5-inch (1.3-cm) pebbles. Some beds are moderately micaceous. Sorting generally is poor, many clasts are irregularly shaped and subangular, and some thicker beds have a grus-like appearance (Fig. 56).

Along the east margin of the mountains south of Montezuma the lower (late Desmoinesian) part of the Alamitos is preserved in the vicinity of Lime Canyon (loc. G., Fig. 62; Fig. 85) where it lies unconformably on the lower part of the Porvenir Formation and is overlain unconformably by the Sangre de Cristo Formation. The Alamitos here is similar to the lower part of the formation in the western part of the Gallinas Creek area. The basal part is feldspathic conglomeratic sandstone that thickens and thins because of channeling at its base. In the upper part of section G red shale occurs above the sandstone. Notably, several units of feldspathic to arkosic sandstone and sandy limestone at Lime Canyon have northerly inclined crossbedding and cross-lamination that suggest a southerly source of clastic sediments, probably the southern part of the Tecolote uplift south of Aqua Zarca. Northward from the vicinity of Montezuma, for about 6 mi (9.6 km), the stratigraphic interval of the Alamitos is cut out by the Montezuma fault (Plate 1; Fig. 32; Baltz, 1972).

Sapello River–Manuelitas Creek—In Las Dispensas syncline northeast of Hermit Peak the Alamitos Formation thickens northward and reaches its maximum thickness (1,828 ft; 557 m) in the area in the Paleozoic Rociada Basin (sec. H, Fig. 63; Plate 4). As the thickness increases northward the proportion of thick feldspathic to arkosic conglomerate increases throughout the formation, although most of the rocks are shale. The basal part of the Alamitos is crossbedded feldspathic to arkosic conglomerate as far north as the northern end of Las Dispensas syncline north of the San Miguel–Mora County line, and locally is as much as 40–80 ft (12–25 m) thick. The conglomerate generally contains thin lenticular red shale interbeds and, at places, thick lenses of greenish-gray shale.

The Alamitos Formation in the Cenozoic Las Dispensas syncline contains relatively thick units of olive-gray shale and thin highly fossiliferous marine limestones. However, some of the thick feldspathic to arkosic conglomerates are broadly lenticular deposits with channeled bases and probably are nonmarine. Feldspathic conglomerates and gravelly arkoses, some of which contain limestone pebbles as well as quartzite, granite-gneiss, and granite pebbles, range in thickness from a few feet to as much as 120 ft (37 m). These

FIGURE 60—Limestone-pebble conglomerate in Alamitos Formation (PIPa) at locality M. Thin, ledge-forming limestone lens in middle of conglomerate (at top of pack) contains Early Permian fusulinids (f10275). Small ledge near top of view is basal feldspathic conglomerate of Sangre de Cristo Formation (Psc).

units have large-scale trough crossbedding, scour-and-fill structures, and some contain unfossiliferous lenticular, red, silty and sandy shale. Thick units of this kind are well exposed in the upper part of the formation near Deer Creek and Rito Chavez just east of Hermit Peak, and they are well exposed in the middle and upper parts of the formation on the north sides of Sapello River and Manuelitas Creek (secs. H and 8, Fig. 63) east of the axis of Las Dispensas syncline.

The largest pebbles observed in the Alamitos are in lenses in feldspathic to arkosic conglomerates in the middle and upper parts of the formation near Deer Creek, Rito Chavez, and Sapello River in Las Dispensas syncline (Plate 1). Fresh, pink, subangular, feldspar pebbles are mostly less than 0.25 inch (0.6 cm) diameter, but they range up to 0.5 inch (1.3 cm). Purple and gray quartz pebbles are irregularly shaped but subrounded, and many are as large as 2 inches (5 cm) across. The lithology of the thick units of feldspathic to arkosic conglomerate suggests proximity to a source of Precambrian rocks. The bedding characteristics suggest that the conglomerates and at least part of the unfossiliferous red shale are mainly subaerial fans that episodically were built rapidly into a subsiding marine basin.

The upper part of the Alamitos Formation in Las Dispensas syncline is laterally varying gray, greenish-gray, and red shale that contains thin beds of fossiliferous limestone and thin to thick feldspathic sandstone and pebbly conglomerates. Many of the limestones contain much feldspathic coarse sand and granules; sandy limestone and limy sandstone intergrade laterally.

Near the eastern front of the mountains, generally between Sapello River and Manuelitas Creek, the lower 600 ft (180 m), approximately, of the Alamitos Formation consists of thick, ridge-forming, feldspathic granule to pebble conglomerates interbedded with gray and olive-gray-weathering shale and thin fossiliferous limestone (loc. 9, Fig. 63). Some conglomerates are notably poorly sorted; they contain angular to subangular clasts of quartz, vein quartz, granite, and fresh-appearing pink feldspar cleavage fragments ranging from medium grains to pebbles as much as 0.5 inch (1.3 cm) across. Red shale occurs locally at the base of the sequence and at several higher stratigraphic positions. Southwest of the junction of New Mexico Highways 266 and 94, *Beedeina sulphurensis* (f10325) occurs in limestone above red shale near the base of this sequence. This fusulinid (f10129, f10130) occurs also at the junction of the highways, above the sequence, indicating that the lower part of the Alamitos west of the Sapello fault is late Desmoinesian. *B. sulphurensis* (f10138, f10326) occurs in the Alamitos west of the Sapello fault also at the north side of the Sapello River valley about 2,200 ft (670 m) south-southwest of the highway junction (loc. B7705, Baltz and O'Neill, 1986). Notably, the Desmoinesian rocks here are as thick as the entire (Desmoinesian to Wolfcampian) Alamitos Formation in the Gallinas Creek area.

Near the eastern front of the mountains west of Sapello, most of the upper part of the Alamitos Formation is concealed by Quaternary deposits (Fig. 86) and soil, and part is cut out by the Sapello fault (Plate 1; Fig. 64). The parts that

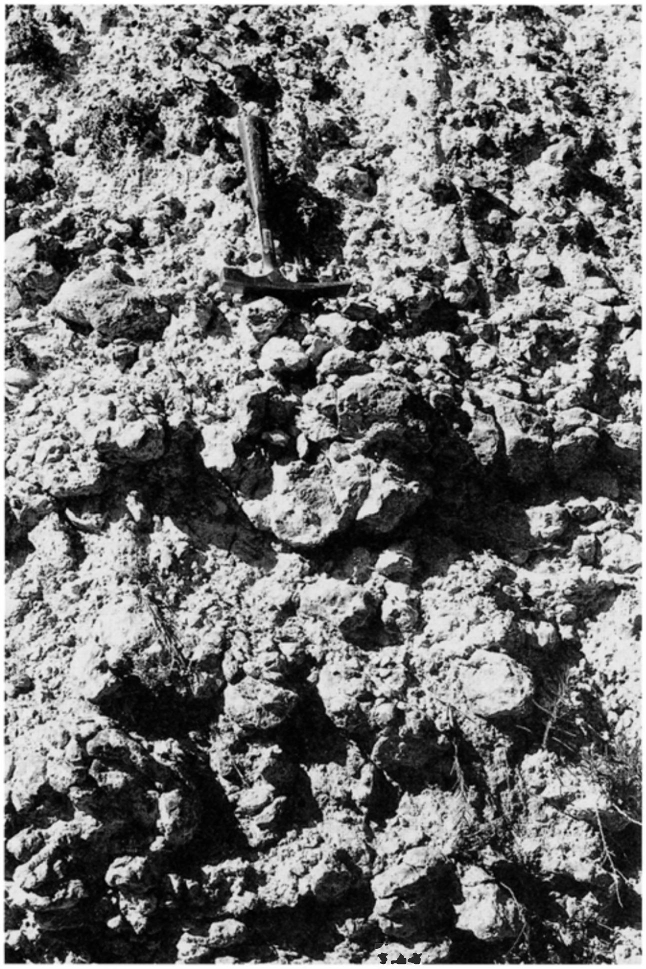


FIGURE 61—Close view of upper unit of limestone-pebble conglomerate in Alamitos Formation at locality M showing rude layering. Contorted layering results from differential compaction of pebbles in marly clay matrix. Hammer shows scale.

can be observed are gray and olive-gray-weathering shale and interbedded gray fossiliferous limestone, some red shale, and some feldspathic to arkosic sandstones. Gray shale near the top of the formation in road cuts near the junction of Highways 94 and 266 and just east of the Sapello fault contains Late Pennsylvanian (probably Virgilian) megafossils.

North of Manuelitas Creek, along the eastern front of the mountains, the lower sequence of arkosic sandstones, shale, and thin limestones of the Alamitos crop out at places as overturned beds in hogback ridges north and south of the San Miguel–Mora County line, but in most of this area the Alamitos and the lower part of the Sangre de Cristo Formation are cut out by the Sapello fault as far north as Rito Cebolla (Plate 1).

Rito Cebolla–Mora River—The Alamitos is exposed fairly well on the terrace at the north side of Rito Cebolla (loc. I, Fig. 65; Fig. 88); however, its top is faulted against the lower part of the Sangre de Cristo Formation, as indicated by greatly sheared and slickensided sandstone in the eastern part of the outcrop. The base is poorly exposed, but the Alamitos seems to lie in depositional contact on rocks tentatively assigned to the uppermost part of the Porvenir Formation. The rocks assigned to the Alamitos are only about 265 ft (81 m) thick with an unknown amount of the upper part (and lower part of the Sangre de Cristo Formation) faulted out. About 2,000 ft (600 m) to the north, the fault at the top of the Alamitos seems to die out (Fig. 88) and the formation is about the same thickness as at Rito Cebolla.

The lithology of the Alamitos Formation at Rito Cebolla is generally similar to the lower part of the formation farther south. At the base is a thick unit of very coarse grained to pebbly feldspathic conglomerate that contains yellowish-gray and pink subangular feldspar sand, granules, and pebbles, some of which are as much as 0.5 inch (1.3 cm) across. The conglomerate contains scattered gray quartzite pebbles as much as 2 inch (5 cm) across. A bed of fossiliferous marine limestone occurs near the base of the conglomerate. Above the conglomerate is a persistent unit of greenish-gray to red and purplish-gray shale that contains interbeds of fossiliferous gray limestone and thin coarse-grained to conglomeratic feldspathic sandstone. This general lithologic character persists northward, and late Desmoinesian fusulinids occur above the basal conglomerate (Fig. 65).

The Alamitos Formation thins northward from Rito Cebolla because rocks younger than Desmoinesian are thin or absent. Although exposures are relatively poor in the hogbacks, there are outcrops of the entire formation and its upper and lower contacts that indicate the thinning is stratigraphic rather than being the result of Cenozoic faulting. South of La Cañada del Guajalote the Alamitos begins to thicken northward. Most of the thickening occurs in the Desmoinesian lower part as shown by the occurrence of late Desmoinesian fusulinids about 600 ft (180 m) above the base of the formation at Mora River (sec. K, Fig. 65). The Late Pennsylvanian upper part also is present and thickens northward from near La Cañada del Guajalote to Mora River.

At Mora River and farther north the Alamitos Formation is olive-gray shale interbedded with feldspathic and arkosic coarse-grained sandstones and pebble conglomerates and thin fossiliferous limestones (sec. K, Fig. 65). Red- to purple-weathering shale occurs near the base (Fig. 66) and at intervals higher in the formation. Many of the shales are silty and are commonly micaceous as are many of the finer grained sandstones. The top of the formation is at the top of a unit of olive-gray shale that contains the stratigraphically highest marine fossils (collection 27356–PC) and also contains thin micaceous sandstone beds and green claystone and silty shale beds (Fig. 67). From La Cañada del Guajalote northward to the north edge of the area (Plate 1) the top of the Alamitos was mapped (Baltz and O'Neill, 1984) at the top of similar greenish-gray and green clay and shale beds that appear to be correlative, although exposures are such that the contact cannot be traced precisely at some places.

Although the Alamitos at Mora River and to the north is partly or mainly marine, many of its beds (particularly, near the middle) are highly feldspathic to arkosic, crossbedded conglomeratic sandstones that have channeled bases and scour-and-fill structures and are probably nonmarine. The clasts of the sandstones generally are very coarse to granule size; pebbles are commonly 0.1–0.5 inch (0.3–1.3 cm) in diameter, and occasionally are as much as 1–2 inches (2.5–5 cm) in diameter. Granules and pebbles are mainly subangular and are mainly quartzite, but fresh-appearing gray and pink feldspar commonly constitutes 10–15 percent of the clasts; in some beds 20–30 percent of the clasts is feldspar. Granules and small pebbles of green deeply weathered amphibolite schist, muscovite schist, and other metamorphic rock fragments are common in some beds but generally are a small fraction of the clasts. Muscovite is a common constituent. The lithology of these rocks suggests a nearby source of Precambrian metamorphic rocks and granite or granitic pegmatites, probably those in the El Oro Mountains area.

The Alamitos at the Amoco "A" and "B" no. 1 Salman

Ranch wells in the subsurface at the east is generally similar to the outcropping rocks from Mora River north (Plate 3). However, the feldspathic sandstones and arkoses seem to be somewhat finer grained at the wells, ranging from fine- to coarse-grained. Samples from the upper part of the formation at the "A" well are contaminated by casing cement and fibrous material. These samples contain conspicuous amounts of small gypsum chips and traces of anhydrite, suggesting that anhydrite beds occur in the upper part of the Alamitos Formation locally. However, gypsum was not observed in this interval in samples from the "B" well, although it occurs stratigraphically higher in rocks assigned to the Sangre de Cristo Formation at the "B" well and at the "A" well also. The gypsum may be a product of hydration of anhydrite during drilling. Gypsum or anhydrite were not observed anywhere at outcrops of the Alamitos, but anhydrite occurs in the southern part of the Las Vegas Basin at the Continental no. 1 Leatherwood–Reed well (Fig. 18).

Contact with overlying rocks

The nature of the contact of the Alamitos Formation and the overlying Sangre de Cristo Formation varies throughout the area of this report. In the southern part of the area, along both flanks of the Paleozoic Bernal uplift, the contact is clearly a low-angle unconformity that bevels 400–600 ft (120–180 m) of the Alamitos in about 2 mi (3.2 km). However, in the adjacent Paleozoic San Geronimo Basin, roughly from San Geronimo to Gallinas Creek, where the Alamitos is relatively uniform in thickness and where its rocks are late Desmoinesian through earliest Permian age, the contact seems to be structurally conformable although the basal arkoses of the Sangre de Cristo channel slightly into the uppermost part of the Alamitos. In the southwestern part of the area, north and northwest of San Jose, the contact is a slightly channeled disconformity, and the youngest marine rocks of the Alamitos are Late Pennsylvanian (Virgilian).

On the southwestern margin of the Paleozoic Tecolote uplift most of the thinning of the Alamitos is intraformational between the late Desmoinesian lower part and the earliest Permian upper part, indicating nondeposition or uplift and erosion in Missourian and Virgilian time. North and south of Ojitos Frios the Alamitos is absent locally because of angular unconformity with the Sangre de Cristo on an echelon series of short, low, northwest-trending anticlines and synclines that do not affect, or only slightly affect, the base of the Sangre de Cristo. At least the northern part of the area of the Cenozoic La Reunion syncline was a shallow syncline also in earliest Permian time. The Cenozoic Ojitos Frios anticline and La Reunion syncline, on which the Sangre de Cristo is folded, are superposed on the Paleozoic echelon structures and represent Cenozoic rejuvenation of the general areas of the Paleozoic folds. However, the Cenozoic fold axes transect the older fold axes.

The northwest-trending synclinal basin, in which the Alamitos Formation is preserved west of Agua Zarca (Plate 1), seems to be primarily a Late Pennsylvanian structure on the central part of the Tecolote uplift. About 0.8 mi (1.3 km) southwest of Agua Zarca, the Alamitos on the south limb of the basin strikes at high angle to the northerly strike of the Sangre de Cristo Formation, indicating angular unconformity. Farther south the Sangre de Cristo overlaps the Alamitos to lie on Precambrian rocks.

Along the eastern front of the mountains, between Agua Zarca and Montezuma, the Alamitos mainly is missing from the Tecolote uplift because of low-angle unconformity with the Sangre de Cristo. To the northwest, on both limbs of the Medina syncline west of Gallinas (Plate 1; Baltz, 1972), the Alamitos thins abruptly beneath the Sangre de Cristo Formation, indicating that the syncline and the parallel Cañon del Medio anticline both are primarily Late Pennsylvanian or Early Permian structures.

In the Paleozoic Rociada Basin the contact generally is poorly exposed, but where seen it is a channeled disconformity. At Manuelitas Creek (loc. H, Fig. 63) limestone pebbles occur in the basal arkosic conglomerate of the Sangre de Cristo. Megafossils near the top of the Alamitos suggest a Virgilian age, but the data are not adequate to determine whether latest Pennsylvanian or earliest Permian rocks are present. However, the upper part of the Alamitos is transitional from marine to nonmarine conditions in the sense that the highest marine shales and limestones of the Alamitos are very sandy. These factors suggest that deposition may have been continuous, or nearly so, from the Alamitos into the Sangre de Cristo, at least in the deep part of the Paleozoic Rociada Basin northeast of Hermit Peak (Plate 4) and possibly also on the Manuelitas saddle northwest of Sapello.

In the northern part of the area, at the front of the mountains north of Rito Cebolla, only thin remnants of the Desmoinesian part of the Alamitos are present, and the contact with the Sangre de Cristo probably is an angular unconformity on a Late Pennsylvanian anticline (Plate 4) for about 3.5 mi (5.6 km) north of Rito Cebolla. However, from there northward the Alamitos thickens internally, and at Mora River the upper part contains Late Pennsylvanian (probably Missourian) megafossils. From La Cañada del Guajalote north, where the uppermost part of the Alamitos at many places is green to olive-green shale and interbedded thin sandstones, the contact with the Sangre de Cristo probably is structurally conformable although locally disconformable because of slight channeling at the base of the rocks assigned to the Sangre de Cristo.

At Mora River the lower 700 ft (215 m), approximately, of the Sangre de Cristo Formation is nonmarine, thick, ridge-forming, reddish- to purplish-brown-weathering arkoses and interbedded shale (Fig. 67; Plate 3). A microflorule collected from about 500 ft (150 m) above the base of this sequence is probably Late Pennsylvanian (Virgilian?) in age. This suggests that, although the sequence is nonmarine and is included in the Sangre de Cristo, most of it is equivalent in age to the upper part of the Alamitos at Manuelitas Creek and farther south.

South of Mora River this Upper Pennsylvanian lower sequence of reddish-brown and purplish-brown arkoses of the Sangre de Cristo Formation thins, and about three-quarters of a mile south of La Cañada del Guajalote it is indistinguishable from other arkoses and shales in the lower part of the Sangre de Cristo. This southward thinning, and the concomitant southward thinning in the Alamitos, suggest wedge out of the Pennsylvanian lower part of the Sangre de Cristo on the north flank of the Late Pennsylvanian anticline north of Rito Cebolla (Plate 4C). If so, the stratigraphic relations are similar to those in the southern part of the area where the post-Desmoinesian part of the Alamitos thickens intraformationally away from structural features that were tectonically active during its deposition.

Previous reports (for example, Read and Wood, 1947, fig. 1; Baltz and Bachman, 1956, fig. 2; Sutherland, 1963, fig. 6) presented regional-correlation diagrams that show the lower part of the nonmarine Sangre de Cristo Formation becoming progressively older northward because of depositional intertonguing with the mainly marine upper part of the Madera (the part equivalent to the Alamitos Formation). The stratigraphic model of Baltz and Bachman (1956, fig. 2 and p. 99–100) for the eastern part of the mountains was based on the recognition that thick arkoses become more common northward in all the Pennsylvanian rocks, and that north of Mora River marine shale and limestone containing

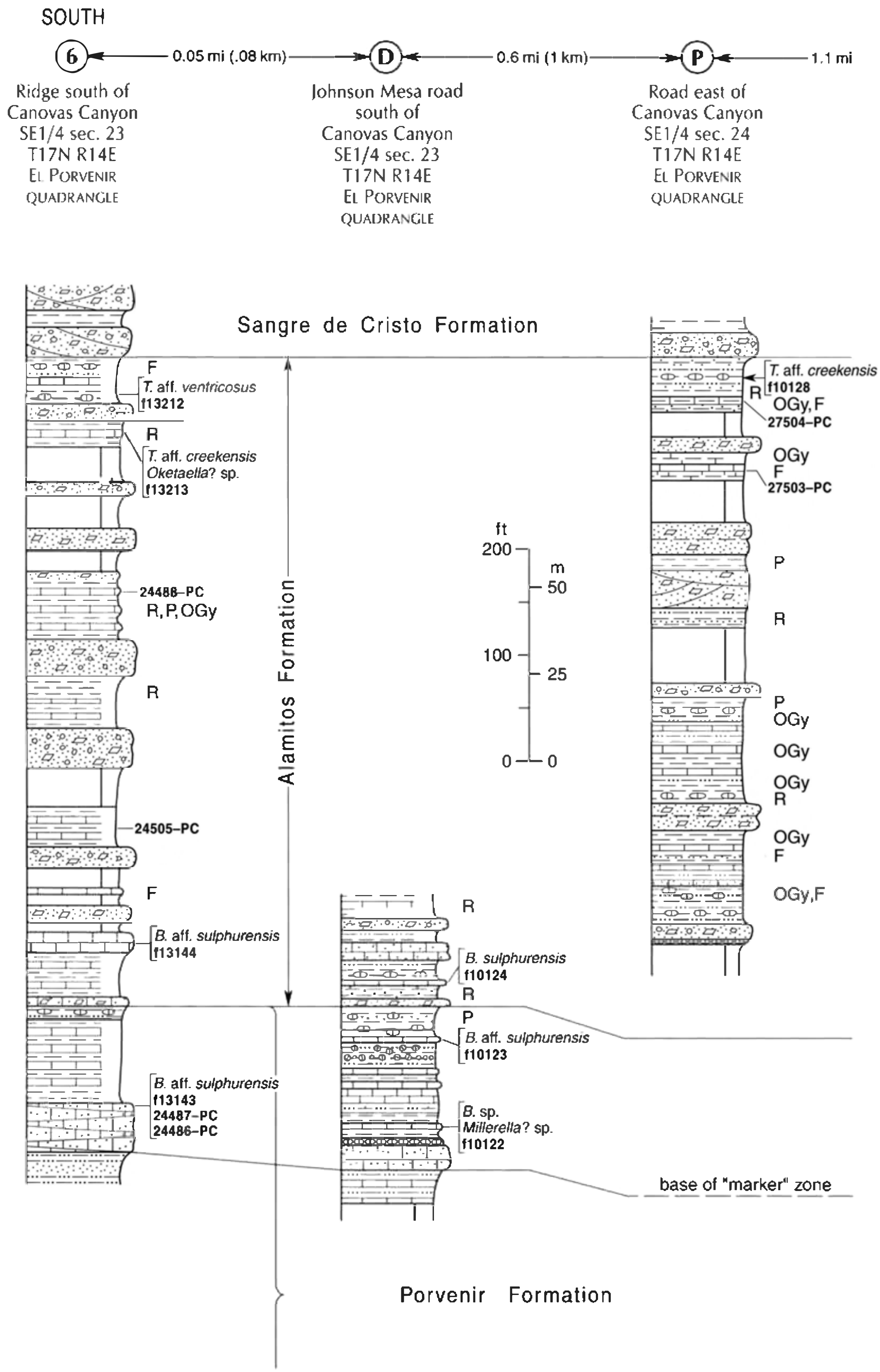
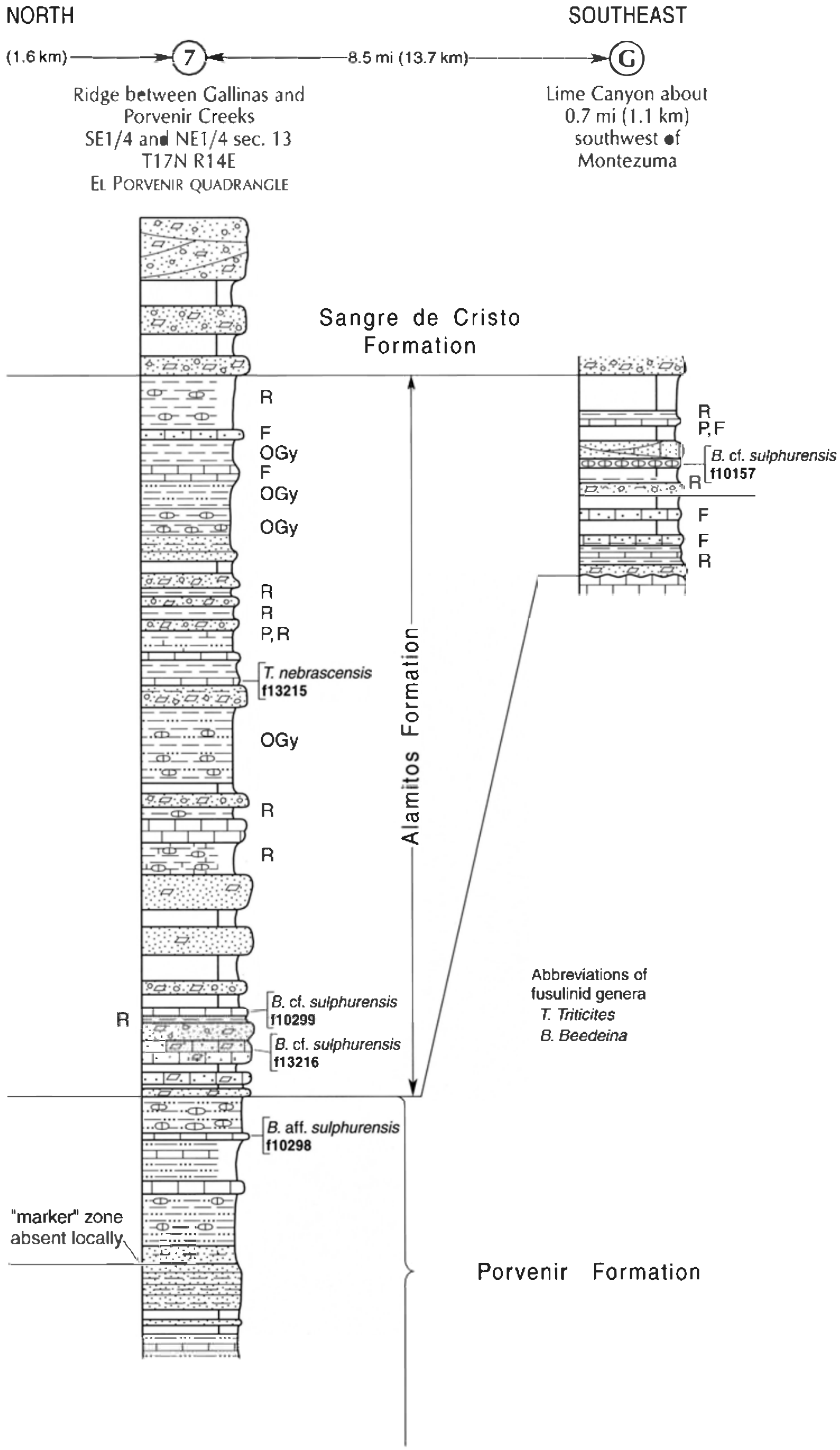


FIGURE 62—Stratigraphic sections of the Alamitos Formation, Gallinas Creek area. Localities of measurement and line of sections are shown in Figure 5, 55, 81, and 85. Symbols are explained in Figure 9.


NORTH
SOUTHEAST
(1.6 km)
7
8.5 mi (13.7 km)
G
Ridge between Gallinas and Porvenir Creeks SE1/4 and NE1/4 sec. 13 T17N R14E
El Porvenir quadrangle
Lime Canyon about 0.7 mi (1.1 km) southwest of Montezuma
Sangre de Cristo Formation
Alamitos Formation
Porvenir Formation
R
F
OGy
P,R
P,F
T. nebrascensis f13215
B. cf. sulphurensis f10299
B. cf. sulphurensis f13216
B. aff. sulphurensis f10298
B. cf. sulphurensis f10157
"marker" zone absent locally
Abbreviations of fusulinid genera
T. Triticites
B. Beedeina

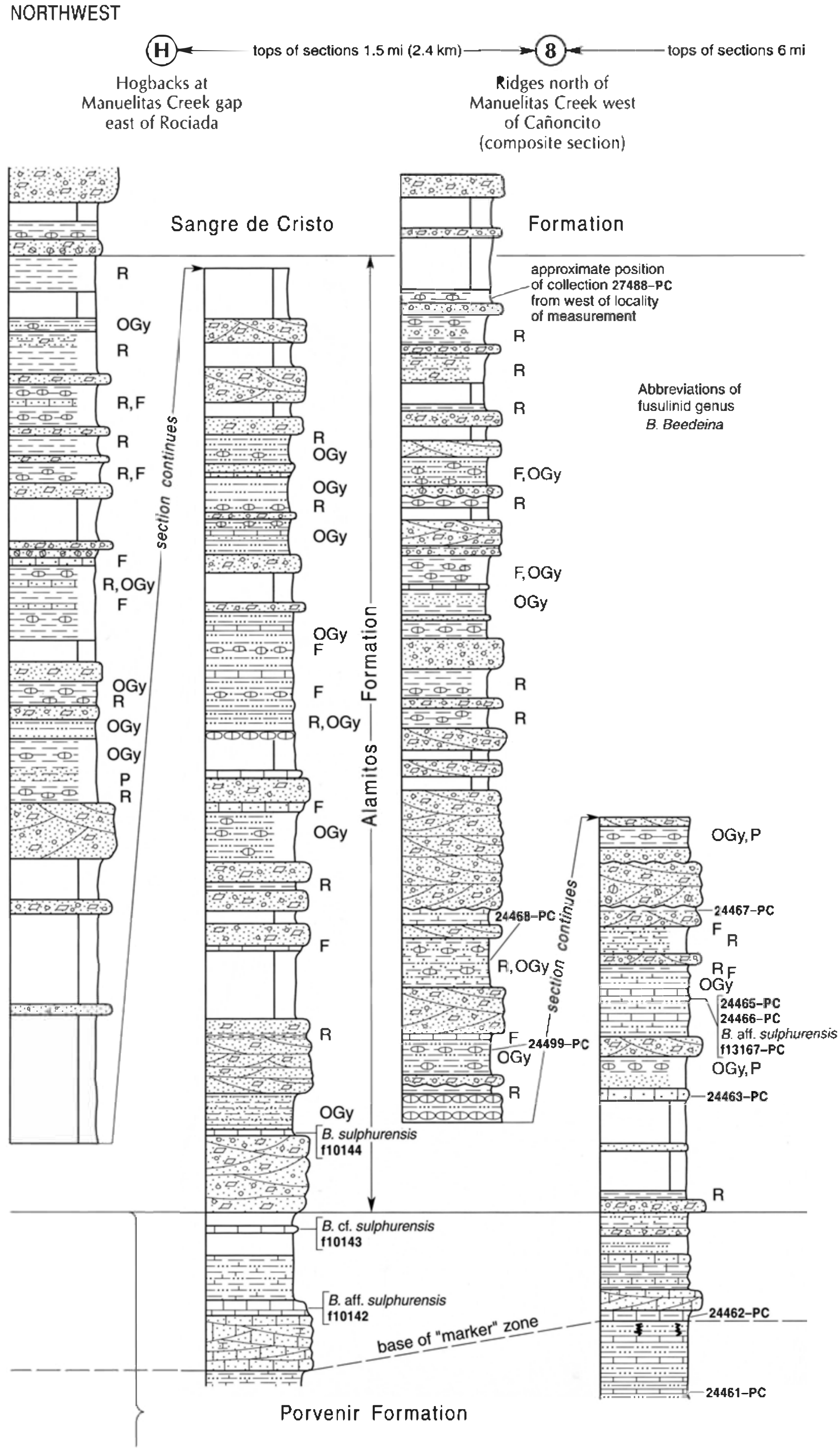
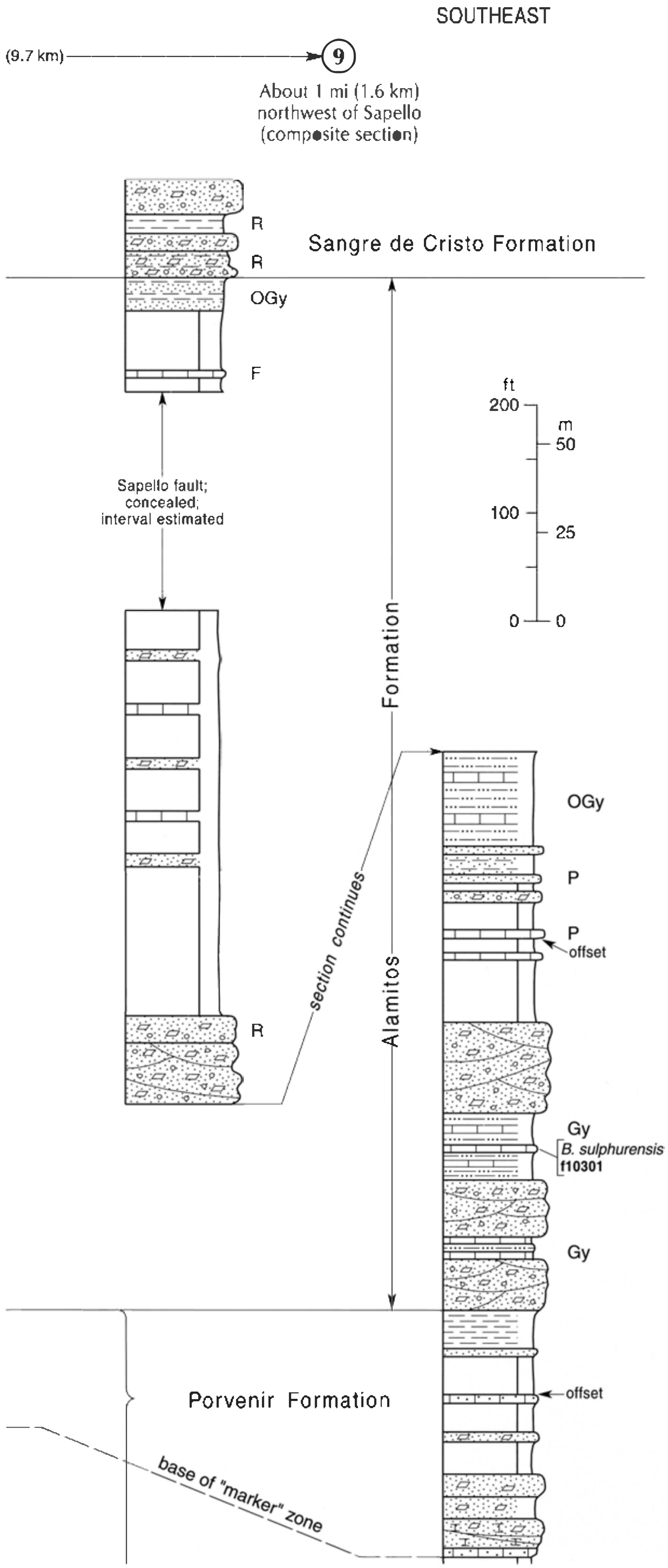


FIGURE 63—Stratigraphic sections of the Alamitos Formation, Manuelitas Creek and vicinity of Sapello. Localities of measurement and line of section are shown in Figure 55. Symbols are explained in Figure 9. Alamitos Formation is about 1,830 ft (558 m) thick at locality H; about 1,260 ft (384 m) thick at locality 8; and probably almost 1,300 ft (395 m) at locality 9.


SOUTHEAST
(9.7 km)
9
About 1 mi (1.6 km) northwest of Sapello (composite section)
R
R
Sangre de Cristo Formation
OGy
F
ft
200
m
50
100
25
0
0
Sapello fault; concealed; interval estimated
Formation
Alamitos
section continues
R
OGy
P
P
offset
Gy
B. sulphurensis
f10301
Gy
Porvenir Formation
offset
base of "marker" zone

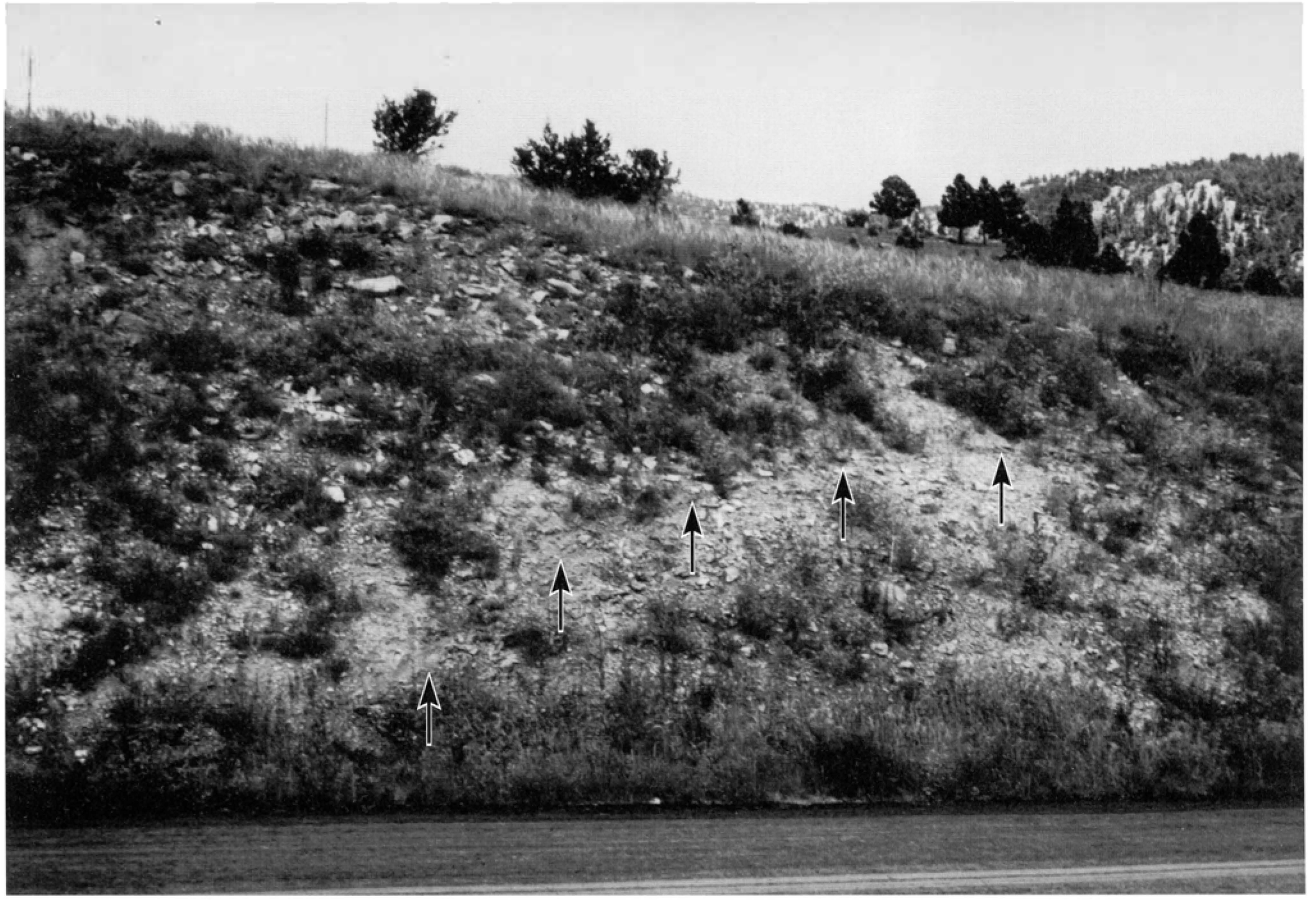


FIGURE 64—Trace of Sapello fault in roadcut at north side of New Mexico Highway 94, just west of "Y" junction with New Mexico Highway 266, about three-quarters mile (1.2 km) west of Sapello. Arrows point to west-dipping slickensided plane of thrust fault. Rocks above the fault are vertical, sheared shale and sandstone of Alamitos Formation. Rocks below the fault are overturned thick arkose, limestone, and shale of Alamitos. Just west (left) of view, limestone of upper plate contains late Desmoinesian fusulinids (*Beedeina* aff. *sulphurensis*, f10129 and f10130). Just east (right) of view in the footwall block, shale within a few feet of the stratigraphic top of the Alamitos contains brachiopods (collection 27501–PC) that suggest Virgilian age. Map of area is shown in Figure 86.

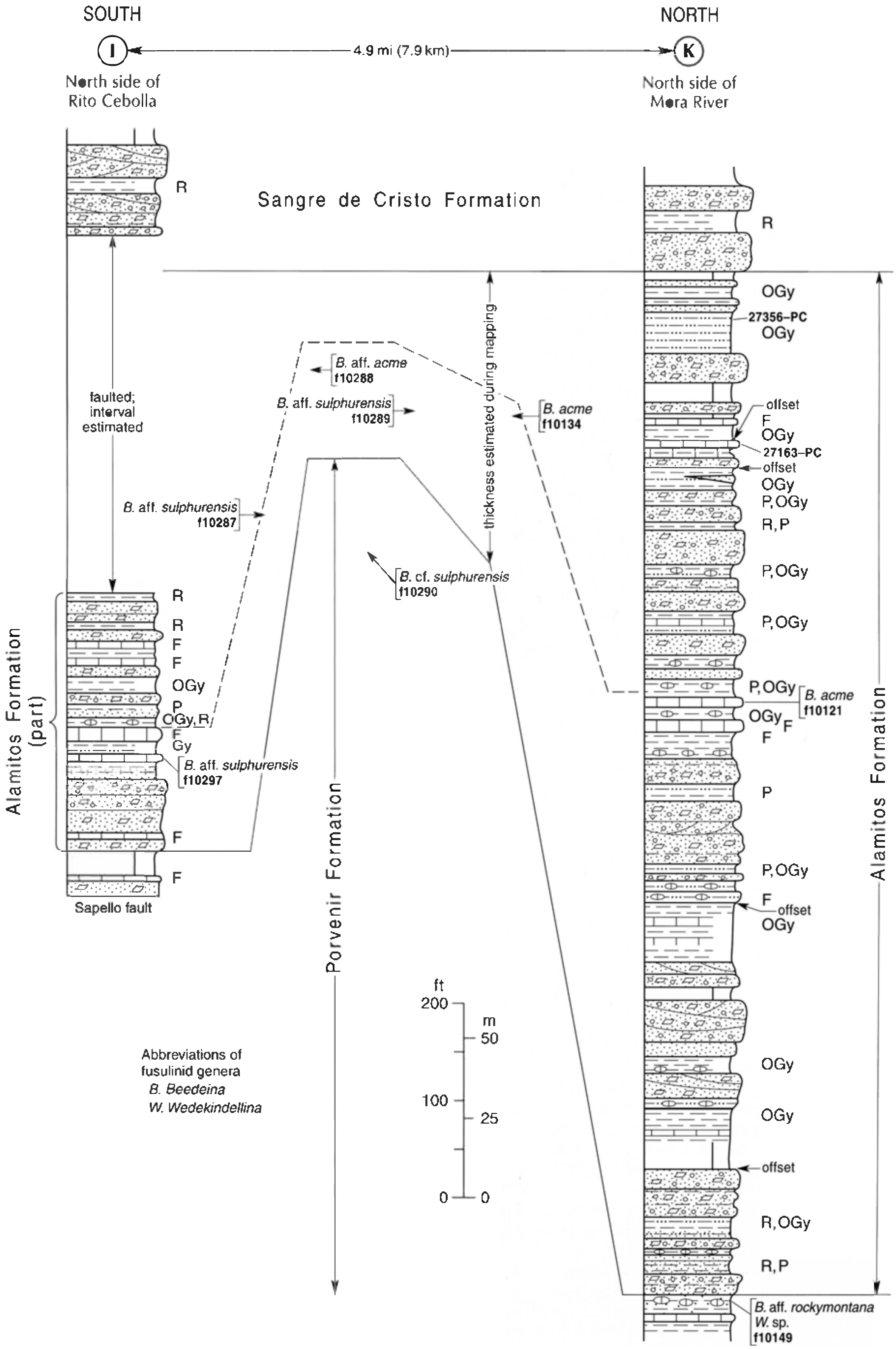
Late Pennsylvanian (probably Missourian) megafossils occur well above the base of the arkoses (Fig. 67). The portrayed intertonguing relationship (Fig. 68*A*) was a diagrammatic convenience to explain these facts in lieu of more detailed information on contacts and ages of various lithologic units from Mora River south. The base of arkosic sandstones within what is now the upper half of the Alamitos at Mora River, was considered to be the lithologic base of the Sangre de Cristo by Baltz and Bachman (1956), and the higher marine beds were considered to be northward-thinning tongues of the arkosic limestone member of the Madera (the Alamitos) within the Sangre de Cristo. Later detailed mapping and tracing of lithologic units (Baltz and O'Neill, 1984, 1986) and biostratigraphic studies for the present report indicate that the earlier model is not correct in its simplified geometric details because Pennsylvanian intrabasinal tectonic features exerted local controls on depositional and erosional environments, at least as far north as the northern edge of the area of this report. The relations, as presently conceived, are shown in Figure 68*B*.

Age and fossils

Fusulinids—The age span of the Alamitos Formation in the southeastern part of the Sangre de Cristo Mountains is late Middle Pennsylvanian through earliest Permian (Fig. 54). Fusulinids that represent this entire age span are known to be present only in the south-central part of the area in the axial part of the Cenozoic Las Gallinas syncline from about Mineral Hill northward to about Gallinas Creek. In this part of the area fusulinids from the Alamitos include representatives of parts of the zones of *Beedeina* (Desmoinesian), *Triticites* (Missourian and Virgilian), and *Schwagerina* (Early Permian, Wolfcampian).

The zone of *Beedeina* (Fig. 54) extends upward from the Porvenir Formation into the lower part of the Alamitos. *Beedeina* cf. and aff. *B. sulphurensis* (Ross and Sabins), 1965 is common in the lower beds throughout most of the area (Plates 6, 8, 9). The youngest species of *Beedeina* in the Alamitos is *B. acme* (Dunbar and Henbest) 1942 (f10134, Plate 12), which was found slightly above the stratigraphic position of *B. sulphurensis* south of La Cañada del Guajalote,

FIGURE 65—Stratigraphic sections of the Alamitos Formation at Rito Cebolla and Mora River. Stratigraphic positions (below top of the Alamitos) of fusulinids collected between the sections are shown by arrows. Dashed line shows approximate correlation of highest rock units in which late Desmoinesian fusulinids were found. Localities of measurement and line of sections are shown in Figure 55. Maps of localities are shown in Figures 88, 89. Lithologic symbols are explained in Figure 9.


SOUTH
NORTH
I
4.9 mi (7.9 km)
K
North side of Rito Cebolla
North side of Mora River
Sangre de Cristo Formation
R
faulted; interval estimated
B. aff. acme f10288
B. aff. sulphurensis f10289
B. acme f10134
thickness estimated during mapping
B. aff. sulphurensis f10287
B. cf. sulphurensis f10290
Alamitos Formation (part)
R
R
F
F
OGy
P
OGy, R
F
Gy
B. aff. sulphurensis f10297
F
F
Sapello fault
Porvenir Formation
OGy
27356–PC
OGy
offset
F
OGy
27163–PC
offset
OGy
P, OGy
R, P
P, OGy
P, OGy
P, OGy
B. acme f10121
OGy
F
F
P
P, OGy
F
offset
OGy
OGy
OGy
offset
R, OGy
R, P
B. aff. rockymontana W. sp. f10149
Alamitos Formation
ft
200
100
0
m
50
25
0
Abbreviations of fusulinid genera
B. Beedeina
W. Wedekindellina

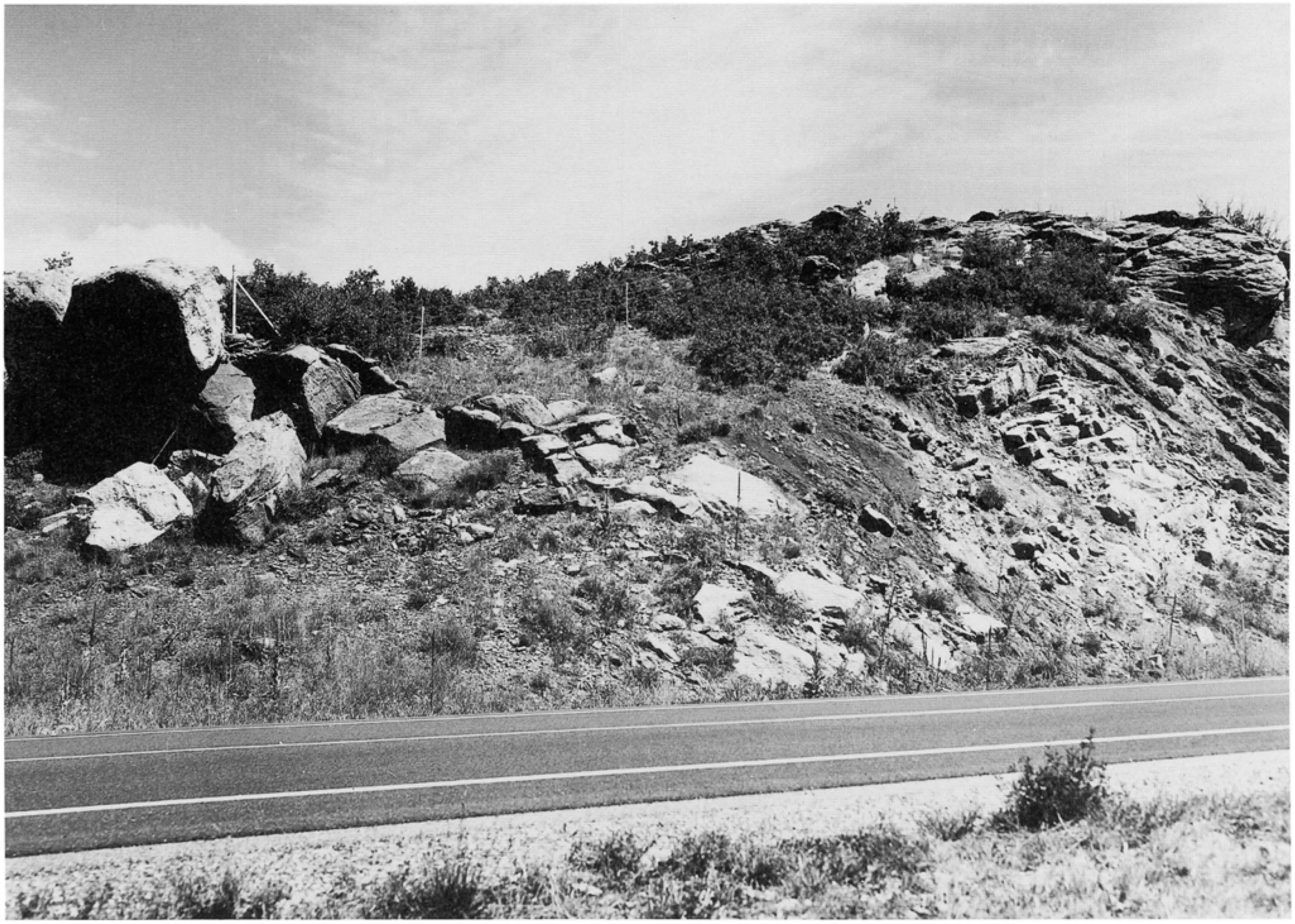


FIGURE 66—Lower part of Alamitos Formation at section K, north side of Mora River valley. Roadcut on New Mexico Highway 518 about 1.4 mi (2.2 km) northwest of La Cueva. Beds dip east (right) about 58°. Top of Porvenir Formation is concealed on slope at left. Ridge-forming feldspathic sandstones at road and at left are units 277–279 of section K at the base of the Alamitos. Overlying beds to the right are olive-gray and purplish-red-weathering shale and shaly sandstone succeeded upward by ridge-forming coarse-grained to pebbly, feldspathic to arkosic conglomeratic sandstones of the Alamitos. Fence posts are about 4.5 ft (1.3 m) high.

where the Alamitos is relatively thin. *B. acme* was found also above the middle of the Alamitos at Mora River (f10121, Plate 10), where the formation is much thicker.

Fusulinids of the zone of *Triticites* were found at only a few places and only in the south-central and southwestern parts of the area from Gallinas Creek south. The oldest Late Pennsylvanian fusulinids found in the Alamitos are the early Missourian *Triticites nebrascensis* Thompson 1934 found near the middle of the Alamitos (Fig. 81) just north of Gallinas Creek (f13215, Plate 7), and *T.* aff. *T. celebroides* Ross, 1965, found in the thin remnant of the Alamitos southwest of the Bernal section (f10323, Plate 14). *Triticites* cf. and aff. *T. ohioensis* Thompson, 1936, an early Missourian species, was also found in the thin remnant of Alamitos at the Bernal section (f10321, f10322, f10328, Plate 14).

The oldest Virgilian fusulinid is *Triticites* aff. *T. coronadoensis* Ross and Tyrrell, 1965 that was found about 130 ft (40 m) below the top of the Alamitos a few hundred yards west of Tecolote Creek about 1.3 mi (2 km) southeast of Blue Haven Camp (f10277, Plate 13). Although this species was not found in the Manzano Mountains, its evolutionary development is close to that of *T.* aff. *T. asperoides* Ross, 1965, from the lower part of the Virgilian assemblage subzone of *T. asperoides* of the Manzano Mountains (Myers, 1988b).

The next younger Virgilian fusulinid, *Triticites bensonensis* Ross and Tyrrell, 1965 (f10319, Plate 14) was found in the upper part of the Alamitos at the Pecos River section west of San Juan. This form can be referred to Myers' (1988b) assemblage subzone of *T. bensonensis* (lower to middle Virgilian) of the Manzano Mountains (Fig. 54). However, at the Pecos River section the *T. bensonensis* specimens are abraded and occur in a unit of oolitic and sandy limestone that contains limestone pebble conglomerate. This suggests that in latest Pennsylvanian time, they were reworked from stratigraphically slightly older beds, probably on the west flank of the Bernal uplift. This is suggested further by their occurrence, at this locality, stratigraphically above *T. whetstonensis*, which occurs above *T. bensonensis* in the Manzano Mountains (Fig. 54).

The youngest Virgilian fusulinids found in the area of this report are *Triticites* aff. *T. whetstonensis* Ross and Tyrrell, 1965 and *Oketaella* sp. that occur about 60 ft (18 m) below the top of the Alamitos at the Pecos River section west of San Juan (f10320, Plate 14). These forms are considered to represent late Virgilian age based on their stratigraphic position in the Manzano Mountains.

In the area of this report, Early Permian (early Wolfcampian) time is represented by two species of *Triticites* that occur elsewhere within the lower part of the Wolfcampian zone of *Schwagerina*. *Triticites* cf. and aff. *T. creekensis* Thompson, 1954 were found about 40 ft (12 m) below the top of the Alamitos Formation (Fig. 81) near the type locality of the Porvenir Formation, and also northwest of San Geronimo (f10128, f10278, Plates 7, 13, 14). *Triticites*

FIGURE 67—Upper part of Alamitos Formation (ℙa) and lower part of Sangre de Cristo Formation (Pℙsc) at locality K, north side of Mora River valley. View north of New Mexico Highway 518 about 1.1 mi (1.8 km) northwest of La Cueva. Approximate contact of formations shown by dashed line. Beds dip east (right) about 58°. Ridge-forming arkosic sandstone cropping out above and left of barn is near top of Alamitos. Uppermost unit of greenish-gray, green, and red shale and interbedded thin sandstone of Alamitos crops out along and right of ranch road that is above and left of barn. Stratigraphically highest marine fossils (collection 27356–PC) were obtained from outcrop (arrow) of light-gray shaly siltstone at right side of road past point where it disappears from view. Marine fossils (collection 27163–PC) also were obtained from limestone exposed on slope in foreground just west (left) of view. The lower parts of the Sangre de Cristo Formation are purplish-pink to reddish-brown weathering, conglomeratic feldspathic to arkosic sandstones and interbedded thin red-weathering shales and siltstones.

(*Leptotriticites*) sp. was found in thin limestone lentils in the upper part of the Alamitos (Fig. 59) on the east flank of Ojitos Frios anticline south of Ojitos Frios (f10275, Plate 13). Here, it is associated with rare specimens of *Ozawainella* sp. (f10275, Plate 14). *Triticites* (*Leptotriticites*) sp. was found also in limestone cobbles in Quaternary pediment deposits west of Agua Zarca.

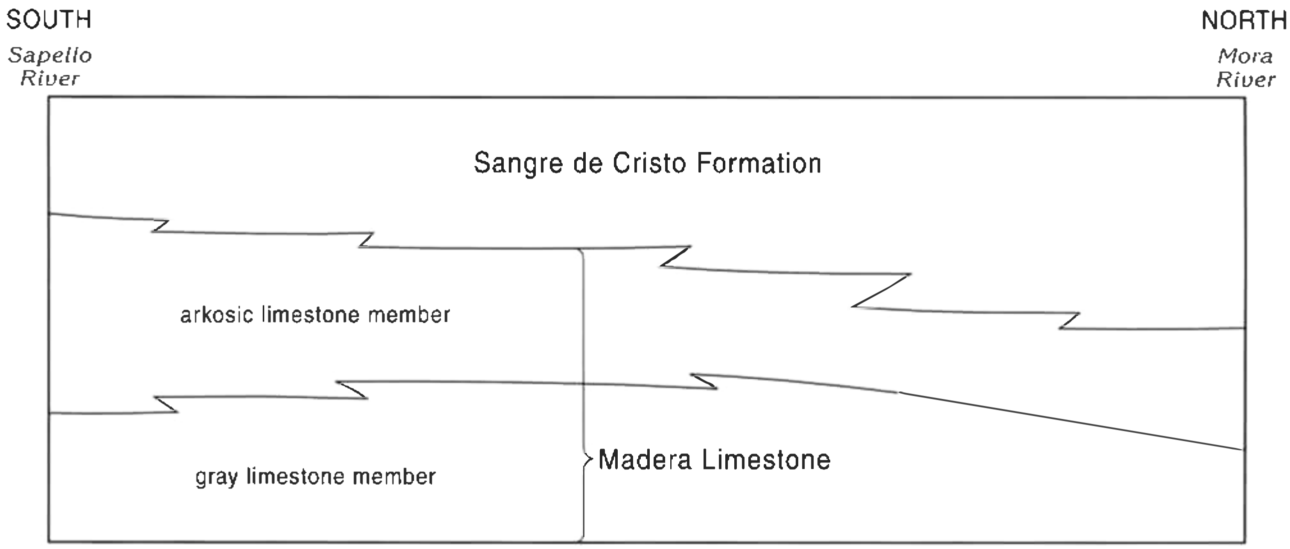
Regional fusulinid–faunal correlations—The general succession of fusulinids of the Alamitos Formation in the southeastern part of the Sangre de Cristo Mountains is summarized in Figure 54 where it is compared with fusulinid successions in the Manzan● Mountains type region of the Madera Group. The following discussion is based mainly on data from Myers (1988b), which are discussed in greater detail in that report.

Beedeina sulphurensis and *B. acme* from the Alamitos Formation are equivalent to the upper Desmoinesian assemblage subzone of *B. sulphurensis* of Myers (1988a) and are typical of fusulinids found in the upper beds of the Desmoinesian Series throughout the United States. Their regional faunal correlations have been specified previously in the discussion of the fusulinids of the Porvenir Formation.

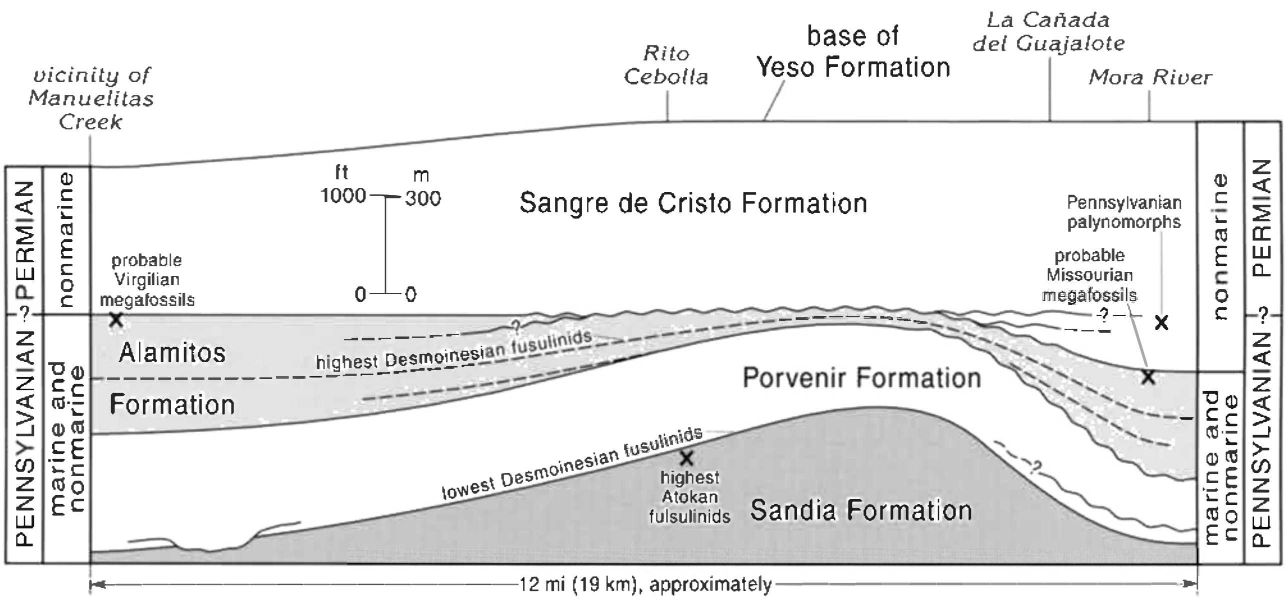
Triticites nebrascensis and *T. celebroides* from the Alamitos Formation are equivalent in age to the lower Missourian assemblage subzone of *T. nebrascensis* in the Wild Cow Formation in the Manzano Mountains. This assemblage subzone is equivalent to the *Triticites celebroides* assemblage subzone of Ross (1965, p. 1,159) from the lower part of the Gaptank Formation in western Texas. The fauna is the same as that illustrated by Myers (1960, plate 16) from the Brownwood Shale Member of the Graford Formation in central Texas. In the Midcontinent region, *T. nebrascensis* is found in the Avoca Member of the Lecompton Limestone of Nebraska and in the Cherryvale Shale of Missouri (Dunbar and Condra, 1927; as described by them, *T. exiguus*). Thompson and Thomas (1953, p. 31) reported *T. nebrascensis* from about 175 ft (54 m) above the base of the Casper Formation near Wheatland Reservoir in Wyoming. Thompson, Verville, and Bissell (1950) described a similar species, *T. springvillensis*, from near the base of the Missourian portion of the Oquirrh Formation in the Wasatch Mountains of Utah. *T. nebrascensis* has been found about 18 ft (5.5 m) below the top of the Lead Camp Limestone in the San Andres Mountains in southern New Mexico (Bachman and Myers, 1969). Beds near the top of the Pennsylvanian section in the Joyita Hills in Socorro County, New Mexico contain *T. nebrascensis* (Kottlowski and Stewart, 1970).

Few, if any, species of *Triticites* older than *T. nebrascensis* have been reported from the Midcontinent region or the Western United States. Therefore, the assemblage subzone to which these species are referred appears to define a widespread biostratigraphic zone that appeared during early Missourian time.

Representatives of the assemblage subzone of *Triticites ohioensis* from the Alamitos Formation correlate with that Missourian assemblage subzone in the Wild Cow Formation in the Manzano Mountains. In western Texas, the assemblage subzone of *T. collus* (Ross, 1965) in the Gaptank Formation is probably equivalent to that of *T. ohioensis* (Myers, 1988b). The assemblage subzone fauna is equivalent to that of the Adams Branch Limestone Member of the Graford Formation of Texas (Myers, 1960); to the *T. ohioensis* fauna of the Brush Creek Shale and Cambridge Limestone Members of the Conemaugh Formation in Galia County, Ohio (Thompson, 1936); to the Livingston Limestone Member of the Bond Formation in Edgar County, Illinois (Dunbar and Henbest, 1942); and to the Winterset Member of the Dennis Limestone in Iowa (Thompson, 1957). In the Western United States, Ross and Tyrrell (1965) have recorded *T.* cf. *T. ohioensis* from about 800 ft (245 m) above the base



A. Older concept of stratigraphic relations. Adapted from Baltz and Bachman, (1956, figure 2). Not to scale.



B. This report. Wavy lines denote unconformities; dashed lines represent bedding; **X** = stratigraphic position of some fossil collections. Datum is base of Sangre de Cristo Formation southward from vicinity of La Cañada del Guajalote; therefore, the diagram portrays the structural conditions of early Wolfcampian time only. Line of diagram is oblique to strikes of folded pre-Sangre de Cristo rocks near east front of mountains; possible Pennsylvanian faults are not shown. Compare with cross section *D*, Figure 27, that is nearly at right angle to the possible Paleozoic folding and faulting near La Cañada del Guajalote.

Figure 68—Diagram of concepts of stratigraphic relations of Pennsylvanian and Lower Permian rocks, Manuelitas Creek– Mora River.

of the Horquilla Limestone in the Whetstone Mountains of Arizona.

Missourian fusulinids younger than *T. ohioensis* have not been found in the southeastern Sangre de Cristo Mountains. On the basis of our present data, there may be a late Missourian faunal hiatus between the highest occurrence of *T. ohioensis* and the lowest occurrence of the Virgilian *T. coronadoensis* (Fig. 54). This hiatus would be equivalent to the upper part of the Missourian Kansas City Group and all of the Lansing and Pedee Groups of the Midcontinent. Part of the time of the hiatus may also include the time of the assemblage subzone of *Triticites asperiodes* of the Manzano Mountains, which fauna resembles material from the Douglas Group and the lower part of the Shawnee Group of early Virgilian age in Kansas. The significance of the faunal hiatus in the southeastern part of the Sangre de Cristos can be evaluated partly. On the Paleozoic Bernal uplift and its flanks upper Missourian and Virgilian rocks of the Alamitos are absent because of angular unconformity between the Alamitos and the Permian Sangre de Cristo Formation. On the Paleozoic Tecolote uplift and its flanks, Missourian and Virgilian rocks are absent because of intraformational unconformity between the Desmoinesian and Wolfcampian parts of the Alamitos Formation and because of unconformity with the Sangre de Cristo Formation. Farther north, rocks of latest Missourian and earliest Virgilian ages might be absent, or they might be represented by nonmarine rocks, or they might be present but unrecognized by us because of the scarcity of fusulinid-bearing rocks.

The oldest Virgilian fusulinids of the Alamitos in the area of the present report are representatives of the assemblage subzone of *Triticites bensonensis* and correlate with the assemblage subzone of that name in the Wild Cow Formation in the Manzano Mountains. They are similar to the fusulinid fauna of Ross's beds H and I in the Gaptank Formation of Texas (Ross, 1965, p. 1,160); to the faunas in the Gunsight Limestone Member of the Graham Formation in central Texas (Myers, 1960); to material from the Shawnee Group in Kansas (Myers, 1988b); and to material from 50–120 ft (15–37 m) above the base of the Earp Formation in the Whetstone Mountains, Arizona (Ross and Tyrrell, 1965, p. 619).

Representatives of the assemblage subzones of *Triticites cullomensis* and *T. beedei* of the Manzano Mountains were not found in the Alamitos in the area of this report, although *T.* cf. *T. cullomensis* is reported from fusulinid zone VII in the Alamitos of the western part of the Sangre de Cristo Mountains (Sutherland and Harlow, 1973, p. 10). The interval of time represented by these assemblage subzones may represent a faunal hiatus in the southeastern part of the mountains that includes part of the time during which the Douglas and Shawnee Groups were deposited in the Midcontinent region. Possible reasons for this apparent hiatus are the same as those discussed previously.

Triticites whetstonensis, the youngest Virgilian fusulinid found in the Alamitos Formation in the southeastern Sangre de Cristo Mountains is found in the assemblage subzone of that name in the Manzano Mountains in the La Casa Member of the Wild Cow Formation. Faunal representatives of this assemblage subzone are not present in the type area of the Gaptank Formation in western Texas. However, similar faunas are present in central Texas in the Breckenridge and Chaffin Limestone Members of the Thrifty Formation (Myers, 1960). The fauna is present in the lower part of the Earp Formation in the Whetstone Mountains in Arizona (Ross and Tyrrell, 1965).

Triticites creekensis, an early Wolfcampian fusulinid, occurs in the upper part of the Alamitos Formation. In the Manzano Mountains, this fusulinid is referred to the assemblage subzone of *T. creekensis*, where it is found in the uppermost beds of the La Casa Member of the Wild Cow Formation, and in the lower beds of the overlying Bursum Formation (Myers, 1988b). The type *Triticites creekensis* is from the Camp Creek Shale Member of the Pueblo Formation in central Texas; the fusulinid has been found also in the basal beds of the Wolfcampian part of the Bird Spring Formation at Arrow Canyon in Clark County, Nevada (Cassity and Langenheim, 1966).

Triticites (*Leptotriticites*) sp. is the youngest fusulinid found in the Alamitos Formation. The genotype, *Leptotriticites hatchetensis* Skinner and Wilde, 1965 was described from the Wolfcampian part of the Horquilla Limestone in the Big Hatchet Mountains of southwestern New Mexico, where it is associated with *Rugosochusenella*, *Pseudoschwagerina*, *Paraschwagerina*, and *Pseudofusulina*. The species found in the southeastern Sangre de Cristo Mountains is similar to, if not conspecific with, the genotype (a subgenus of *Triticites*). It is found in the southern part of the Manzano Mountains in the uppermost beds of the La Casa Member of the Wild Cow Formation (Myers, 1988b) and in the Bursum Formation; it occupies a similar stratigraphic position in the southern part of Los Pinos Mountains (Myers, Sharps, and McKay, 1986). In both the Manzano and Los Pinos Mountains, *Triticites* (*Leptotriticites*) sp. is associated with *Triticites creekensis*. *Leptotriticites* was assigned by Skinner and Wilde (1965, p. 100) to the Lower Permian (Wolfcampian) of the South-central and Southwestern United States.

The fusulinids of the Alamitos Formation in the area of this report are equivalent to those of fusulinid zones V–VII of the Alamitos in its type region (Sutherland and Harlow, 1973, p. 10) in the southwestern part of the Sangre de Cristo Mountains. However, the lower part of the Alamitos Formation at its type locality contains middle Desmoinesian fusulinids including *Beedeina rockymontana* that may indicate that the lower part is slightly older than the late Desmoinesian lower part of the formation in the area of this report. Sutherland (1963, fig. 10) reported that the Missourian fusulinid *Triticites* cf. *T. ohioensis* occurs higher in the formation and that the Virgilian *Triticites* cf. *T. cullomensis* occurs near the top. Therefore, the uppermost part of the type Alamitos appears to be not as young as the youngest part in the area of the present report. South of the type locality, in the southwestern part of the mountains, near Cañoncito, Booth (1976, p. 31) found *Triticites rhodesi* Needham (identified by D. A. Myers) that indicates a late Virgilian age for rocks Booth assigned to the upper arkosic member of the Madera Formation, and Brill (1952, p. 846) reported *T. rhodesi* from the uppermost part of the Madera east of Rowe. Therefore, at least in the southwestern part of the mountains, rocks referable to the Alamitos are as young as latest Pennsylvanian but are not reported to contain Early Permian fossils.

Megafossils from northern part of area—Megafossils were collected from throughout the Alamitos Formation in the northern half of the area, but they were not collected in a manner that would determine their complete stratigraphic ranges in the formation. The collections are listed on Plate 5 in their relative stratigraphic positions as determined mainly from stratigraphic sections, and as estimated at other places from field relations and physical-stratigraphic correlations.

At many places throughout the northern half of the area the lower part of the Alamitos Formation contains *Beedeina sulphurensis* and *Beedeina acme* that fix the age of this part as late Desmoinesian. Identifiable fusulinids were not found in the upper parts of the Alamitos north of the Gallinas Creek area. Megafossils from the upper parts of the Alamitos at several localities near Sapello River and Manuelitas Creek are clearly post-Desmoinesian. However, many of the fossils are poorly preserved because of their occurrence in sharply folded rocks or because they occur as fragmented or abraded specimens in sandy limestones deposited in high-energy environments. According to J. T. Dutro, Jr., and E. L. Yochelson (written comm., 1980), such specimens are difficult to identify at the species level, an essential requirement to refine age designations in this part of the Pennsylvanian. Most invertebrate assemblages in the Missourian–Virgilian interval contain elements of the same groups of genera, and differences are due to minor evolutionary and environmental changes. Recurring environments produce similar assemblages.

Collection USGS 27501–PC was obtained from gray shale 15–30 ft (4.6–9 m) stratigraphically below the top of the Alamitos in the roadcut at the north side of the junction of New Mexico Highways 94 and 266 northwest of Sapello

(Fig. 86). It contains *Isogramma renfrarum* Cooper, which was described from the Gonzales Limestone Member of the Graham Formation in the lower part of the Cisco Group in Texas, and it also contains *Stegocoelia (Taosia) percostata* (Girty) that was originally described from the upper part of the Magdalena Group in La Luz Canyon near Tularosa, New Mexico. These species, taken together, suggest a Virgilian age (J. T. Dutro, Jr., and E. L. Yochelson, written comm., 1980). *Bellerophon (Pharkidonotus) percarinatus* (Conrad), found at this locality northwest of Sapello, ranges from Middle through Late (Virgilian) Pennsylvanian (E. L. Yochelson, written comm., 1980). *Myalina (Orthomyalina)* sp., which also occurs in this collection, has an age range of Desmoinesian through Early Permian (Wolfcampian), but the specimens were not preserved well enough for more precise species and age designation (John Pojeta, Jr., written comm., 1980).

Collection USGS 27489–PC was obtained from sandy limestone about 40 ft (12 m) below the top of the Alamitos on the north side of Sapello River a short distance east of the axis of Las Dispensas syncline (loc. BM7903, Baltz and O'Neill, 1986). This collection contains *Linoproductus* cf. *L. platyumbonus* Dunbar and Condra and *Myalina (Orthomyalina)* cf. *M. (O.) slocumi* (Sayre), which suggest a Missourian age, although both species are known to occur in older and younger Pennsylvanian rocks, and *M. (O.) slocumi* is known to range into Lower Permian rocks (J. T. Dutro, Jr., written comm., 1979). *Myalina (Orthomyalina)* cf. *M. (O.) slocumi* (Sayre) occurs also in collection USGS 27488–PC from about 50 ft (15 m) below the top of the Alamitos north of Manuelitas Creek about 1 mi (1.6 km) east of the axis of Las Dispensas syncline (loc. BM7902, Baltz and O'Neill, 1986). Sutherland and Harlow (1973, Fig. 9) reported *Linoproductus* cf. *L. platyumbonus* from rocks they show to be late Missourian age in the southwestern part of the mountains.

Collection USGS 27824–PC was obtained from sandy limestone east of Hermit Peak near the crest of the east-trending ridge between Rito Chavez and Deer Creek about 800 ft (240 m) east of the National Forest boundary (loc. BM8003, Baltz and O'Neill, 1986). These rocks are estimated to be about 100 ft (30 m) stratigraphically below the top of the Alamitos. According to J. T. Dutro and John Pojeta (written comm., 1981) this collection contains *Linoproductus* specimens most of which appear to be *Linoproductus* cf. *L. prattenianus* (Norwood and Pratten), and one of which may be *L. platyumbonus* Dunbar and Condra, as used by Sutherland and Harlow (1973). The collection also contains the bryozoan *Rhombopora lepidodendroides* Meek that was identified by O. L. Karklins (written comm., 1981) who indicated that its known range is Late Pennsylvanian to Early Permian.

In summary, the meager evidence from megafossils suggests that the upper part of the Alamitos probably is as young as Virgilian in the eastern part of the mountains west of Sapello, and late Missourian or possibly Virgilian east of Hermit Peak and on Sapello River and Manuelitas Creek. We were unsuccessful in obtaining identifiable fossils from the sandy bioclastic limestones that occur in the uppermost part of the formation in Las Dispensas syncline (sec. H and loc. 8, Fig. 63); therefore, the possibility is not excluded that the highest part of the Alamitos there is Virgilian or younger. At any rate, the youngest marine beds from which megafossils were obtained here do not seem to be as young as the upper part of the Alamitos at locality P (Fig. 62) just south of Gallinas Creek where the Virgilian brachiopod *Neospirifer* cf. *N. dunbari* King occurs abundantly in collections USGS 27503–PC and 27504–PC, and the early Wolfcampian fusulinid *Triticites* aff. *T. creekensis*, (f10128) occurs near the same stratigraphic position in collection 27504–PC. The difference in age may be the result of nonmarine deposition becoming dominant slightly earlier at the north than at the south.

In the northern part of the area, from Mora River north, the Alamitos is only sparingly fossiliferous. Limestone near the middle contains *Beedeina acme* of late Desmoinesian age at several localities. A few fusulinids were found in shale interbedded with thick arkose in the upper part of the formation, but they were too recrystallized to be identified.

A relatively persistent limestone about 180 ft (55 m) below the top of the Alamitos at locality K (Fig. 65) north of Mora River contains abundant brachiopods. Collection USGS 27163–PC from this locality (Fig. 89) includes *Echinaria* cf. *E. semipunctata* (Shepard), *Antiquatonia* sp. (see n. sp. A of Sutherland and Harlow, 1973), and *Neospirifer* cf. *N. alatus* Dunbar and Condra (J. T. Dutro, Jr., written comm., 1978). Similar assemblages were reported by Sutherland and Harlow (1973) from rocks in the Alamitos that they consider to be Missourian in the southwestern part of the mountains. Also at locality K, a small collection of pelecypods and fragmented brachiopods was obtained from shale about 45 ft (14 m) below the top of the Alamitos. This collection (USGS 27356–PC; Fig. 89) contains two specimens of *Acanthopecten* that may represent a new species but are close to *A. carboniferus* (Stevens). The known range of *A. carboniferus* is Desmoinesian through Virgilian; therefore, these fossils do not indicate whether the rocks are Missourian or Virgilian (John Pojeta and J. T. Dutro, Jr., written comm., 1978). In any case, the occurrence of probable Pennsylvanian palynomorphs about 500 ft (150 m) above the base of the overlying nonmarine rocks assigned to the Sangre de Cristo Formation indicates that the upper part of the Alamitos probably is not youngest Pennsylvanian age at Mora River.

Brill (1952, p. 819) reported a collection of brachiopods from rocks he considered to be the "Whiskey Creek Pass Limestone Member" that he assigned to the arkosic limestone member of the Madera Formation at Mora River. However, from his meager description we are not able to identify the rocks from which his collection was obtained, and we have not recognized Brill's Whiskey Creek Pass Limestone Member as a lithologic unit in the southeastern part of the Sangre de Cristo Mountains.

The only other published report of identified marine megafossils in rocks possibly referable to the Alamitos in this part of the mountains is that of Tschanz et al. (1958, p. 349–350). They reported that northwest of Lucero, about 5 mi (8 km) north of the area of this report, sponges, corals, crinoids, bryozoans, brachiopods, and mollusks occur in a 25-ft (7.6-m) thick limestone 140 ft below the top of the Magdalena Group. They do not specify a precise locality, or localities, of collection of these fossils and some of their descriptions of rock units and generalized stratigraphic sections are sufficiently confusing to make the stratigraphic positions of the fossils uncertain. Field examination indicates that Tschanz et al. (1958, plate 24) mapped the top of their Magdalena Group at about the same position as did Bachman (1953) and Zeller and Baltz (1954, plate 1) at the north side of the road in the water gap west of Los Cisneros (USGS Lucero quadrangle). This stratigraphic position is at about the top of the stratigraphically highest, thin, fossiliferous marine limestone in this vicinity and would be near the top of the Alamitos as we consider it (loc. 4, Plate 3 of this report). However, the rocks stratigraphically below this limestone are identical to the rocks described by Tschanz et al. (1958, p. 353) as the basal "Red arkose unit" of their Sangre de Cristo Formation, although their map includes them in the Magdalena. If their collection came from the upper part of the interval mapped as the Magdalena, it is from the Alamitos. The brachiopod fauna is listed here, although its stratigraphic position is uncertain. This collection included the brachiopods *Meekella striatocostata* (Cox), *Linoproductus* cf. *L. platyumbonus* Dunbar and Condra, *Echinoconchus semipunctatus* (Shepard), *Neospirifer* cf. *N. latus* Dunbar and Condra, and *Composita subtilita* (Hall). The *Linoproductus* and *Neospirifer* were said to suggest Missourian age (Mackenzie Gordon, Jr., written comm., 1953).

Tschanz et al. (1958, p. 354) reported that marine limestones occur also in the lower 950 ft (290 m) of the rocks they assigned to the lower part ("Red arkose unit") of the Sangre de Cristo Formation. These rocks were assigned to the lower part of the Sangre de Cristo also by Brown (1984, p. 116), who classified them as a unit of distal alluvial fans and floodplain deposits, but he did not mention the presence of marine beds. The collecting localities of these marine fossils, specified by Tschanz et al. (1958), are south of the alluviated valley and road west of Los Cisneros, except for BZ–21, which appears to be in error and probably should be BZ–22, which also is south of the valley (Zeller and Baltz, 1954, p. 3). Fossils from these limestones include *Linoproductus* sp., *Myalina* sp., *Hypselentoma*? sp., *Pseudorthoceras* cf. *P. knoxense* (McChesney), and indeterminate pelecypods and bellerophontid gastropods identified by Mackenzie Gordon, Jr., S. A. Northrop, and E. L. Yochelson. Yochelson (written comm., 1954) reported that the genus *Hypselentoma* was known only from the Upper Pennsylvanian in the Midcontinent region. Despite the previous assignments of these fossiliferous rocks south of the valley to the lower part of the Sangre de Cristo, we believe they are actually in the Alamitos Formation and are equivalent to rocks north of the valley and road that were mapped by all previous investigators as the upper part of the Magdalena Group.

The fossiliferous rocks south of the valley west of Los Cisneros strike north toward outcrops of the unfossiliferous lower part of the Sangre de Cristo Formation (of Plate 3, this report) north of the valley, but the fossiliferous rocks are concealed by Quaternary alluvium within the valley and the apparent stratigraphic relation cannot be confirmed by tracing. The assignment of the fossiliferous rocks to the Sangre de Cristo south of the valley by Bachman (1953), Zeller and Baltz (1954), Tschanz et al. (1958), and Brown (1984, fig. 2) probably is the result of all these workers accepting what appears to be the correlation across the valley. However, near the sharp northward bend of the road 2,800 ft (850 m) west of Los Cisneros, fusulinid-bearing lower Desmoinesian oolitic limestone at the base of the Porvenir Formation just south of the creek terminates abruptly against stratigraphically higher sandstone of the Porvenir north of the creek. A little farther west another thick, ridge-forming limestone also terminates northward against sandstone. These relations suggest that one or more southeast-trending, left-lateral, strike-slip faults occur beneath the alluvium of the valley, and that they have juxtaposed the Alamitos south of the valley against the lower part of the Sangre de Cristo north of the valley. If so, this explains the northward termination of the fossiliferous Upper Pennsylvanian rocks south of the valley. They correlate with rocks we include (Plate 3) in the Alamitos north of the valley and with rocks north of the valley that were mapped in the upper part of the Magdalena by the previously cited investigators. This explanation also negates previous interpretations that large-scale intertonguing occurs between the Sangre de Cristo and the mixed marine-nonmarine Upper Pennsylvanian rocks in this area, although we do not preclude the possibility of interfingering at the top of the Alamitos and the base of the Sangre de Cristo.

Paleotectonic and sedimentational interpretations

The Alamitos Formation in the southeastern part of the Sangre de Cristo Mountains was deposited in complex, tectonically active environments (Plate 4). The marine rocks are mainly shallow-water deposits that contain terrigenous debris ranging from silt to granule and pebble gravel. These rocks are interlayered with nonmarine alluvial deposits of sand and pebble gravel. The local variations in thickness and lithology of the Alamitos indicate multiple sources of terrigenous clastics, some of which were in the area of this report (Fig. 55).

The Tecolote uplift was active tectonically after the deposition of the lower part of the Porvenir Formation and prior to the deposition of the late Desmoinesian basal part of the Alamitos Formation (Fig. 32). Northerly inclined crossbedding and cross-lamination in pebbly arkoses in the late Desmoinesian lower part of the Alamitos south of Montezuma indicate sediment transport from southerly or southeasterly sources. The thin, slightly feldspathic sandstone, quartz-pebble conglomerates, and sandy limestone at the base of the late Desmoinesian part of the Alamitos in the southern part of the area are coarsest in the southeast and were derived from emergent areas of Precambrian rocks on the southern part of the Tecolote uplift. The Precambrian rocks southwest of Agua Zarca are quartzofeldspathic gneiss, mica schist and gneiss, and quartzite, all intruded by coarse-grained granite and thick alaskite pegmatites. These rocks are lithologically appropriate to have been the sources of part of the clastics of the Alamitos. In particular, the abundant feldspar granules and pebbles in some beds southwest of Agua Zarca indicate this nearby local source.

Subsurface data in the Las Vegas Basin suggest that the Sierra Grande uplift also was active and probably a source of clastics at this time because the Alamitos lies on a thin section of the Porvenir at the J. D. Hancock no. 1 Sedberry well (Plate 4, Fig. 18), but, farther south, the Alamitos lies on the Sandia Formation at the Continental no. 1 Shoemaker–Reed and the Continental no. 1 Leatherwood–Reed wells. It seems likely that the Precambrian of the Sierra Grande uplift was a source of clastics of the Alamitos in the area of the Las Vegas Basin and probably as far north as the Manuelitas saddle.

Present data are inadequate to determine whether Missourian and Virgilian rocks of the Alamitos were deposited on the Tecolote uplift and northern margin of the Sierra Grande uplift and then were eroded, or whether these areas were intermittently uplifted during Missourian and Virgilian time and were not depositional sites until earliest Permian time when the youngest marine beds of the Alamitos were deposited. The latter hypothesis seems more likely because the Upper Pennsylvanian rocks thicken intraformationally away from the Tecolote uplift into the Paleozoic San Geronimo Basin.

Some details of Late Pennsylvanian history and structure of the Bernal uplift are known. At the south, near Bernal, the middle Desmoinesian part of the Porvenir is overlain by lower Missourian beds of the Alamitos, indicating that the southern part of the uplift was emergent or was an area of nondeposition in late Desmoinesian and again in Virgilian time, as were nearby southern parts of the Tecolote uplift. The clastics of the Alamitos near Bernal are not as coarse as they are farther north and east and probably were derived from Precambrian rocks of the Tecolote or Sierra Grande uplifts. The San Jose Basin west of the Bernal uplift probably was the site of at least intermittent deposition throughout Late Pennsylvanian. Some sediments of the Alamitos may have been uplifted and eroded along the west margin of the uplift and redeposited farther west, as suggested by the previously discussed fusulinid data at the Pecos River section.

To the north-northwest, along the eastern flank of the

Bernal uplift, thin remnants of the Alamitos are known to be preserved beneath the Sangre de Cristo Formation at only three places; at two of these places (Fig. 58) the Alamitos lies on upper Desmoinesian beds of the "marker" zone of the Porvenir suggesting conformity between the formations. However, at and near Dead Horse Canyon, the Alamitos lies on Porvenir rocks that are stratigraphically below the position of the "marker" zone. In this part of the area also, the terrigenous clastics of the Alamitos are not as coarse and do not form as large a proportion of the formation as they do elsewhere. These factors suggest that the structural relief of most of the Bernal uplift was low (a few hundred feet) during most of Late Pennsylvanian time and that a relatively thin section of the Porvenir probably remained on the southern part of the uplift.

The eastward thickening of the Alamitos into the San Geronimo Basin, and the fossils present there, indicate that at least the northern part of this basin subsided throughout Late Pennsylvanian and earliest Permian time. Mainly marine sediments accumulated episodically in the basin throughout this time, but some of the feldspathic and arkosic conglomerates and shales, particularly in the middle and upper parts, probably are nonmarine alluvial deposits. North and south of Gallinas Creek some conglomerates, both marine and nonmarine, contain large amounts of granules and small pebbles of unweathered pink feldspar. The lithology of these rocks suggests proximity to a source of Precambrian rocks that may have been west or north of the present outcrops. One possible source is Precambrian quartzofeldspathic gneiss and pegmatites west of the Cenozoic Blue Canyon fault (Plate 1) west of Johnson Mesa on what may have been the northern part of the Bernal uplift (Fig. 55). A more conspicuous source, as indicated by a northward thickening and coarsening of arkose units, is the eastern part of the present Hermit Peak structural block.

The Manuelitas saddle (Plate 4) and the trough of the Rociada Basin on its west side are syndepositional structures as shown by the thickening of the Alamitos Formation into these features where deposition seems to have been mainly continuous in late Desmoinesian through Virgilian time. The coarseness, angularity, and poor sorting of some conglomeratic sediments in the saddle and the trough suggest a nearby source terrane of Precambrian rocks. The coarse-grained granite, alaskite pegmatites, and included patches of metasedimentary and meta-igneous rocks exposed on the east side of the present Hermit Peak are lithologically appropriate to have been the source of feldspar-rich sediments and quartzite pebbles if the Hermit Peak block was a narrow, west-tilted, asymmetric anticline that was raised intermittently along a reverse fault adjacent to the deepening trough. The thick, crossbedded arkoses and interbedded unfossiliferous red shales of the Alamitos, especially those just east of the present Hermit Peak at Rito Colorado, Rito Chavez, and Deer Creek, appear to be alluvial fans, as do the thick arkoses and unfossiliferous red shales in the middle and upper parts of the formation in the Cenozoic Las Dispensas syncline at Sapello River and Manuelitas Creek. Even the uppermost marine limestones and shales in these areas contain much coarse sand and granules, and their fossils are thick-walled varieties, suggesting deposition in a rigorous, nearshore environment.

The lithology of the thick feldspathic conglomerates in the lower (late Desmoinesian) part of the Alamitos at the east front of the mountains west of Sapello also suggests nearby source areas, possibly to the west, or in the nearby part of the Sierra Grande uplift to the east. The upper part of the Alamitos near the eastern front of the mountains is poorly exposed and partly cut out by the Sapello fault but, where it can be seen west of Sapello, the upper part contains thicker limestones and a greater proportion of gray to olive-gray marine shale than does the upper part of the formation to the west. This suggests that the mainly Late Pennsylvanian upper part of the Alamitos in the eastern part of the area was deposited in a more seaward environment, although it, too, contains some thick feldspathic beds.

The depositional model envisioned for the Alamitos Formation in the Manuelitas saddle is one in which subsidence was mainly continuous, and uplift of the Hermit Peak block was episodic. Lobate alluvial fans and mud-flat deposits prograded eastward episodically into the Rociada Basin and onto the saddle from the Hermit Peak island, but these deposits were inundated by shallow seas that transgressed back westward across the saddle as basinal depression continued. Perhaps the Hermit Peak "island" itself was inundated at times and fine-grained sediments were derived from more distant sources. This model explains some of the facies distribution and directions of thickening and coarsening of sediments in the Alamitos, but the model is not entirely satisfactory because thick conglomerates at the eastern front of the mountains also contain locally abundant fresh pink feldspar clasts that range from granules to small pebbles. Some of these sediments may have been derived from as far away as the southern part of the Tecolote uplift and the adjacent part of the Sierra Grande uplift southeast of Las Vegas. On the Manuelitas saddle northwest of Manuelitas thick feldspathic sandstone and conglomerate in the lower part of the Alamitos may have had sources of Precambrian rocks in the area of the present El Oro Mountains.

North of the Manuelitas saddle, the Pennsylvanian anticline between Rito Cebolla and Mora River (Plate 4C; Fig. 68) is inferred mainly from the thinning of the Alamitos in the linear belt of outcrops near the eastern front of the mountains. The internal stratigraphy of the Alamitos indicates that the anticline was active (Fig. 68*B*) during Desmoinesian and Late Pennsylvanian time and that it influenced the deposition of the parts of the Alamitos to the north and south. Therefore, most of the feldspathic and arkosic rocks at Mora River probably were not derived from the south.

The coarse, poorly sorted nature of feldspathic to arkosic sediments of the Alamitos Formation at Mora River and farther north suggests another nearby source area of Precambrian rocks, as does the presence of thick units of crossbedded, broadly lenticular, stream-channel sandstones and conglomerates and unfossiliferous red shales that apparently are mainly nonmarine or mudflat deposits. The Precambrian rocks of El Oro Mountains contain thick quartzofeldspathic rocks, quartz veins, and thick alaskite pegmatites that could have been a local source for the arkoses if these basement rocks formed an exposed core of an anticlinal uplift or faulted anticline that was part of the older El Oro uplift (Fig. 27). The arkoses at Mora River contain common but minor amounts of amphibolite fragments, muscovite-schist fragments, and abundant mica that also could have been derived from the Precambrian rocks of the eastern part of El Oro Mountains. The model envisioned is, again, that of a narrow, west-tilted, asymmetric anticline, uplifted episodically along faults on its east side, to form a low island that shed first-cycle sediments (those derived directly from crystalline rocks). These formed alluvial fans or fan deltas that periodically prograded eastward or northeastward into the Rainsville trough and periodically were inundated by shallow seas as basin subsidence continued. Although local sources for the arkoses of the Alamitos seem likely, the silt, clay, and finer grained, better sorted sand in the formation, especially in the marine beds, could have been derived from greater distances and from multiple source areas. The model would require that eastward-merging angular unconformities occurred in Desmoinesian and older sedimentary rocks

(Fig. 27) that are not present now on the west flank of the anticline because of Cenozoic erosion. This postulated relationship would be similar to the inter- and intra-formational unconformities in Pennsylvanian rocks that still are discernible on the west flank of the Tecolote uplift.

Thick feldspathic to arkosic sandstones in the Alamitos Formation are interbedded with marine shale and thin limestones at outcrops north of the area of this report at least as far north as Guadalupita (loc. 4, Plate 3). The sediments of the northern areas may have been derived from Precambrian rocks of the eastern part of what is now the Rincon Range north of Mora, a possible source that was suggested previously in this report for some of the coarse sediments of the Sandia and Porvenir Formations. The Precambrian rocks in the Rincon Range are mainly micaceous quartzites, but alaskite pegmatites and quartzofeldspathic rocks also are present at outcrops in the eastern part of the valleys just east of the mountains and west of a zone of Cenozoic reverse faults (Plate 2; Bachman, 1953).

Outcrops near Los Cisneros (loc. 4, Plate 3) about 5 mi (8 km) north of the mapped area of this report, that previously were discussed in connection with their fossils, provide additional evidence suggesting a nearby source of detritus from Precambrian rocks during deposition of the Alamitos Formation. The Alamitos consists primarily of thick, very coarse grained to pebbly, sandstones that form massive ridges. These rocks contain abundant angular to subangular, unweathered pink feldspar clasts some of which range up to 0.75 inch (1.9 cm) diameter. Pebbles of granitic gneiss, schist, and quartzite are common, and muscovite is common in some beds. A small proportion of the Alamitos here is red to greenish-gray shale and siltstone and a few beds of gray shale. A few beds of gray limestone are interlayered, and several of them contain Late Pennsylvanian marine fossils.

The Alamitos near Los Cisneros is similar in some respects to the Alamitos at Mora River, but a considerably greater proportion is conglomeratic sandstone near Los Cisneros. These rocks are mainly alluvial-fans deposited on the western margin of the Rainsville trough adjacent to the El Oro–Rincon uplift. The proportions of sandstone and their coarseness decrease eastward in only about 6 mi into the Rainsville trough where the Alamitos may be mainly marine at the Amoco "B" and "A" no. 1 Salmon Ranch wells (Plate 3).

If Precambrian rocks of the eastern flank of the El Oro–Rincon uplift were the sources of these sediments of the Alamitos Formation, the sediments should become finer to the northeast of the place where the Precambrian of the Rincon Range plunges northward beneath older Pennsylvanian rocks (Plate 2) and could not have been a source of Late Pennsylvanian first-cycle sediments. A section measured by May et al. (1977, loc. 2, plate 1) north of Black Lake suggests that this is the case. The lower 500 ft (150 m) of their section is mostly very fine to medium-grained sandstone. Some brown, gray, and green shale is interlayered and at least two thin beds of fossiliferous marine limestone occur in the interval. This part of their section is similar to the Alamitos, although we have no paleontologic data to confirm this correlation. Possibly, part of the overlying 950 ft of their section also is Alamitos. These upper rocks also are predominantly very fine to fine-grained sandstone. The well nearest this section is the True Oil Co. no. 25–21 Medina, which is about 4 mi (6 km) southeast of the surface section. (See Fig. 72 for location of the well.) We are not able to identify the Alamitos confidently from logs of the well, but the interval several hundred feet above a depth of about 3,600 ft may be equivalent to the Alamitos. It is mostly shale that contains some limestone and thin units of fine- to coarse-grained sandstone, which suggests that the area was farther to the northeast from a possible source of coarse clastics in the El Oro–Rincon uplift.

Alternatives to our hypothesis of local sources of coarse to conglomeratic feldspathic and arkosic sediments of the Alamitos Formation in the El Oro–Rincon uplift include the more traditional views that they were derived predominantly from the Brazos (Uncompahgre) uplift (Fig. 4) west of the Rowe–Mora Basin (Sutherland, 1963, p. 41–44), or from the Sierra Grande uplift to the east, or from both. (See discussion in Foster et al., 1972, p. 15; and Roberts et al., 1976, p. 143.) If the coarse sediments had been derived from the Brazos uplift, the shortest distance of transport to the Mora River area would have been a little more than 20 mi (32 km). The exact areas of wedgeouts of Pennsylvanian rocks onto Precambrian rocks on the flanks of the Sierra Grande uplift are not known. However, using the scanty well data available in the Las Vegas Basin, some approximate minimum distances of the wedgeouts from various parts area of this report are estimated. (See Fig. 72.) If the coarse sediments in the Mora River area were derived from the southern part of the Sierra Grande uplift in the subsurface southeast of Las Vegas, the shortest distance of transport would have been 26–28 mi (41-45 km). If the coarse sediments in the Mora River area were derived from the western part of the Sierra Grande uplift east of the area of this report, the shortest distance of transport would have been about 30 mi (48 km). Actual distances of transport in streams crossing the subsiding and recurrently marine interior of the Rainsville trough probably would have been considerably greater. If the distribution of part of the coarse sediments was a result of shallow marine processes, such as longshore currents, the distances of transport also would have been greater.

The poor sorting, the angularity of clast shapes, the low degree of rounding, and the coarseness of many clasts in the arkoses of the Alamitos from Mora River north suggest that fluviatile or marine transporting mechanism did not operate on these sediments through great distances. In particular, the general abundance of clasts of unweathered feldspar in the size range from granules to small pebbles, some almost 1 inch (2.5 cm) diameter, does not indicate long distances or times of transport before deposition, nor does the presence of abundant muscovite in some beds at the surface and in the subsurface. The large size of many feldspar clasts suggests they were derived mainly from pegmatites; therefore, the large bodies of granite in the western and northern parts of the mountains were not necessarily their sources. The argument is, admittedly, intuitive; we have no quantitative data to support it for the postulated Pennsylvanian sedimentary environments.

The Cimarron arch (Fig. 4) on the northeast side of the Rainsville trough also might have been a source of sediments of the Alamitos. However, the northward change to predominantly shaly rocks in the subsurface does not indicate that the Cimarron arch was a major contributor of first-cycle coarse sediments to the western part of the Rainsville trough at this time (Late Pennsylvanian). On the other hand, if the arch and perhaps the San Luis uplift to the northwest (Fig. 4) were sources of sediments, the sediments have been decreased in grain size and sorted relatively well, or they are predominantly second-cycle clasts which were eroded from uplifted older Pennsylvanian sedimentary rocks. Because the intrabasinal uplifts (Fig. 55) do not seem large enough to have supplied the total volume of sediments of the Alamitos Formation, much of the finer grained sediment of the Alamitos in the area of this report probably was derived from the Sierra Grande uplift and possibly from other basin-marginal uplifts.

Sangre de Cristo Formation

Terminology of earlier investigations

The name Abo Sandstone was applied by Darton (1922, p. 181, 195–205) to the nonmarine, feldspathic to arkosic, coarse-grained to conglomeratic sandstones and interbedded mainly red shales that lie on the Alamitos Formation (upper part of the Magdalena Group of Darton) across the southern part of the Sangre de Cristo Mountains from Lamy to Bernal. Darton correctly assessed the Permian age of the nonmarine rocks, and he noted their lithologic similarity to the Abo in the Sandia Mountains and at its type locality at the south end of the Manzano Mountains in central New Mexico.

The name "Sangre de Cristo conglomerate" had been used by Hills (1899) for what he termed Carboniferous rocks in the mountains west of Trinidad, Colorado. Later, Melton (1925b, p. 811–812) subdivided these rocks into the "Upper Sangre de Cristo conglomerate" and the "Lower Sangre de Cristo conglomerate," specifying that the rocks are Pennsylvanian and Permian. Melton (1925b, fig. 1) correlated his "Upper Sangre de Cristo conglomerate" with the then-designated Abo Sandstone and overlying Permian rocks in the Las Vegas–Mora region in the southeastern Sangre de Cristo Mountains of New Mexico. He indicated that the "Lower Sangre de Cristo conglomerate," including his marine Veta Pass limestone member, of Colorado, is equivalent to the Magdalena Group of New Mexico.

Darton (1928a, p. 255–269) continued to classify the mainly marine rocks in the southern part of the Sangre de Cristo Mountains as the Magdalena Group and to classify the overlying arkose and shale as the Permian Abo Sandstone. On the geologic map of New Mexico, Darton (1928b) showed the Abo Sandstone as persisting northward along the eastern front of the mountains to the latitude of Mora. Darton (1928a) included several hundred feet of medium-grained, brick-red sandstones and interbedded red shale and thin dolomites and limestones in the upper part of his Abo, although he noted (p. 261) that these rocks might correlate with the then-designated Yeso Member of the Chupadera Formation (now abandoned) of central New Mexico. These finer grained upper beds in the southern part of the Sangre de Cristo Mountains were assigned later to the Yeso Formation (Needham and Bates, 1943; Read et al., 1944) that lies above the Abo at its type locality.

Read et al. (1944) and Read and Wood (1947, p. 223) introduced the term "Sangre de Cristo Formation" for the rocks between the Magdalena Group and the Yeso Formation in the southern Sangre de Cristo Mountains in New Mexico and assigned the formation an age of Pennsylvanian and Permian(?). Since then, the term Sangre de Cristo Formation has been used in the literature of this region in New Mexico as a unit of Late Pennsylvanian and Early Permian age.

Type region and type locality

The rocks called by Hills (1899) and Melton (1925b) the Sangre de Cristo Conglomerate in the Sangre de Cristo Mountains west of Huerfano Park, Colorado, were reexamined by J. H. Johnson (1929). Johnson described a "Lower Sangre de Cristo Formation," and an "Upper Sangre de Cristo Formation," which were said to be separated, at least in some localities, by a local angular unconformity. The lower formation of Johnson (1929) is mainly marine, Pennsylvanian in age, and was said to correlate closely with the Magdalena Group of New Mexico. The upper formation is pebble-to-boulder conglomerate and interbedded mainly red shale. Johnson (1929, p. 10) reported that, at one locality, a limestone bed, probably several thousand feet above the base of the upper formation, contains marine fossils. The "Lower Sangre de Cristo Formation" was said to be 1,800–2,600 ft (550–790 m) thick, and the upper formation was said to be 8,000–11,000 ft (2,440–3,350 m) thick. Johnson (1929, p. 10–12) wrote that "the general opinion among geologists would place at least a considerable portion" of his "Upper Sangre de Cristo Formation" in the Permian, but he pointed out that the fossils he found provided inconclusive evidence. He reported that the Sangre de Cristo Formation was overlain unconformably by Jurassic rocks.

Brill (1952) extended the terms Sandia Formation and Madera Formation northward from New Mexico into the Huerfano Park region of Colorado and applied them to fossiliferous marine rocks that are, apparently, mainly the same as the Lower Sangre de Cristo of Johnson (1929). The youngest marine rocks assigned to the Madera in Colorado by Brill are Middle Pennsylvanian (Desmoinesian). Brill (1952, p. 828–832) reported that, in Colorado, the contact is obscure between his Madera and the overlying, mainly nonmarine, red beds of his restricted Sangre de Cristo Formation. He noted (p. 834) that reptilian bones had been found in his restricted Sangre de Cristo Formation, and he assigned it to the Early Permian (Wolfcampian) on the basis of these fossils, although he suggested that, inasmuch as marine rocks of Missourian and Virgilian ages were not found in northernmost New Mexico and southern Colorado, the lower part of his Sangre de Cristo might be nonmarine Pennsylvanian.

In later work in the Huerfano Park area, R. B. Johnson (1959) mapped the marine Pennsylvanian rocks as an unnamed unit. Johnson (1959) wrote that these rocks are gradational into overlying red conglomerate and shale that he mapped as the Sangre de Cristo Formation. Johnson (1959, p. 93) wrote that gray nodular and crystalline limestones are not abundant but are most common near the base of the Sangre de Cristo Formation. The upper 50–100 ft (15–30 m) of the Sangre de Cristo Formation, as mapped by Johnson (1959), is fine-grained sandstone, siltstone, and shale; his Sangre de Cristo Formation is overlain by the Middle Jurassic Entrada Sandstone. Johnson (1959) assigned the Sangre de Cristo to the Pennsylvanian and Permian, citing C. B. Read for this age designation.

Inasmuch as a type locality for the Sangre de Cristo Formation had never been specified, Bolyard (1959, p. 1922–1924) proposed a type locality near Crestone, Colorado. He did not describe a continuous type section because the rocks are faulted and because the rugged topography and inaccessibility make measurements difficult. Bolyard (1959, p. 1924–1925) described a lower member and the overlying Crestone Conglomerate Member that intertongues with his lower member. Bolyard's Crestone Conglomerate Member is Melton's (1925b) "Upper Sangre de Cristo conglomerate." Bolyard specified the base of the Sangre de Cristo as "the lowest red beds characteristic of the formation", indicating that the Sangre de Cristo is transitional downward into more somber colored and mainly marine beds he assigned to the Madera Formation. Although most of the Sangre de Cristo defined by Bolyard is terrestrial, he included (p. 1924) limestone with marine fossils in at least one place. He did not specify or describe an upper boundary for the Sangre de Cristo, but he mentioned that the oldest overlying formation is the Middle Jurassic Entrada Sandstone. Bolyard (1959, p. 1926) dated the Sangre de Cristo Formation in southern Colorado as Middle Pennsylvanian (late Desmoinesian) to Early Permian (Wolfcampian).

De Voto et al. (1971) included thin stromatolitic limestones in the lower part of the Sangre de Cristo Formation of the northern Sangre de Cristo Mountains in Colorado. Although these limestones are not otherwise fossiliferous, De Voto et al. (1971, p. 155) considered them to be marine, but of Permian age, because of palynomorphs and other plant fossils from the lower part of the formation. They tentatively concluded (p. 161) that rocks of Missourian and Virgilian (Late Pennsylvanian) ages are not present beneath their Sangre de Cristo, but they pointed out the possible conflict of this conclusion with vertebrate-fossil data. In the area considered by De Voto et al. (1971) the Sangre de Cristo Formation is overlain unconformably by the Jurassic Entrada Sandstone.

Lindsey and Schafer (1984) measured and described a detailed section of most of the Sangre de Cristo Formation at the type locality of Bolyard (1959) west of the crest of the Sangre de Cristo Mountains in the USGS Electric Peak 15-minute quadrangle in Colorado. They designated their section as the principal reference section for the formation, and described the lower member, 1,985 ft (605 m) thick, as consisting of red conglomerate, sandstone, siltstone, and a minor proportion of shale. The Crestone Conglomerate Member, 3,715 ft (1,132 m) thick, consists of boulder conglomerate, conglomeratic sandstone, sandstone, and minor proportions of siltstone and shale. The lower member interfingers with the Crestone Conglomerate Member and grades laterally and abruptly into the Crestone southeast of the reference section. The top of the Sangre de Cristo is not present at the reference section because of Cenozoic erosion.

According to Lindsey and Schafer (1984), the Sangre de Cristo Formation at the reference section is nonmarine and is conformable with the underlying fossiliferous Middle Pennsylvanian Minturn Formation. However, to the northwest, their mapping indicates that the lower member of the Sangre de Cristo intertongues with the Minturn Formation, and the lower part of the Sangre de Cristo there (Lindsey and Schafer, 1984) contains abundant marine limestone. Southeast of the reference section, the stratigraphically expanded (by intertonguing) Crestone Conglomerate Member lies unconformably on the Minturn and cuts out about 395 ft (120 m) of the uppermost part of the Minturn.

The uppermost limestone bed assigned to the Minturn by Lindsey and Schafer (1984) contains the fusulinid *Beedeina* sp. of Desmoinesian age, and limestones within their Sangre de Cristo Formation contain other marine invertebrates that are also assigned a Desmoinesian age. No other fossil data were obtained at or near the reference section of the Sangre de Cristo (Lindsey and Schafer, 1984); therefore, its age is fixed only as Desmoinesian or Desmoinesian and younger. Lindsey et al. (1986, p. 546–547) discussed the evidence of age and concluded that an age younger than Middle Pennsylvanian is possible for the upper part of the Sangre de Cristo Formation, mainly because the upper part is unfossiliferous and undated.

At places along the eastern front of the Sangre de Cristo Mountains from west of Vermejo Park, New Mexico, to the south end of Huerfano Park, Colorado, thin but lithologically distinct rock units lie between the Sangre de Cristo Formation and the Middle Jurassic Entrada Sandstone. Rocks in this position in New Mexico and for about 8 mi (13 km) north of the Colorado line were separated from the Sangre de Cristo and were named the Johnson Gap Formation of Triassic(?) age by Johnson and Baltz (1960). These rocks in Colorado were mapped by Johnson (1969). Other rocks in the same position in Colorado, but having slightly different lithology, were correlated by Johnson and Baltz (1960) with the Lykins(?) Formation of Late Permian and Early Triassic age. No fossils (other than unidentified wood fossils) were found by these writers in the Johnson Gap or Lykins(?) Formations, and their age assignments were based only on stratigraphic position and lithologic correlation. Later, Triassic plant fossils were reported from the Johnson Gap Formation at Ricardo Creek just south of the Colorado border (Pillmore and Laurie, 1976, p. 47). Therefore, the Sangre de Cristo in southernmost Colorado probably is not younger than Permian. Elsewhere, in southern Colorado the latest age of the Sangre de Cristo is known only to be older than the Middle Jurassic Entrada Sandstone that overlies it.

Definition in area of this report

The Sangre de Cristo Formation, as mapped for this report in the southeastern part of the mountains, consists of red, purple, and some greenish-gray shale that contains interbeds of thin to thick, reddish- to yellowish-gray, feldspathic to arkosic sandstone, pebbly arkosic conglomerate, and a few gray to purplish-gray, nonfossiliferous, bedded limestones and beds of limestone nodules. Throughout the area the basal beds are pebbly, feldspathic to arkosic, conglomerates. The formation is believed to be entirely nonmarine throughout the area except for a bed of fossiliferous sandstone near the base at one locality west of Sapello. Throughout the area of this report (and entirely across the southernmost part of the mountains) the Sangre de Cristo Formation is overlain by the Lower Permian (Leonardian) Yeso Formation. The Yeso Formation consists of fine- to medium-grained, arkosic, mainly parallel-bedded, sandstone and interbedded red shale, and locally contains a few thin beds of gray dolomite and limestone, and a few thin beds of gypsum. The Yeso is generally brick-red, and the color contrasts with the maroon, purplish-gray, and yellowish-gray colors of the underlying Sangre de Cristo Formation.

South of Gallinas Creek, the Sangre de Cristo Formation probably is entirely Early Permian (Wolfcampian) age. To the north, it may be entirely Permian as far north as the vicinity of La Cañada del Guajalote. From there north the lower part contains nonmarine rocks that are probably Late Pennsylvanian (Virgilian?), on the basis of a microflorule.

North of the area of this report, the Alamitos Formation is present as a recognizable stratigraphic unit beneath the Sangre de Cristo Formation at least as far north as Los Cisneros, as was discussed previously. Paleobotanical evidence from the lower part of the Sangre de Cristo south of Guadalupita indicates that most of the formation is Early Permian age at least that far north.

The general similarity of lithology of the Sangre de Cristo Formation of the southeastern part of the mountains to parts of the Sangre de Cristo in its type region in Colorado suggests that the two are partly correlative. However, the lower part of the formation in Colorado contains marine rocks that are as old as Middle Pennsylvanian (about mid-Desmoinesian) and, thus, are equivalent to the upper part of the Porvenir Formation. Part of the Sangre de Cristo Formation in Colorado may correlate with the Alamitos Formation, depending on varying interpretations of the ages of the scanty collections of vertebrate fossils in Colorado. In New Mexico an additional factor of uncertainty of correlations results from paleotectonic conditions whereby the entire Pennsylvanian and Permian section is missing from the ancient Cimarron uplift north of the area of this report. At places on this uplift Triassic rocks lie with sedimentary contact on the Precambrian (Robinson et al., 1964, plate 3; Baltz, 1965, p. 2049, fig. 4; Goodknight, 1976).

We believe it would have been advisable to retain the name Abo Formation for the nonmarine Lower Permian rocks of the southern part of the Sangre de Cristo Mountains because these rocks are lithologically similar to and have generally the same age and stratigraphic relations to adjacent rocks as the Abo in the mountain ranges of central New Mexico. However, we continue to use the name Sangre de

Cristo Formation in the area of the present report because this term has been used widely, and exclusively, in the literature of northeastern New Mexico since the work of Read et al. (1944).

Distribution and thickness

In the belt of hogbacks along the east front of the mountains the Sangre de Cristo Formation crops out as steeply dipping beds, that are overturned at many places from about Montezuma north past Mora River and are broken by several major faults. The outcrop belt is nearly continuous except between Montezuma and Cañon Bonito where the formation is cut out entirely by the Montezuma fault (Plate 1; also see Fig. 32). In the southern part of the area the Sangre de Cristo Formation is exposed in broad areas of gently dipping beds on the south-plunging Creston anticline, in the Chapelle syncline, and in a broad area of gently south- and southwest-dipping beds in the drainage basin of Pecos River. In the central part of the area erosional remnants of only the lower part of the formation are preserved, mainly in the axial parts of Las Gallinas and Las Dispensas synclines. The Sangre de Cristo is present at wells in the Las Vegas Basin, suggesting that it is generally present in the subsurface (Plate 4*D*) except on the Paleozoic Sierra Grande uplift.

The greatest known thickness of the Sangre de Cristo Formation in the area of this report is 2,575 ft (785 m) at Mora River and farther north (Plate 3). May et al. (1977, plate 1) reported a thickness of about 3,050 ft (930 m) at Mora River, but they included in the lower part of their Sangre de Cristo Formation about 470 ft (143 m) of partly marine rocks that we assign to the upper part of the Alamitos Formation. (See Fig. 69.)

Along the eastern front of the mountains and in the Las Vegas Basin the Sangre de Cristo Formation thins southward (Plate 4*D*). At Rito Cebolla, the Sangre de Cristo and the Alamitos Formation are in fault contact (Baltz and O'Neill, 1984), and an unknown but probably small amount of both formations is missing. The Sangre de Cristo is at least 2,300 ft (700 m) thick on the north side of Rito Cebolla. From Rito Cebolla south to Manuelitas Creek the Sangre de Cristo is in fault contact with Pennsylvanian rocks, and its total thickness cannot be determined.

Northwest of Sapello the slightly overturned Sangre de Cristo Formation is in sedimentary contact with underlying and overlying rocks, but most of the middle part of the formation is concealed by alluvium in the valleys of Sapello River and Manuelitas Creek (Baltz and O'Neill, 1986). The minimum thickness of the Sangre de Cristo just south of New Mexico Highway 94 is estimated to be about 1,500 ft (460 m), but the formation may be thinned tectonically by squeezing and by a probable intraformational reverse fault that is concealed by the alluvium.

Farther south, between Sapello River and Sanguijuela Arroyo, the base of the Sangre de Cristo Formation is cut out by the Sapello fault, but a short distance south of that arroyo, the formation does not seem to be faulted (Baltz, 1972), although exposures are poor. About 0.3 mi (0.5 km) south of Sanguijuela Arroyo its thickness is about 1,300 ft (395 m). Still farther south, in a small area just north of Cañon Bonito, the Sangre de Cristo may not be faulted (Baltz, 1972), and it is about 900 ft (275 m) thick. Northrop et al. (1946, loc. 13) show a thickness of 920 ft near here, but they considered the base of the section to be faulted. If the Sangre de Cristo is only about 900 ft thick at Cañon Bonito, it has thinned rapidly southward from Sapello River onto the northern part of the Paleozoic Tecolote uplift.

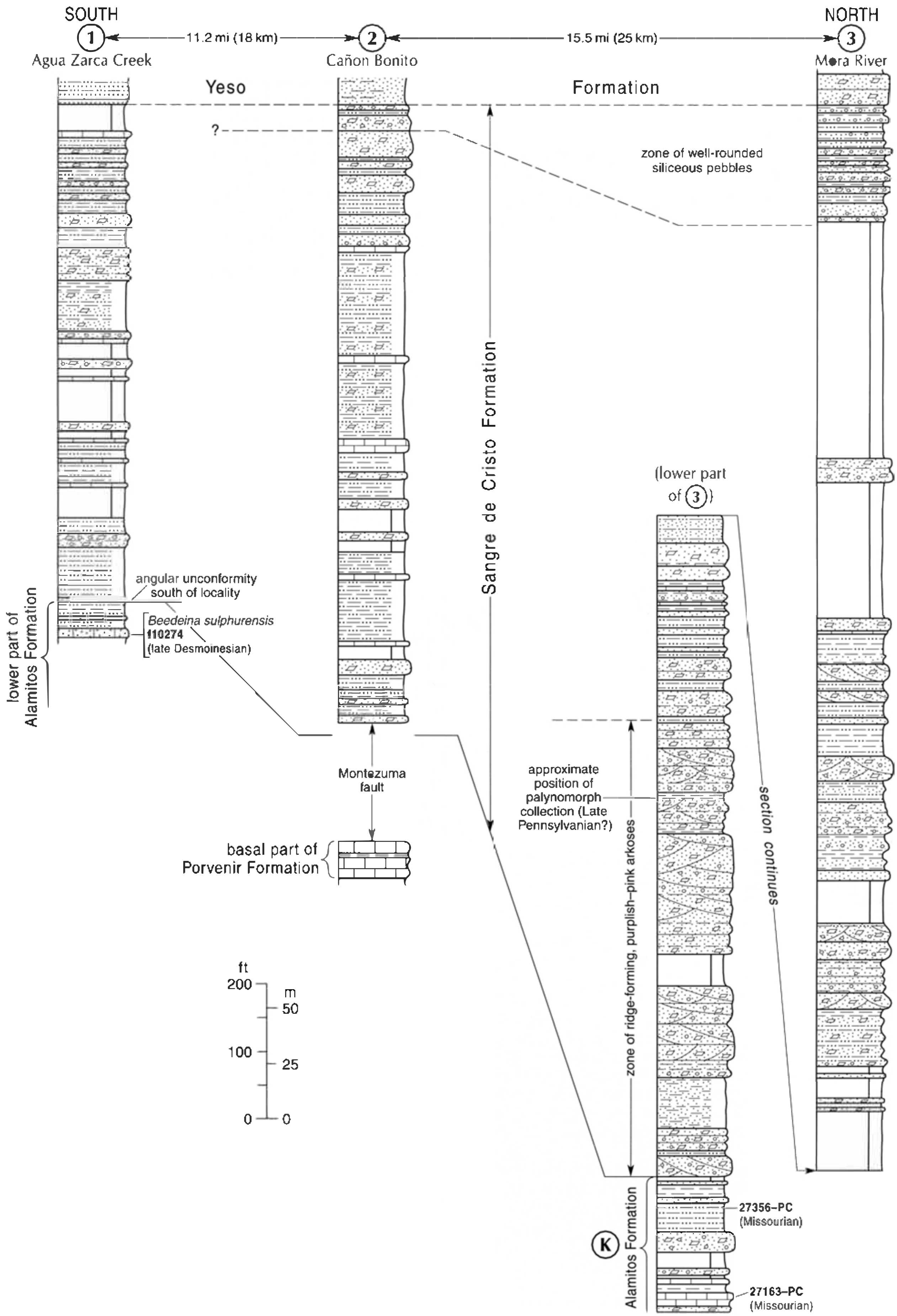
The Sangre de Cristo Formation also thins rapidly southeastward in the subsurface from Sapello to the J. D. Hancock no. 1 Sedberry well in the Las Vegas Basin where the formation is only about 560 ft (170 m) thick. The positions of the isopachs (Plate 4*D*) suggest that the subsurface thinning occurs on a northwest-plunging broad anticlinal uplift that may have been active tectonically during the deposition of the Sangre de Cristo.

From Cañon Bonito south past Montezuma the Sangre de Cristo Formation is cut out entirely or mainly by the Montezuma fault (Baltz, 1972). May et al. (1977, p. 8) indicated that the Sangre de Cristo is only a few hundred feet thick near Montezuma, possibly because of thinning on the Tecolote uplift. However, outcrops on the north face of the hill just south of Gallinas Creek at Montezuma (Baltz, 1972) show that the east-dipping lower part of the Porvenir Formation is thrown against the sharply overturned upper part of the Sangre de Cristo along the Montezuma fault. The outcropping Sangre de Cristo east of the fault is greatly sheared, and its beds are dislocated internally along small faults. Southward from Montezuma, as the fault dies out, progressively more beds of the Sangre de Cristo and the underlying Alamitos and Porvenir Formations appear west of the fault (Baltz, 1972), and about 1.5 mi (2.4 km) south of Montezuma, the formation is estimated to be about 850 ft (260 m) thick.

Farther south along the eastern front of the mountains, isopachs of data from the stratigraphic sections of Northrop et al. (1946) suggest two Early Permian structural culminations and an intervening structural sag on the Paleozoic Tecolote uplift west of Aqua Zarca (Plate 4*D*) where the Sangre de Cristo ranges from about 300 ft (90 m) to 740 ft (225 m) thick. On the west slope of Tecolote Peak the Sangre de Cristo is about 350 ft (105 m) thick, and west of the Precambrian outcrop on Ojitos Frios anticline, the Sangre de Cristo is estimated from the topographic map to be about 350 ft (105 m) thick. The formation thickens westward into the Chapelle syncline, and the preserved part is at least 700 ft (210 m) thick between Dead Horse Canyon and Fisher Hill (USGS San Geronimo quadrangle) west of San Geronimo where the upper part of the formation has been removed by Cenozoic erosion. Farther south in the Chapelle syncline, sections 23 and 25 of Read et al. (1944) show the Sangre de Cristo thinning southward along Tres Hermanos Creek from about 960 ft (290 m) to about 650 ft (198 m) northwest of Bernal.

In the south-central part of the area, on the north slope of Starvation Peak west of Bernal, the contact of the Sangre de Cristo Formation and the underlying Porvenir Formation is concealed by thin pediment deposits, but the thickness of the Sangre de Cristo is about 320 ft (98 m). West of Starvation Peak, the Sangre de Cristo thickens conspicuously toward Pecos River. The thickness west of the river is between 900 and 1,000 ft (275 and 300 m), as determined from constructing a cross section from the base of the formation north of San Juan to the top near Punta de la Mesa de San Jose on Glorieta Mesa west of Pecos River (USGS North San Ysidro quadrangle). Well data show that, in the subsurface south of San Jose, the Sangre de Cristo is more than 1,000 ft (300 m) thick (Foster et al., 1972, fig. 6).

FIGURE 69—Stratigraphic sections of the Sangre de Cristo Formation, eastern front of mountains. Localities and line are shown on Plate 4*D*. Lithologic symbols are explained in Figure 9. Locality 1 adapted from Northrop et al. (1946), sec. 4, measured along New Mexico Highway 283 about 0.4 mi (0.6 km) west of Agua Zarca. Locality 2 adapted from Northrop et al. (1946), sec. 13, measured on north side of Cañon Bonito about 5 mi (8 km) north-northwest of Montezuma. Locality 3 mainly adapted from May et al. (1977, plate. 1), sec. 7, measured on north side of Mora River about 4 mi (6.4 km) southeast of Mora; upper and basal parts of section 3 are modified in the present report.


SOUTH
1
11.2 mi (18 km)
2
15.5 mi (25 km)
NORTH
3
Agua Zarca Creek
Cañon Bonito
Mora River
Yeso
Formation
?
zone of well-rounded
siliceous pebbles
Sangre de Cristo Formation
(lower part
of 3)
angular unconformity
south of locality
Beedeina sulphurensis
110274
(late Desmoinesian)
lower part of
Alamitos Formation
Montezuma
fault
basal part of
Porvenir Formation
approximate
position of
palynomorph
collection (Late
Pennsylvanian?)
zone of ridge-forming, purplish-pink arkoses
section continues
ft
200
100
0
m
50
25
0
Alamitos Formation
K
27356–PC
(Missourian)
27163–PC
(Missourian)

The thickness variations in the southern part of the area show that the Paleozoic Tecolote and Bernal uplifts, the San Jose and San Geronimo Basins, and probably an anticlinal feature in the subsurface of the Cenozoic Las Vegas Basin were active tectonically during deposition of the Sangre de Cristo Formation. Although the sediments of the Sangre de Cristo buried most or all of the uplifts, recurrent tectonic movements determined the areas of greater and lesser sediment accumulation.

West of the area of this report, along the northern edge of Glorieta Mesa, the Sangre de Cristo Formation thins westward from San Jose and near Rowe is only 513 ft (156 m) (Brill, 1952, p. 846) to 563 ft (170 m) thick (Foster et al., 1972, p. 13), indicating that an Early Permian anticline was west or southwest of the San Jose Basin (Fig. 4). Farther northwest, near Cañoncito, the Sangre de Cristo is more than 3,000 ft (915 m) thick (Booth, 1976, p. 36), indicating that a deep Early Permian basin lay west of the Rowe area and just east of the Paleozoic Cañoncito uplift where the Sangre de Cristo is only about 300 ft (90 m) thick (Booth, 1976, p. 36).

General lithology

In the southeastern part of the mountains the Sangre de Cristo Formation consists of red, purple, and greenish-gray shale and interbedded thin to thick, feldspathic to arkosic sandstones, and pebble conglomerates. The sandstones and conglomerates are similar generally to those in the Alamitos Formation, usually being very coarse grained to granule-grained and containing angular to subangular, pink feldspar clasts ranging from fine sand to pebbles. Lenses of quartzite pebbles and vein-quartz pebbles are common; limestone-pebble conglomerates occur at places, especially near the base, but are not common. Silica and clay are the main cementing agents of the sandstones, but some beds have calcareous cement. The color of fresh surfaces of sandstones is usually yellowish-gray, but the weathered colors are commonly light reddish brown to coppery brown. Although thick to massive arkosic sandstones and conglomerates are the most conspicuous lithologic types because of their resistance to weathering and erosion, much of the formation is composed of shale and siltstone and soft, fine- to coarse-grained sandstone in thin to thick beds that intergrade with shaly sandstone and shale.

Shales vary widely in lithology, ranging from claystone and siltstone to shaly sandstone. Some shales are gray to green, but most shales are reddish pink to maroon. In the lower half, many of the shales are slightly marly and contain lenses and scattered nodules of light-gray limestone and limestone concretions.

Limestone is common in the lower half, mainly in the shales, and is present also in the upper half, but it is a minor constituent. Distinctly bedded gray, micritic limestone occurs at places. A relatively persistent limestone bed, as much as 10 ft (3 m) thick, occurs in the lower third of the Sangre de Cristo north and south of Cañon Bonito on the eastern edge of the mountains. Other notable occurrences of bedded, gray limestone are in the bottom of Falls Creek west of Mineral Hill, at locality N (Fig. 58) at Dead Horse Canyon southwest of San Geronimo, and in roadcuts west of Agua Zarca. Several light-gray well-bedded limestones occur not far above the base of the Sangre de Cristo along New Mexico Highway 94 west of Sapello and farther north. Some of the bedded limestones have an appearance of being marine, but the only fossils found were a few tiny fragments that appear to be fish ribs in the limestone north of Cañon Bonito. The limestones of the Sangre de Cristo probably all are nonmarine.

Most of the limestones are nodular or are concretions in zones a few inches to 3 ft (1 m) thick. Irregular, botryoidal limestone masses are common at places. Internally, the masses are light-gray to white, dull-lustered patches of calcite, argillaceous calcite, and highly calcareous clay. Some of these limestones may have formed during diagenesis of sediments that were deposited as marly clay mud. Brown (1984, p. 116) suggested that some nodular limestones in the lower part of the Sangre de Cristo north of the area of this report originated as pedogenic caliche or in playa lakes.

The complex internal stratigraphy of the Sangre de Cristo Formation was not studied in detail; however, general observations of overall lithologic variations made during our field work and comparisons of stratigraphic sections published by Read et al. (1944), Northrop et al. (1946), and May et al. (1977) permit some generalized conclusions. The Sangre de Cristo is shalier at the south than the north and, although thick sandstones and conglomerates occur at many stratigraphic positions throughout the formation at all localities, the thickest sandstones and sequences of sandstones occur mainly in the north, notably north of Rito Cebolla. May et al. (1977, fig. 5) gave a sandstone to shale ratio of 0.6 for the formation west of Agua Zarca southwest of Las Vegas (loc. 1, Fig. 69); the ratio (including the upper part of the Alamitos of this report) at Mora River (loc. 3, Fig. 69) is given as 1.3. North of the area of the present report the ratio is given as 1.6. In general, the middle part of the formation is more shaly than the lower and upper parts. This characteristic, in the hogbacks at the eastern front of the mountains, causes the middle part to be eroded into strike valleys and to be poorly exposed.

Areal stratigraphy and lithology

Southern and south-central part of area—In the southwestern part of the area near San Juan (Plates 1, 4), where the Sangre de Cristo Formation is about 900–1,000 ft (275–300 m) thick, the lower 100 ft (30 m) of the formation is mainly ledge-forming, broadly lenticular, stream-channel sandstones, although about 30 percent is red clay shale. The basal part of this zone is light-gray, highly crossbedded medium- to coarse-grained feldspathic sandstone that is 30-40 ft (9–12 m) thick. At places angular limestone pebbles, 0.25–0.5 inch (0.6–1.3 cm) in diameter, occur as lenses near the top of this sandstone. Locally, the basal sandstone forms a single massive ledge, but at places, the beds are split by lenses of red shale. About 10 percent of the basal sandstone is pink feldspar clasts, and the sandstone is finer grained than the conglomerates that generally occur at the base of the Sangre de Cristo elsewhere in the southeastern part of the mountains.

The overlying rocks of the lower part of the Sangre de Cristo Formation near San Juan consist of three to four ledge-forming conglomeratic feldspathic sandstones interbedded with red shales. The sandstone beds average about 10 ft (3 m) thick and the shale units average about 20 ft (6 m) thick; sandstone and shale units both thicken and thin laterally. These sandstones are more typical of those of the Sangre de Cristo elsewhere in the area and are composed of angular to subangular coarse sand that contains granules and pebbles as much as 0.4 inch (0.9 cm) in diameter. Subangular pink feldspar clasts are abundant in all clast sizes including small pebbles.

The medial part of the Sangre de Cristo Formation, which forms the main bulk of the formation southwest of San Jose, is about 60 percent red shale and siltstone. The shales contain many interbeds of lenticular medium to very coarse grained arkosic sandstone. The medial part in this area is a distinctive facies of the Sangre de Cristo that was deposited on flood plains and in clearly defined stream channels. The upper several hundred feet of the formation is less shaly and contains thick, medium to very coarse grained feldspathic to arkosic sandstones that are generally more persistent than many of the lenticular sandstones of the medial part.

Eastward from Pecos River, the thinning of the Sangre de Cristo occurs mainly within the medial stream-channel and floodplain facies of the formation. Just west and northwest of Bernal, where the formation is about 320 ft (98 m) thick, the lower 100–150 ft (30–45 m) is ledge-forming, conglomeratic, feldspathic sandstones and interbedded poorly exposed red shales. The sandstones probably constitute only about 30 percent of the lower part, and generally are 10–15 ft (3–4.5 m) thick. The conglomeratic sandstones in the lower part of this interval are composed mainly of coarse sand and granules but commonly contain pebbles 0.25–1.5 inch (0.6–3.8 cm) diameter. The sand and granules are mainly subangular quartz, but 10–15 percent is pink feldspar. Pebbles are mostly gray and white subangular vein quartz, but red quartz is common, and a few pebbles of quartzofeldspathic gneiss were observed. Subangular feldspar clasts are granules and small pebbles. Stratigraphically higher in the lower part, some medium- to coarse-grained slightly feldspathic sandstones are similar to those at the base of the Sangre de Cristo near San Juan, but most beds west and northwest of Bernal are feldspathic to arkosic granule to pebble conglomerates. The upper part of the Sangre de Cristo exposed south of Bernal is red shale containing ledge-forming beds of very coarse grained feldspathic sandstone and is similar to the upper part near Pecos River. A general eastward coarsening of the lower part of the formation suggests a source terrane of Precambrian rocks to the east.

Lee (1909, p. 35–36) described a "conglomerate-breccia" containing pebbles and cobbles of igneous and metamorphic rocks, red sandstone, and fossiliferous limestone as being at the base of what is now called the Sangre de Cristo Formation along the railroad 1 mi (1.6 km) west of Bernal. He suggested that the sediments were derived from the uplifted mountains to the north. We were not able to find rocks of this description in the Sangre de Cristo. However, the description fits Tertiary or Quaternary terrace deposits that lie with angular unconformity on the Porvenir and Sangre de Cristo south of the railroad tracks west of Bernal and in roadcuts on the access road north of Interstate Highway 25 west of the crossover to Bernal. It is likely that the outcrops available to us are better than those observed by Lee. At any rate, we do not know of any evidence near Bernal to suggest that the Bernal uplift supplied very coarse detritus to this part of the area during deposition of the Sangre de Cristo Formation.

On the west limb of the Chapelle syncline, about 3 mi (4.8 km) northwest of Bernal, fossiliferous limestone pebbles and rounded limestone boulders as large as 1.5 ft (45 cm) across are present in the thin basal beds of the Sangre de Cristo Formation (loc. 1, Fig. 58). Much of the overlying lower and middle parts of the Sangre de Cristo are red shale that contains interbedded thin feldspathic sandstones. Presumably, the limestone pebbles and boulders were derived from the Porvenir Formation on a nearby part of the Bernal uplift.

Farther north, on the north fork of San Pablo Creek, limestone pebbles were not observed in the thick, coarse arkoses of the lower part, although the Sangre de Cristo in the vicinity of San Pablo Creek lies unconformably on the lower part of the Porvenir. In the lower valley of San Pablo Creek, east of San Pablo, the lower part of the Sangre de Cristo also contains thick beds of feldspathic to arkosic conglomerate and interbedded red shale, as it does in the upper reaches of the creek. These rocks may be fans locally derived from adjacent Precambrian granitic rocks of the Paleozoic Bernal uplift. Higher beds are thick shale and some interbedded feldspathic conglomeratic sandstones. On the north fork of San Pablo Creek several beds of limestone-pebble conglomerate were observed an estimated 200 ft (60 m) above the base of the Sangre de Cristo. Some thick beds of medium- to coarse-grained sandstone in this part of the formation are moderately calcareous, and the inclined cross beds and laminae indicate sediment transport from the east, suggesting sources of calcareous sediment in the Pennsylvanian rocks on the Tecolote uplift.

To the north, on the west limb of the Chapelle syncline, the basal part of the Sangre de Cristo in the vicinity of Dead Horse Canyon (loc. N, fig. 58) is a pebbly coarse-grained feldspathic sandstone that locally is only about 1 ft (0.3 m) thick, but that thickens northward. The pebbles are mainly white to gray vein quartz and quartzite, but some are pink feldspar. In this vicinity the lower 250 ft (75 m) of the formation is mainly shale and contains two relatively persistent units of limestone. However, farther north, at Santillanes Creek and Falls Creek, the lower part, about 200 ft (60 m) thick, contains thick feldspathic to arkosic conglomerates, interbedded red shales, and some gray and tan shale. From Falls Creek northeastward past Gallinas Creek this general character of the lower part persists, and the conglomerates are thick, crossbedded, very coarse grained, pebbly rocks. Only the lower 200–250 ft (60–75 m) of the Sangre de Cristo is preserved in the outliers south of Gallinas Creek. The northward change of the lower part (Fig. 58) from the mainly shaly rocks at Dead Horse Canyon to thick conglomeratic sandstone and shale at Santillanes Creek and farther north suggests that these fan deposits were derived from local sources of Precambrian rocks, possibly in the structural block west of the Cenozoic Blue Canyon fault (Plate 1) on the northern part of the Paleozoic Bernal uplift, and possibly from the vicinity of Hermit Peak.

The following section of the lower part of the Sangre de Cristo in Las Gallinas syncline, measured at locality 6 (Fig. 81), describes the general lithology of the lower part of the formation (Fig. 58) that is preserved in outliers near Gallinas Creek, NE¼SE¼ sec. 23 and NW¼SW¼ sec. 24 T17N R14E, El Porvenir quadrangle. Base of section is on north side of U.S. Forest Service Johnson Mesa road just west of intersection with road to Mineral Hill. Top is topographically highest ridge east of Johnson Mesa road.

Unit	Lithology	Thickness (ft)	(m)
	Sangre de Cristo Formation (lower part):		
25.	Sandstone, conglomeratic, feldspathic, light-brown-weathering. Matrix is subangular very coarse sand and granules; about 20 percent of clasts is pink feldspar. About 30 percent of rock is pebbles that range up to 1.5 inches (3.8 cm) across. Pebbles are irregularly shaped and subrounded. Pebbles are gray vein quartz, purple quartzite, black- and gray-banded quartzite, resinous-yellow quartz, and granite. Crossbeds are inclined mainly southerly. Forms highest ledge east of road.	15	4.6
24.	Concealed; forms slope.	9.8	3.0
23.	Shale, red; contains many irregularly shaped gray limestone nodules that range from 0.5 to 1.5 inches (0.6 to 3.8 cm) in longest dimension. Forms slope.	6.9	2.1
22.	Conglomerate, arkosic. Matrix is granules and pebbles as much as 0.25 inch (0.6 cm) diameter; 25 percent, in		

	all clast sizes, is pink feldspar. Near middle and top are lenses of irregularly shaped pebbles of pink and gray vein quartz, 0.5–1.25 inch (1.3–3.1 cm) in diameter. Forms gently sloping ledge north of abandoned sanitary landfill east of road.	12.7	3.9
21.	Shale, red, poorly exposed on east side of Johnson Mesa road.	21	6.4
20.	Sandstone, conglomeratic, feldspathic, medium-grained at base but coarsening upward to very coarse and pebbly. About 10 percent of sand and granules is pink feldspar. Upper part contains scattered, angular to subround pebbles of pink and gray quartz, 0.25–0.5 inch (0.6–1.3 cm) in diameter. Forms small ledge at south side of Johnson Mesa road.	14	4.3
19.	Shale, red; contains some soft thin sandstone. Poorly exposed at south side of Johnson Mesa road.	19.5	5.9
18.	Sandstone, conglomeratic, feldspathic, light-yellowish-gray. Matrix is subangular to angular very coarse sand and granules. Contains 1–2-inch (2.5–5-cm) thick lenses of irregularly shaped, subrounded pebbles of pink and gray quartz as much as 1 inch (2.5 cm) diameter. About 15 percent of sand, granules, and pebbles up to 0.25 inch (0.6 cm) is pink feldspar. Forms ledge north of Johnson Mesa Road at sharp northward bend.	9	2.7
17.	Shale, red, clay.	23.8	7.25
16.	Sandstone, conglomeratic, arkosic; matrix is very coarse sand, granules, and pebbles as large as 0.25 inch (0.6 cm) diameter. Clasts are irregularly shaped and subangular to subround. About 25 percent of clasts is pink feldspar. Contains scattered pebbles of gray, yellow, and tan quartz that are irregularly shaped but rounded and 0.5–0.75 inch (1.3–1.9 cm) in diameter. Highly crossbedded. Lower half is soft but upper half forms a ledge on north side of Johnson Mesa road.	21	6.4
15.	Shale, red, clay.	4.8	1.47
14.	Sandstone, feldspathic, light-yellowish-brown. Lower part is medium grained; upper part is coarse grained. About 15 percent of clasts is pink feldspar. Thin-bedded and soft.	5.3	1.6
13.	Shale, red, clay; slightly micaceous.	5.3	1.6
12.	Shale, light-greenish-gray, clay.	9.5	2.9
11.	Sandstone, light-yellow-brown; stained by manganese and iron oxides. Clasts are subangular to subround, coarse sand and granules; contains a trace of pink feldspar. Forms ledge.	1.0	0.3
10.	Shale, light-grayish-yellow.	4.4	1.35
9.	Sandstone, tan-gray, feldspathic. Clasts are subangular to subround very coarse sand and granules. About 10 percent is pink feldspar. Forms small ledge on north side of Johnson Mesa road.	4.8	1.45
8.	Shale, red; exposed on south side of Johnson Mesa road.	8.7	2.6
7.	Sandstone, conglomeratic, feldspathic. Matrix is subangular to subround very coarse sand and granules. Contains numerous 1–3-inch (2.5–7.6-cm) thick lenses of angular to subangular granules and pebbles as large as 0.25 inch (0.6 cm) of pink feldspar and gray to pink quartz; about 20 percent of all clasts is feldspar. Forms low ledge on south side of Johnson Mesa road; base concealed.	16.5+	5.0+
	Thickness of preserved part of Sangre de Cristo Formation:	213+	64.9+
	Alamitos Formation (upper part):		
6.	Interval concealed by colluvium at head of north-draining valley at junction of Johnson Mesa road and road to Mineral Hill and San Geronimo. A few exposures on slopes to the north suggest this interval is mostly shale and sandy shale containing some coarse arkosic sandstone. Part of the interval may be Sangre de Cristo Formation rather than Alamitos.	55	16.8
5.	Shale, red; contains some shaly, red, fine-grained sandstone and limestone nodules; poorly exposed. Top is concealed in north-draining valley that is the site of an abandoned Forest Service road. Early Wolfcampian fusulinids *Triticites* aff. *T. creekensis* (f10128) were obtained from nodular limestone exposed in gully on abandoned road in this unit about 500 ft (150 m) north of Johnson Mesa road.	24	7.3
4.	Conglomerate, arkosic, greenish-gray-weathering, purple-stained. Clasts are angular to subround granules and pebbles as large as 0.25 inch (0.6 cm). About 30 percent of clasts in all sizes is pink feldspar. Forms poorly exposed ledge on north side of Johnson Mesa road.	7	2.1
3.	Shale, light-greenish-gray; purplish-gray-weathering. Contains scattered nodules of gray limestone.	8	2.4
2.	Shale, light-greenish-gray. Contains many 1-inch (2.5-cm) thick beds of limestone nodules. Contains a few brachiopods.	6	1.8
1.	Limestone, gray, fine-grained, bioclastic. Contains a few fusulinids. Forms small ledge on north side of Johnson Mesa road.	0.3	0.1

East of Hermit Peak the outlier of the lower part of the Sangre de Cristo Formation north of Rito Chavez contains red shale, but much of it is thick feldspathic to arkosic conglomerates that are highly crossbedded and are similar to thick conglomerates in the underlying Alamitos Formation. The distinction between the two formations is the occurrence of gray shale and sandy marine limestone in the uppermost part of the Alamitos. Farther north in Las Dispensas syncline, similar thick, gravelly arkoses occur in the lower part of the Sangre de Cristo, but the proportion of red shale may be a little greater than near Rito Chavez. The lithology suggests a nearby source of first-cycle, mainly granitic detritus for the lower part of the Sangre de Cristo (as well as for the Alamitos). This source may have been the mainly granitic rocks of the Hermit Peak area.

Southeastern part of area—The basal part of the Sangre de Cristo Formation in the southeastern part of the area is feldspathic coarse-grained conglomeratic sandstone that contains subangular to subround quartz and feldspar pebbles, and, locally (as at loc. M, Fig. 59), a few limestone pebbles. Southeast of the confluence of Tecolote Creek and San Pablo Creek, the basal conglomeratic sandstone of the Sangre de Cristo is similar to the basal sandstone of the thin Alamitos Formation and to a stratigraphically higher sandstone in the lower part of the Alamitos. Southeast of the confluence of San Pablo and Tecolote Creeks, near the place where the Sangre de Cristo truncates the Alamitos (Plate 1), the basal sandstone of the Sangre de Cristo is difficult to distinguish from the sandstones of the Alamitos except by careful tracing. Farther southeast the basal sandstone of the Sangre de Cristo ranges from less than 10 ft (3 m) to 30 ft (10 m) thick and seems to be persistent through locally poor exposures to the places where it laps onto Precambrian rocks on the Ojitos Frios anticline.

On the east limb of Ojitos Frios anticline, the basal conglomeratic sandstone and the overlying shale and thin sandstone units of the Sangre de Cristo Formation can be followed, nearly continuously, from the Precambrian outcrops northward past Tecolote Mountain to near the place where the Sangre de Cristo laps onto granitic Precambrian rocks on the Cenozoic Creston anticline (Plate 1). At this place, north of the Ojitos Frios road, the basal sandstone and some stratigraphically higher rocks of the Sangre de Cristo merge to become thick, irregularly bedded, arkosic conglomerate, indicating that Precambrian rocks of this part of the Paleozoic Tecolote uplift were a local source of coarse sediment during deposition of the lower part of the Sangre de Cristo.

The middle part of the Sangre de Cristo Formation, generally poorly exposed in the southeastern part of the area, is mainly red shale containing thin feldspathic to arkosic sandstone interbeds. This sequence is fairly well exposed on the east flank of Ojitos Frios anticline at and east of locality M southeast of Ojitos Frios (Fig. 55). At locality M, rocks above the basal sandstone include dark-red highly calcareous siltstone and sandstone that contains pebbles of chocolate-brown calcareous siltstone and silty limestone. The cross-bedding of these rocks and the basal sandstone is inclined south-southeast, suggesting that the source of the sediments was on the Tecolote uplift to the north.

The upper part of the Sangre de Cristo Formation in the vicinity of Tecolote Peak is a zone 150–200 ft (45–60 m) thick in which thick ledge-forming coarse to conglomeratic, feldspathic sandstones are interbedded with red shales. Some of these sandstones appear to be persistent and of relatively uniform thickness for distances of more than a mile, giving a "board-bedded" appearance to outcrops of the upper part of the formation. These rocks generally are similar to and probably correlate with the upper part near Pecos River in the southwest part of the area. Good exposures of the upper 100 ft (30 m) of the Sangre de Cristo occur near Interstate Highway 25 west of the axis of the Cenozoic Creston anticline. Generally, the sandstones are feldspathic to arkosic, very coarse grained, and some are conglomeratic. They are commonly only 5–10 ft (1.5–3 m) thick; whereas, intervening red shale units are 20-40 ft (6–12 m) thick. In this vicinity the highest bed of the Sangre de Cristo is very coarse grained arkose that contains scattered, well-rounded, goose-egg-shaped pebbles of vein quartz and irregularly shaped but well-rounded quartzite pebbles. These pebbles are mainly 0.5–1 inch (1.3–2.5 cm) in diameter, but some range up to 3 inches (7.6 cm). The rocks may correlate with sandstones containing similar highly rounded siliceous pebbles that are near the top of the Sangre de Cristo at Montezuma and in the northern part of the area (Fig. 69; Plate 3). The highest part of the formation grades abruptly upward into the finer grained rocks of the overlying Yeso Formation.

Eastern front of mountains—In the hogback belt along the southeast margin of the mountains the Sangre de Cristo Formation is poorly exposed at many places because of colluvial and alluvial deposits of Quaternary age. Some of the best exposures are in road cuts on New Mexico Highway 283 just west of Agua Zarca (loc. 1, Fig. 69). Here, the basal arkosic sandstone is pebbly, only 7–10 ft (2–3 m) thick, and is overlain by maroon siltstone and shale about 70 ft (21 m) thick. The general lithologic aspect of these rocks is similar to that of the lower part near locality M (Fig. 59) south of Ojitos Frios. Above the maroon shaly unit near Agua Zarca several conspicuous, ledge-forming, feldspathic and arkosic conglomeratic sandstones are interbedded with red shale, throughout an interval of 50 ft (15 m). The individual sandstones are 10–15 ft (3-4.5 m) thick, and the poorly exposed shale interbeds are 10–20 ft (3-6 m) thick. Parts of the conglomerates are highly arkosic, but other parts are only slightly feldspathic. Pink, white, and gray angular to subangular vein-quartz pebbles are abundant in short lenses and scattered through the sandstones. Most of the pebbles are 0.1–1 inch (0.3–2.5 cm) in diameter, but they range up to 2 inches (5 cm). Two beds contain subangular, pink feldspar pebbles that are as large as 0.5–0.75 inch (1.3–1.9 cm) diameter; about 40 percent of one thin bed is feldspar pebbles. The lithology of these rocks indicates a nearby source of Precambrian pegmatites, presumably the Precambrian rocks of the Tecolote uplift a short distance to the south that probably also was the source of the feldspar-pebble conglomerates of the Alamitos Formation in this vicinity.

The medial part of the Sangre de Cristo, about 350 ft (105 m) thick west of Agua Zarca (loc. 1, Fig. 69), is mostly red shale. However, it contains 3–5-ft (0.9–1.5-m) thick beds of feldspathic, granule- to small-pebble conglomerates, thin zones of limestone nodules, and at least one bed of gray, dense limestone. The upper part of the formation, about 250 ft (75 m) thick, consists of red and purple shale and siltstone containing thin, ledge-forming, medium to very coarse grained, feldspathic to arkosic sandstones. Some beds contain scattered 0.5–1-inch (1.3–2.5-cm) subangular vein-quartz pebbles. At least two beds of limestone and nodular limestone occur in this interval.

Southwest of Agua Zarca the medial and upper parts of the Sangre de Cristo bury the Precambrian rocks (Plate 1), which were the local sources of sediments of the lower part. The sediments of the medial and upper parts of the Sangre de Cristo were derived from more distant sources probably from the Sierra Grande uplift to the east where the formation locally is only 180 ft (55 m) thick. At the Continental Oil Co. no. 1 Leatherwood–Reed well, where the Sangre de Cristo is about 200 ft (61 m) thick, it consists of thick upper and lower feldspathic conglomerates and a medial shale and sandstone unit that is about 100 ft (90 m) thick. The lower conglomerate contains fragments of granite and limestone.

In the hogbacks north of Agua Zarca, the general lithology of the Sangre de Cristo is similar to that at Agua Zarca, being predominantly red shale but containing interbedded coarse arkosic sandstones, some of which contain quartz pebbles. From Montezuma north almost to Cañon Bonito the Sangre de Cristo is cut out by the Montezuma fault.

In the hogback belt along the eastern front of the mountains, from Cañon Bonito (loc. 2, Fig. 69) north to Manuelitas Creek, the lower two-thirds of the Sangre de Cristo Formation is mainly red shale, but it contains thick ridge-forming, coarse-grained feldspathic to arkosic sandstones and pebbly conglomerates, as well as easily eroded, arkosic sandstones and some bedded limestone and nodular limestone. Thin, gray limestones and nodular limestones that are interbedded with marly shale near the base occur at Cañon Bonito and between Sapello River and Manuelitas Creek. From Manuelitas Creek northward a little past Rito Cebolla the lower part of the formation is cut out by the Sapello fault (Plate 1; Baltz and O'Neill, 1986).

From Rito Cebolla northward to about 1 mi (1.6 km) south of La Cañada del Guajalote, the lower third contains about equal proportions of shale and thin to thick, relatively easily eroded, feldspathic to arkosic, coarse-grained sandstone and small-pebble conglomerate. Locally, some units of conglomerate are 100–200 ft (30-60 m) thick, but most are 20–30 ft (6-9 m) thick. Stratigraphically higher parts of most of the formation are poorly exposed or concealed, but, where observed, they are easily eroded, coarse-grained feldspathic sandstones and red to greenish-gray shales.

Northward from a little south of La Cañada del Guajalote the lower part of the Sangre de Cristo Formation is a zone of ridge-forming, reddish-pink to purplish-pink feldspathic and arkosic conglomeratic sandstones interbedded with red, green, and gray shales. This lower zone distinctly thickens northward from the vicinity of La Cañada del Guajalote, and it may be older than the lower part of the Sangre de Cristo at Rito Cebolla (Fig. 68). At Mora River (loc. 3, Fig. 69) the conglomerates of the lower zone contain shaly sandstone, thin shales, and a few thin nodular, nonmarine limestones. The lower zone is about 700 ft (215 m) thick, and is overlain by more easily eroded arkosic sandstones and red shales that constitute the main bulk of the Sangre de Cristo Formation. Some units of conglomeratic sandstone in the lower zone are 130–190 ft (40-60 m) thick. The lower zone appears to persist northward to the edge of the mapped area of this report. As discussed previously, the nonmarine rocks of the zone, or most of it, may be the same age (Virgilian?) as the uppermost part of the Alamitos Formation in the Manuelitas River area.

From Cañon Bonito northward past the north edge of the area of this report, the uppermost part of the Sangre de Cristo Formation is a persistent zone of highly crossbedded very coarse grained to conglomeratic sandstones that exhibit scour-and-fill structures (Fig. 69; Plate 3). Thin red and green shale interbeds occur. The sandstones are feldspathic but, at places, only moderately so. A distinctive characteristic of the sandstones is that they contain abundant lenses of well-rounded siliceous pebbles that are 1–4 inches (2.5–10 cm) in longest dimension. The pebbles characteristically are resinous-appearing, yellow, greenish-gray, grayish-purple, brownish-gray, and dark-gray quartz and quartzite. Some white vein-quartz pebbles occur also, and a few chert pebbles were observed at places. Some of the pebbles are nearly spherical; others are egg-shaped to discoid. The degree of roundness contrasts sharply with that of most of the pebbles in the underlying parts of the Sangre de Cristo.

The persistence of the zone of well-rounded siliceous pebbles was established during mapping (Baltz and O'Neill, 1984, 1986), but it is mainly poorly exposed, and its thickness was determined at only a few places. At Cañon Bonito and Sanguijuela Arroyo it is 30–90 ft (9–27 m) thick. Good exposures of the zone occur a short distance south of Rito Cebolla, but its thickness was not measured. At Mora River the zone is about 170 ft (52 m) thick. The zone probably correlates with parts of the "variegated sandstone" and "conglomeratic sandstone" units of Tschanz et al. (1958, p. 350–353) near the top of the Sangre de Cristo near Los Cisneros north of the area of this report, and the zone is about 270 ft (82 m) thick there (Plate 3). The zone is similar to the gravelly "valley fill" unit described by Brown (1984, p. 120) that, east of Los Cisneros, is about 40 ft (12 m) thick and constitutes the highest part of the Sangre de Cristo Formation there.

In the mapped area of this report the zone of well-rounded siliceous pebbles locally is overlain directly by fine- to medium-grained, well-sorted, brick-red sandstone of the Yeso Formation, but at other places a few beds of red shale and thin, coarse-grained, feldspathic sandstones intervene. On the basis of stratigraphic position, the zone in the northern part of the area probably correlates with part of the upper beds of the Sangre de Cristo in the southern part of the area. However, in the southern part of the area, distinctive, large, rounded, siliceous pebbles in the upper part of the formation were observed only just south of Montezuma and at a few places northeast of Tecolote. A conglomerate of large, well-rounded, siliceous pebbles occurs west of Tres Hermanos Creek in the SE¼SW¼ sec. 9 T14N R15E (USGS Villanueva quadrangle). This conglomerate is in the upper part of the Sangre de Cristo, but not in the uppermost part; therefore, its correlation is uncertain, and it may be a local facies.

In the subsurface northeast of Mora, the lithology of the Sangre de Cristo Formation generally is similar to that at outcrops from Mora River north (Plate 3). However, the proportion of thick sandstones in the lower 700 ft (215 m) seems to decrease northeastward in the subsurface as well as northward along outcrops. Also, the sandstones in this lower interval in the subsurface seem not to be as coarse grained as the pebbly conglomerates at Mora River. Gypsum occurs in well samples from the lower interval, but gypsum was not seen anywhere at the surface. The zone of siliceous pebbles at the top of the Sangre de Cristo was recognized in samples from the Amoco "B" no. 1 Salman Ranch well.

Contact with overlying rocks

The Sangre de Cristo Formation is overlain with probable structural conformity by the Yeso Formation of Leonardian age. The fine- to medium-grain size and relatively good sorting of the sandstones, and the generally parallel bedding of the sandstones, siltstones, and shales of the Yeso suggest that it was deposited in an offshore, shallow marine environment. Thin dolomite and limestone beds occur in the formation throughout the area but are most common in the southern part. Dolomite and relatively thick gypsum occur in the Yeso in the southern part of the Las Vegas Basin at the Continental Oil Co. no. 1 Leatherwood–Reed well. No fossils have been reported in the Yeso in this part of New Mexico that would confirm a marine origin but, in central and southeastern New Mexico, the formation is marine. Most investigators have assumed that the contact of the Sangre de Cristo and Yeso is gradational or intertonguing, but little direct evidence of intertonguing has been given in the literature. Many outcrops show an abrupt transition, through several feet, from coarse-grained pebbly feldspathic sandstone of the Sangre de Cristo into fine- to medium-grained arkose and siltstone of the Yeso, but thin lenses of coarse sandstone in the basal part of the Yeso at places might indicate some interfingering of the two formations. However, in places, such as at Mora River, the contact is sharp and slightly undulatory, suggesting a disconformity.

Exposures of the lower part of the Yeso on the west bank of Tecolote Creek at Tecolote reveal bedding structures that probably represent a littoral or shallow-water offshore environment. The Yeso lies on very coarse grained, pebbly sandstone that is the top of the Sangre de Cristo. The basal part of the Yeso, about 25 ft (7.6 m) thick, is gray sandstone that weathers brown. The clasts are well-sorted, coarse, angular to subangular quartz. Bedding is subparallel, and the beds are cross-laminated. The upper part contains fossil burrows. This basal sandstone is overlain by about 30 ft (9 m) of red, medium-grained, highly crossbedded sandstone that contains thin red shale laminae and a few scattered rounded pebbles of red clay shale. The beds are mainly 1–6 inch (2.5–15 cm) thick and occur in inclined concave-upward sets that are as much as 4 ft (1.2 m) high. Sets of beds truncate other sets and dip in opposing directions. The overall lithology and bedding structure suggests a bar deposit or tide-dominated sand ridge, such as those described by Johnson (1979, p. 235–236). The crossbedded sandstone is overlain disconformably by a tan, but red-weathering, coarse-grained, well-sorted sandstone that is subparallel bedded and cross-laminated. The beds are 3-4 ft (0.9–1.2 m) thick. The sandstone is about 20 ft (6 m) thick and thins slightly northward in the outcrop. These rocks are overlain by more characteristic brick-red, fine- to medium-grained, parallel-bedded sandstone and shale of the main part of the Yeso Formation.

The deposits at the base of the Yeso Formation near Tecolote may represent beach or strandline deposits of a briefly static or slightly oscillatory transgressing sea, which would seem to be a necessary condition if marine rocks of the Yeso intertongue with nonmarine rocks of the Sangre de Cristo. However, we did not observe rocks of this kind elsewhere at the base of the Yeso. The thin, vertically transitional deposits and disconformities that occur at many places suggest that the Yeso sea transgressed rapidly northward across most of the area, slightly reworking the uppermost part of the Sangre de Cristo. However, the hiatus at the contact may be small.

The Yeso Formation is seen overlying the Sangre de Cristo Formation at poor exposures along the east front of the mountains as far north as Lucero (USGS Lucero quadrangle) north of the mapped area of this report, but rocks lithologically similar to the Yeso are not present at the better exposures several miles north of Lucero. There, rocks assigned to the Sangre de Cristo are overlain directly by the Lower Permian Glorieta Sandstone that lies on the Yeso farther south. May et al. (1977, p. 5) wrote that they had traced the Yeso Formation northward as far as Guadalupita, but they did not describe its lithology in that area nor did they elaborate on their identification of the formation. Presumably, they correlated the Yeso with part of the upper "conglomeratic sandstone unit" of the Sangre de Cristo of Tschanz et al. (1958, p. 353).

Several writers including Bachman (1953), Baltz and Bachman (1956, p. 101) and Baltz (1965, fig. 6) suggested that the Yeso disappears northward by gradation into the upper part of the Sangre de Cristo, but this suggestion was not based on detailed tracing because of a general lack of exposures north of Lucero. Some of the rocks north of Lucero that were assigned to the "conglomeratic sandstone unit" at the top of the Sangre de Cristo near Los Cisneros by Tschanz et al. (1958) might be beach or nearshore deposits, as they suggested, although some of the rocks contain clasts as large as pebbles. Brown (1984, p. 116, 120) also has interpreted the upper 100 ft (30 m), approximately, of the Sangre de Cristo near Los Cisneros as consisting of transgressive marine(?) sandstone enclosed by gravelly valley-fill deposits that resulted from a rapid rise in sea level prior to deposition of the overlying marine Glorieta Sandstone. Possibly, the sandstone is equivalent to the Yeso, but we note that both the upper and lower gravel near Los Cisneros (loc. 4, Plate 3) are similar to the widespread zone of well-rounded siliceous pebbles at the top of the Sangre de Cristo at the Amoco no. 1 "B" well (Plate 3) and in the mapped area of the present report where the Yeso Formation intervenes between the gravelly upper part of the Sangre de Cristo and the Glorieta Sandstone. Therefore, it is possible that the Yeso disappears northward by depositional wedgeout or because of disconformity with the overlying Glorieta, rather than by grading into the upper part of the Sangre de Cristo. Additional work will be necessary to establish the relation of the Yeso of the area of this report to the rocks at the top of the Sangre de Cristo near Los Cisneros.

Age and fossils

In most of the southeastern part of the Sangre de Cristo Mountains the Sangre de Cristo Formation is Early Permian (Wolfcampian) age. No fossils were found in the Sangre de Cristo south of Sapello River. However, south of Gallinas Creek, it is no older than Wolfcampian because early Wolfcampian fusulinids occur in the upper part of the subjacent Alamitos Formation at several localities as far south as the vicinity of Ojitos Frios. To the southwest, Late Pennsylvanian (late Virgilian) fusulinids occur near the top of the Alamitos northwest of San Juan and just east of Rowe, indicating that the disconformably overlying lower part of the Sangre de Cristo probably is Permian.

Throughout the entire mapped area of this report the Yeso Formation of Early Permian (Leonardian) age lies on the Sangre de Cristo. Fossils have not been reported from the Yeso in the Sangre de Cristo Mountains, but it is dated as Leonardian by lithologic correlation and mapping to its type locality northeast of Socorro, New Mexico (Read et al., 1944; Dane and Bachman, 1965); thence, to the Leonardian Series of the Delaware Basin of southeastern New Mexico (Needham and Bates, 1943, p. 1661; Skinner, 1946, p. 1866; Hayes, 1964, p. 12, 17; Dane and Bachman, 1965; Harbour, 1970).

From Gallinas Creek northward to at least Manuelitas Creek the Sangre de Cristo Formation probably is entirely Permian because it lies on rocks of the uppermost part of the Alamitos whose megafossils (collection. 27501–PC) from west of Sapello are of Late Pennsylvanian (probably Virgilian) age. About 0.8 mi (1.3 km) west of Sapello (loc. BM7701, Baltz and O'Neill, 1986) marine fossils were found in a feldspathic, limy sandstone in the lower part of the rocks that were assigned to the Sangre de Cristo Formation. Although the fossils are poorly preserved, they appear to be indigenous and not reworked. This is the only place in the area of this report where marine fossils were found in the rocks assigned to the Sangre de Cristo. The fossils disappear abruptly north of the collecting locality, and the sandstone wedges out or becomes indistinguishable from other sandstones assigned to the lower part of the Sangre de Cristo. To the south the fossiliferous sandstone passes under alluvium in the valley of Sapello River and was not recognized farther south. Because of its restricted occurrence, this sandstone is not a useful datum for separating the Alamitos from the Sangre de Cristo, and the contact here is placed stratigraphically lower at the top of fossiliferous greenish-gray shale and limestone of the Alamitos that is overlain by conglomeratic, arkosic sandstone, red marly shale, and locally present unfossiliferous, thin nodular to bedded limestone assigned to the lower part of the Sangre de Cristo.

E. L. Yochelson (written comm., 1978) examined fossils we collected from the sandstone west of Sapello, but he was unsuccessful in extricating the fossils from the extremely hard matrix. He reported that the pelecypods might be *Schizodus* sp. or *Permophorus* sp., but that naming them from cross sections only is not satisfactory. A bellerophontacean gastropod, possibly *Bellerophon*, is present also. Yochelson commented that the fossils provide no evidence as to age, other than being of the kind that might be expected in the Wolfcampian. If the fossils are Permian, they are in rocks that were deposited probably during a rapid and short-lived northward transgression of the last stage of the earliest Permian (uppermost part of the Alamitos) sea of the southern part of the area. If so, the deposits represent the northernmost evidence of that sea.

In the northern part of the area, from Rito Cebolla north, the Sangre de Cristo is assigned a Permian and Pennsylvanian(?) age on Plate 1. This assignment is based on a sample containing palynomorphs that was collected about 500 ft (150 m) stratigraphically above the base of the zone of ridge-forming purplish-pink arkoses of the lower part of the Sangre de Cristo at Mora River (loc. 3, Fig. 69). The sample was collected from a thin carbonaceous shale and siltstone in massive arkoses at a roadcut on New Mexico Highway 518 on the north side of Mora River about 2,500 ft (0.75 km) east of St. Joseph Church (Fig. 89). According to R. M. Kosanke (written comm., 1980, 1981) the sample contained the following forms

Convolutispora sp.
Cyclogranisporites sp.
(?)*Densosporites* (fragment of *D. annulatus* type)
Illinites cf. *I. unicus*
Laevigatosporites crassus
Laevigatosporites cf. *L. medius*
Pityosporites sp.
Punctatisporites sp.
Raistrickia sp.
Triquitrites sp.

According to Kosanke, the evidence from this meager assemblage is not conclusive as to age because these palynomorphs occur elsewhere in both Pennsylvanian and Permian strata. However, assemblages of saccate forms typical of the Wolfcampian are absent, and the sample probably is Late Pennsylvanian, based on the presence of *Illinites* cf. *I. unicus* and the heavy-walled *Laevigatosporites crassus*. If this is the case, these rocks could be Virgilian, based on their stratigraphic position above the underlying highest marine rocks of the Alamitos Formation that contain probable Missourian megafossils at Mora River. This collection of palynomorphs is the only paleontologic data known to us that suggests Pennsylvanian age of part of the Sangre de Cristo in the area of this report.

The only other paleontologic evidence known to us concerning the age of rocks we assign to the lower part of the Sangre de Cristo Formation in this part of the mountains is a small collection of fossil leaves (Fig. 70) from the lower part of the formation in hogback ridges just south of the water gap of Coyote Creek south of Guadalupita, and about 6.5 mi (10.5 km) north of the area of this report. This collection, obtained from an abandoned copper prospect by Zeller and Baltz (1954, p. 3), is from above the stratigraphically highest marine limestone, which the present writers assign to the Alamitos Formation. The position of the fossil-plant collection, relative to the base of the Sangre de Cristo in the mapped area of the present report (Plate 1), is not known with certainty, but the collection probably is within several hundred feet of the base, south of Guadalupita, depending on interpretations of faults just west of the collecting locality.

This fossil-plant collection was reported by S. H. Mamay (written comm., 1981) to contain three recognizable genera—*Walchia*, *Taeniopteris*, and *Neuropteris*. According to Mamay, the *Walchia* is confidently referred to *W. piniformis* (Schlotheim) Sternberg. There may be two species of *Neuropteris*; one specimen is a small-pinnuled form that may be related to *N. rarinervis*. The *Taeniopteris* is represented by several small fragments whose veination suggests *T. multinervia* Weiss, but more complete specimens would be necessary to confirm this assessment. Another fragment suggests the genus *Callipteris*, but Mamay wrote that he must stringently qualify this last interpretation, "...lest the very appearance of the name *Callipteris* here unduly flavor possible future applications of the content of this report."

On the basis of the limited taxonomic determinations permitted by this collection, Mamay reported that the enclosing rocks could be either Late Pennsylvanian or Early Permian age. He noted, however, that the flora is similar to that of the Early Permian flora of the Abo Formation from the Spanish Queen Mine in the Jemez Mountains of north-central New Mexico that is discussed by Read and Mamay (1964, p. K–12, K–13). Mamay wrote, "Without any knowledge of the Spanish Queen flora, I think I would have called your collection Wolfcampian with a certain amount of reservation. However, the similarities between it and the Spanish Queen material contribute to what I regard as a very strong case for Permian age for your material." Therefore, the main bulk of the (restricted, nonmarine) Sangre de Cristo, which is about 2,900 ft (880 m) thick south of Guadalupita, probably is Permian; its lower part, below the position of the plant fossils, might be Late Pennsylvanian or Permian age.

Paleotectonic and sedimentational interpretations

The Sangre de Cristo Formation in the southeastern part of the mountains was deposited in a nonmarine environment except for the estuarine(?) sandstone near Sapello that may represent a short-lived northward incursion of the shallow early Wolfcampian sea of the southern part of the area. The initial tectonic-depositional events of Late Pennsylvanian and early Wolfcampian time were similar to and a continuation of those of the Alamitos Formation, with intrabasinal uplifts supplying sediments to adjacent local basins. Later Wolfcampian events differed because of regional depression of basinal areas and pronounced rise of the major sediment-shedding uplifts (Fig. 4) that caused intrabasinal uplifts to be buried by sediments derived from outside the area. However, the intrabasinal uplifts continued to be structurally active during regional depression of the Pecos shelf and the Taos and Rainsville troughs and controlled the local thickness of accumulating sediments of the Sangre de Cristo so that the formation thickens northward from the Tecolote uplift and the southwestern part of the Sierra Grande uplift and the formation also thickens southwestward from the Bernal uplift into the San Jose Basin. By late Wolfcampian time the basin containing the Pecos shelf and the Taos and Rainsville troughs was filled with sediments of the Sangre de Cristo Formation, and even the Precambrian rocks of the basin-marginal main part of the Sierra Grande uplift were overlapped by thin deposits. This completed the orogenic cycle that began in this region in Early Pennsylvanian (Morrowan) time. Deposition of the marine Yeso Formation and younger Leonardian marine rocks followed more uniform regional patterns (Foster et al., 1972, p. 11–12) that reflect broad epeirogenic movements or eustatic sea-level changes, or both. There is, however, a suggestion from the stratigraphic sections of Northrop et al. (1946) that the older tectonic features of the southern part of the area influenced small thickness variations of the Yeso Formation.

In Late Pennsylvanian time, the sediments of the zone of purplish-pink feldspathic and arkosic conglomerates of the lower part of the Sangre de Cristo Formation north of Rito Cebolla were deposited mainly as medial parts of subaerial fans that prograded eastward and northeastward into the subsiding Rainsville trough. The sources of the sediments were Precambrian rocks in the rising southern part of the El Oro–Rincon uplift (Plate 4*D*; Fig. 27). In the Rainsville trough the arkoses are finer grained and are interbedded

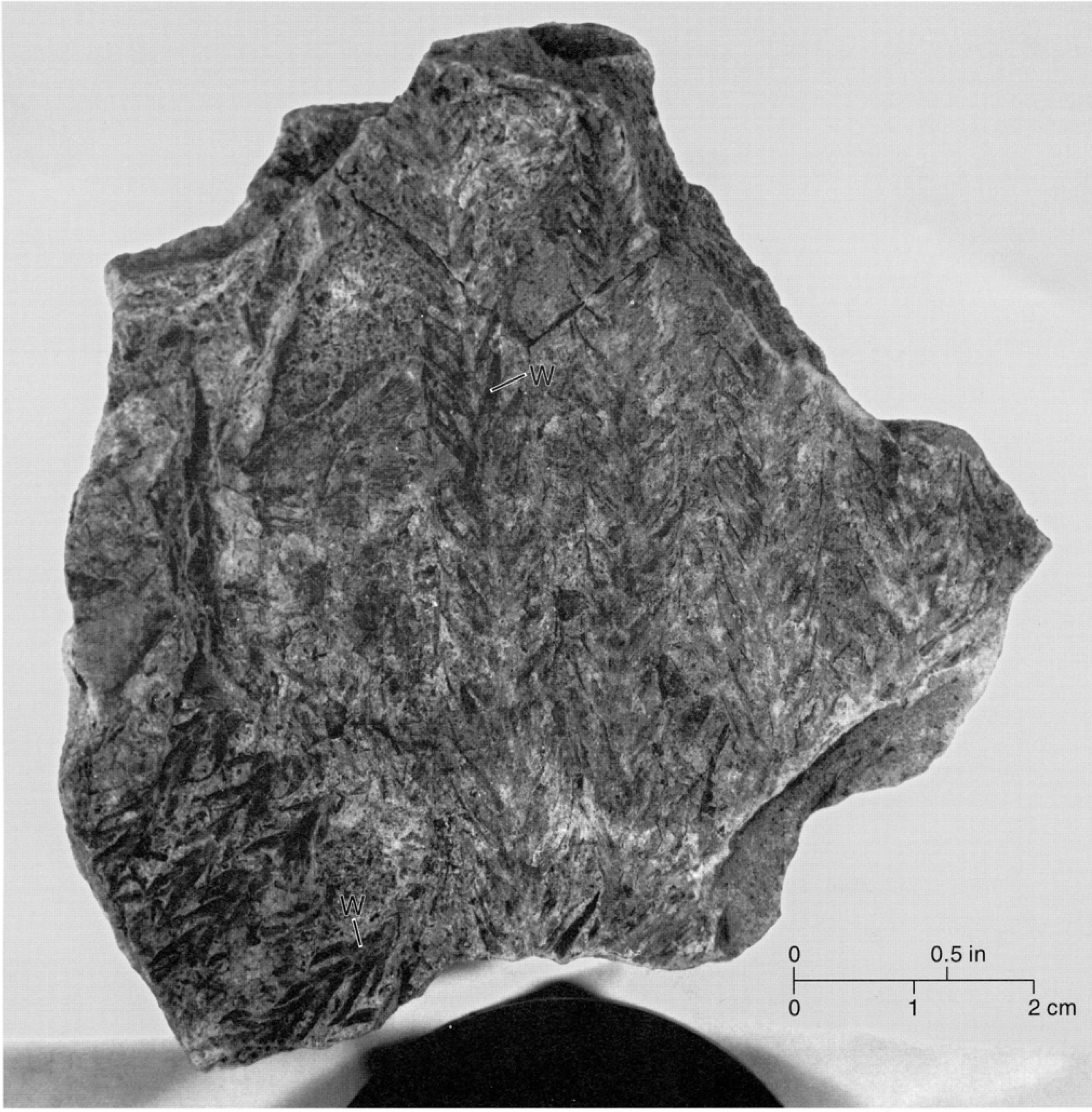


FIGURE 70—Plant fossils from lower part of Sangre de Cristo Formation. Collected from silty claystone in prospect pit in hogbacks just south of Coyote Creek about 1.8 mi (2.9 km) southeast of Guadalupita (Zeller and Baltz, 1954, p. 3). W, *Walchia piniformis* leaves on small branches.

with probable playa deposits of red and green shale, limestone, and some gypsum or anhydrite of the lower 700–800 ft (215–245 m) of the Sangre de Cristo at the Amoco wells (Plate 3). To the north, at Los Cisneros (loc. 4, Plate 3), the lower 800–900 ft (245–275 m) of the Sangre de Cristo consists of red, green, and some black carbonaceous shale that contains arkosic sandstone and conglomerates and numerous nonmarine, thin, nodular and bedded limestones. These rocks (transition unit of Tschanz et al., 1953; coastal-plain unit of Brown, 1984) are distal-fan floodplain, paludal, and lacustrine deposits also of the structurally deep part of the Rainsville trough.

The tectonic-depositional conditions of the lower part of the Sangre de Cristo to the north were a nonmarine continuation of the conditions postulated for the Alamitos Formation in that area (Fig. 27). On a regional basis, the tectonic activity is consistent also with conditions to the south where Upper Pennsylvanian rocks are absent from the intrabasinal uplifts, but Upper Pennsylvanian rocks were deposited in the adjacent structural basins.

In Late Pennsylvanian(?) time the Precambrian rocks of the El Oro–Rincon uplift could have been only local sediment-source areas because presently, southwest of Black Lake, they plunge northward beneath Pennsylvanian rocks. At outcrops north of Black Lake the 1,100 ft (335 m) of rocks assigned to the lower part of the Sangre de Cristo (above the highest fossiliferous marine limestone) by May et al. (1977, loc. 3, plate 1) are predominantly fine to very fine grained sandstone and shale. At the True Oil Co. 21–25 Medina well drilled southeast of Black Lake (Fig. 72), possibly equivalent rocks in the depth interval 2,650–3,250 ft, are logged as predominantly shale that contains some limestone and some relatively thin, mainly fine- to medium-grained sandstones. Samples are not reported from several thick intervals of the overlying part of the Sangre de Cristo at this well, but the intervals sampled are mostly shale that contains some coarse arkose and fine- to medium-grained sandstone. The northward and eastward fining accords with the concept of a northward-plunging El Oro–Rincon uplift. Even if the relatively narrow El Oro–Rincon uplift was bordered by thrust faults (Fig. 27) it is not likely that it was the main source of the great volume of clastics of the mainly Wolfcampian middle and upper parts of the Sangre de Cristo that are on the order of 2,000 ft (600 m) thick in the northern part of the area and even thicker farther north. By analogy with the southern part of the area, this intrabasinal uplift may have been buried in Wolfcampian time by sediments derived from basin-margin uplifts.

The Cimarron arch (Fig. 4), about 25 mi (40 km) north of the area of this report, probably rose in Late Pennsylvanian and earliest Permian time and later, because remnants of probable Mississippian and Pennsylvanian rocks are on its southern flank (Smith and Colpitts, 1980). However, thin sections of both the Sangre de Cristo Formation and Triassic rocks lie on the Precambrian at various places on the arch (Robinson et al., 1964, plate 5; Baltz, 1965, p. 2049; Goodknight, 1976). The Precambrian granite and metamorphic rocks of the Cimarron arch might have been a source of some of the sediments of the Sangre de Cristo of the northern part of Rainsville trough, but the general northward and northeastward fining of much of the formation suggests it is floodplain deposits consisting mainly of reworked Early to Middle Pennsylvanian sediments eroded from the southern flank of the arch, rather than being predominantly first-cycle sediments.

A more traditional interpretation would be that, as the general basinal area subsided in Early Permian time, fans and floodplain deposits were built eastward from the Brazos (Uncompahgre) uplift, filling the Taos trough segment of the basin (Sutherland, 1963, p. 44) and lapping into and filling the Rainsville trough. The Sierra Grande uplift may have contributed sediments from the east, also (Roberts et al., 1976, p. 143–144). However, present data, surface and subsurface, are not adequate to determine the relative importance of the Brazos, Cimarron, and Sierra Grande uplifts as contributors of the sediments of the Sangre de Cristo in the Rainsville trough.

To the south, on the west side of the Paleozoic Manuelitas saddle and in the northern part of the San Geronimo Basin, the lower, probably Wolfcampian, part of the Sangre de Cristo contains thick, feldspathic to arkosic, conglomeratic sandstones and some interbedded red shales that represent medial parts of fans. The coarseness, relative angularity of clasts, and the freshness of feldspars in the sandstones suggest that Precambrian granite and metamorphic rocks of the eastern part of the Hermit Peak uplift were their source. The fans prograded eastward and northeastward into shalier floodplain deposits of the Manuelitas saddle and prograded southward into the northern part of the San Geronimo Basin. The Early Permian tectonic setting was a continuation of the intermittent uplift of the Hermit Peak block and the concomitant downwarping of the Rociada Basin that occurred in Late Pennsylvanian time during deposition of the Alamitos Formation. Only the lower part of the Sangre de Cristo is preserved in this part of the area; therefore, the record of later Wolfcampian events is lost to Cenozoic erosion.

In the eastern part of the Paleozoic Manuelitas saddle, the northward intraformational thickening of the Sangre de Cristo shows that there was differential subsidence between the saddle and the Tecolote uplift in Wolfcampian time, but the northern part of the uplift could not have been a source of first-cycle sediments. The Sangre de Cristo here is mainly floodplain deposits that contain distal parts of alluvial fans and some lacustrine limestones similar to those near Cañon Bonito (loc. 2, Fig. 69) on the north flank of the Tecolote uplift. Pebbles of quartzite occur in coarse-grained feldspathic to arkosic sandstones in the eastern part of the saddle, but the overall grain sizes of these rocks seem to be smaller than in some beds to the west near Hermit Peak. Possibly, some of the sediments of the lower part of the formation in the eastern part of the saddle were derived from Hermit Peak, but a primary source was the rising Sierra Grande uplift to the southeast. The northern part of the Tecolote uplift probably was buried by the Sangre de Cristo, as was the southern part.

To the south, in the western part of the San Geronimo Basin where the Sangre de Cristo Formation lies unconformably on the Porvenir Formation near Falls Creek and Santillanes Creek, the lower part of the Sangre de Cristo contains thick feldspathic to arkosic pebble conglomerates that probably are medial and distal parts of fans that thin southeastward into a shaly facies of the lower part at Dead Horse Canyon (loc. N, Fig. 58). This suggests that in early Wolfcampian time a source of Precambrian rocks was the nearby northern part of the Bernal uplift. Migmatized metamorphic rocks containing granitic pegmatites in the structural block west of the Cenozoic Blue Canyon fault (Plate 1) may have been this source. South of Dead Horse Canyon at San Pablo Creek, the lower part of the Sangre de Cristo again contains thick arkoses that may have been derived from Precambrian granite west of the Cenozoic El Barro fault. Farther south (loc. 1, Fig. 58) thin conglomerate at the base of a mainly shaly facies of the lower part of the Sangre de Cristo contains limestone pebbles and boulders derived from the Porvenir Formation of the southern part of the Bernal uplift.

In the southeastern part of the area, the lower half of the Sangre de Cristo Formation on the Tecolote uplift (loc. 1, Fig. 69) and in the adjacent eastern part of the San Geronimo Basin is mainly siltstone and shale that contains bedded and nodular limestone. They were deposited on flood plains and in ephemeral lakes. Stream deposits of thin, feldspathic to arkosic sandstones and pebble conglomerates were derived from Precambrian rocks of the southern part of the Tecolote uplift. Some of the sediment of the lower part of the Sangre de Cristo in the southern part of the area is second-cycle and reworked from the Alamitos Formation and the Porvenir Formation on the flanks of the Tecolote uplift, as is indicated by limestone pebbles and calcareous siltstone pebbles in the basal sandstone and overlying beds of the Sangre de Cristo south of Ojitos Frios (sec. M, Fig. 59).

In the Las Vegas Basin, at the Continental no. 1 Leatherwood–Reed well, the Sangre de Cristo Formation contains conglomeratic, feldspathic sandstones near the base and near the top and lies on a thin section of the Alamitos Formation. At the Phillips no. 1 Leatherwood well the thin Sangre de Cristo also contains conglomeratic arkose and lies on Precambrian rocks. The stratigraphic relations between these wells (Fig. 18) are similar to those at the surface on the Tecolote uplift. Isopachs (Plate 4) suggest that a northwest-plunging anticline, probably the southwestern part of the Sierra Grande uplift, was active tectonically during deposition of the Sangre de Cristo. This part of the Sierra Grande uplift shed first-cycle clastics to the north and west, eventually burying the Tecolote uplift. The first-cycle sediments probably were derived by successive episodes of uplift and pedimentation of Precambrian rocks of the Sierra Grande uplift, whereby southward-thinning parts of the Sangre de Cristo eventually began to lap back onto the earlier-eroded areas. Stream-channel and floodplain deposits of the middle part of the Sangre de Cristo Formation that bury the southern part of the Bernal uplift and thicken into the San Geronimo and San Jose Basins, probably were derived mainly from the Sierra Grande uplift during the postulated pedimentation events.

The youngest part of the Sangre de Cristo Formation buries the Precambrian rocks of the Sierra Grande uplift southeast of Las Vegas (Plate 4). Foster et al. (1972, fig. 6) indicated by isopachs that the uplift east and northeast of Las Vegas also was buried completely by a veneer of the Sangre de Cristo, but Roberts et al. (1976, fig. 6) indicated that a broad area of the uplift east and northeast of Las Vegas was not overlapped by Wolfcampian rocks and, therefore, it might have continued to supply some first-cycle sediments to the area of this report until the end of Wolfcampian time. The zone of "board-bedded" fluviatile sandstones of the upper part of the Sangre de Cristo in the southern part of the area persists westward at the surface across the San Jose Basin and probably as far west as the Lamy--Cañoncito area where a thin section of the Sangre de Cristo lies on the Paleozoic Cañoncito uplift (Fig. 4). It seems likely that much of the sediment of this upper part of the Sangre de Cristo was derived from westerly sources in the Brazos (Uncompahgre) uplift and perhaps even from the Paleozoic Pedernal uplift. The Pedernal uplift was active in Pennsylvanian and Early Permian time, and the Yeso Formation laps onto Precambrian rocks (Kottlowski, 1961, p. 101–102).

The zone of well-rounded siliceous pebbles at the top of the Sangre de Cristo Formation in the northern part of the area probably represents the deposits of a major river system or its basinal distributaries. The provenance of the pebbles is not known, but abundant clasts of quartzite and other metamorphic rocks indicate that the major sources were Precambrian rocks. Common chert pebbles and a few limestone pebbles indicate that Paleozoic rocks also were sources. A general northward increase of pebble sizes suggests northerly sources. Near Los Cisneros the size of well-rounded clasts ranges up to cobbles about 8 inches (20 cm) across.

Float blocks of similar conglomerate occur on the upper part of the Sangre de Cristo Formation at the Angel Fire ski course south of Eagle Nest. We did not determine the original stratigraphic position of these blocks, but their lithology suggests correlation with the zone of well-rounded pebbles to the south.

Summary of depositional history and paleotectonics

In early Paleozoic time, much of northern New Mexico and south-central Colorado was a structurally low, positive area on which sedimentary rocks older than Devonian or Mississippian probably were not deposited. This positive area was a part of the Transcontinental arch of King (1951). Structurally complex Precambrian crystalline rocks were beveled by a surface of very low relief that was cut mainly in late Precambrian and that was modified, probably only slightly, by uplift, weathering, and erosion in early Paleozoic.

In northern New Mexico, the oldest sedimentary rocks on the positive area are the shallow-marine, sandy carbonates of the Mississippian Arroyo Peñasco Group, which is as much as 110 ft (34 m) thick in the area of this report. A basal conglomeratic sandstone and other quartz sand were derived, probably by wave action, from low quartzite hills on the pre-Mississippian surface. Widespread unconformities within and at the top of the Arroyo Peñasco indicate that the positive area was slightly emergent at times during Mississippian and earliest Pennsylvanian because of gentle epeirogeny or eustatic sea-level changes. Mississippian structural activity in the area of this report was negligible, although the Arroyo Peñasco thins internally on or adjacent to some places that became Pennsylvanian and Early Permian uplifts.

From Early Pennsylvanian (Morrowan) through Early Permian (Wolfcampian), part of the early Paleozoic positive area in north-central New Mexico was warped and locally faulted down to form basins, whereas other parts became sediment-shedding uplifts of the Ancestral Rocky Mountains. The area of this report included, on the south the tectonically unstable Pecos shelf and on the north the deep Rainsville trough. The area also included the southwestern part of the ancestral Sierra Grande uplift that flanked the Rainsville trough to the east. The upper Paleozoic rocks are locally only 300 ft (90 m) thick on the southern part of the Pecos shelf, but they are about 10,000 ft (3,050 m) thick in the Rainsville trough 25 mi (40 km) to the north, indicating the magnitude of structural relief. The Pennsylvanian and Early Permian structures of the report area are shown in Figure 71.

Northwesterly and northerly trending anticlinal uplifts and synclines on the shelf south of Sapello and Hermit Peak began to develop in Morrowan and Atokan, were slightly active in early and middle Desmoinesian, and were recurrently active from late Desmoinesian until near the end of Wolfcampian time. The developing structures controlled the thicknesses and the facies of coastal-plain, marine-carbonate shelf, and alluvial sediments deposited there. Pennsylvanian rocks are absent from the southern part of the Tecolote uplift where the Permian is only about 300 ft (90 m) thick, but in the southern part of the San Geronimo Basin Morrowan through Wolfcampian rocks are about 1,900 ft (580 m) thick. To the north in this basin Pennsylvanian rocks alone are more than 2,000 ft (600 m) thick where only the basal part of the Permian is preserved.

The Sierra Grande uplift was recurrently active from Morrowan through most of Wolfcampian and its Precambrian metamorphic and igneous rocks probably were sources of much of the clastic sediments of the entire area. Some of the finer grained clastics of the Pecos shelf may have been derived from the Pedernal uplift to the southwest and the Brazos uplift on the west (Fig. 4), but the intrabasinal uplifts of the shelf were emergent at times and restricted the transportation of sediments from these more distant basin-marginal uplifts. At times the Precambrian cores of parts of the intrabasinal uplifts were structurally high enough to be local sources of coarse clastics.

Where the Tecolote uplift plunged north, the southern shelf merged into the structurally lower Manuelitas saddle and into the north-plunging Rociada Basin (Fig. 71). Morrowan through Wolfcampian rocks of the Manuelitas saddle are about 5,000 ft (1,500 m) thick and probably were thicker in the Rociada Basin where preserved Morrowan and Atokan rocks alone are more than 2,000 ft (600 m) thick. West of the area of Figure 71 the Rociada Basin was bounded by part of the Pecos shelf (Fig. 4) where Morrowan and Atokan rocks are about 400 ft (120 m) thick and lower and middle Desmoinesian rocks are about 900 ft (275 m) thick (Sutherland, 1963, fig. 10). North of the area, the Rociada Basin merged, around the north end of the Pecos shelf, into the Taos trough where Morrowan through middle Desmoinesian rocks are at least 5,700 ft (1,700 m) thick, (Sutherland, 1963), but younger rocks are not preserved.

As the Pennsylvanian and Permian rocks thicken into the Rociada Basin and onto the Manuelitas saddle their facies

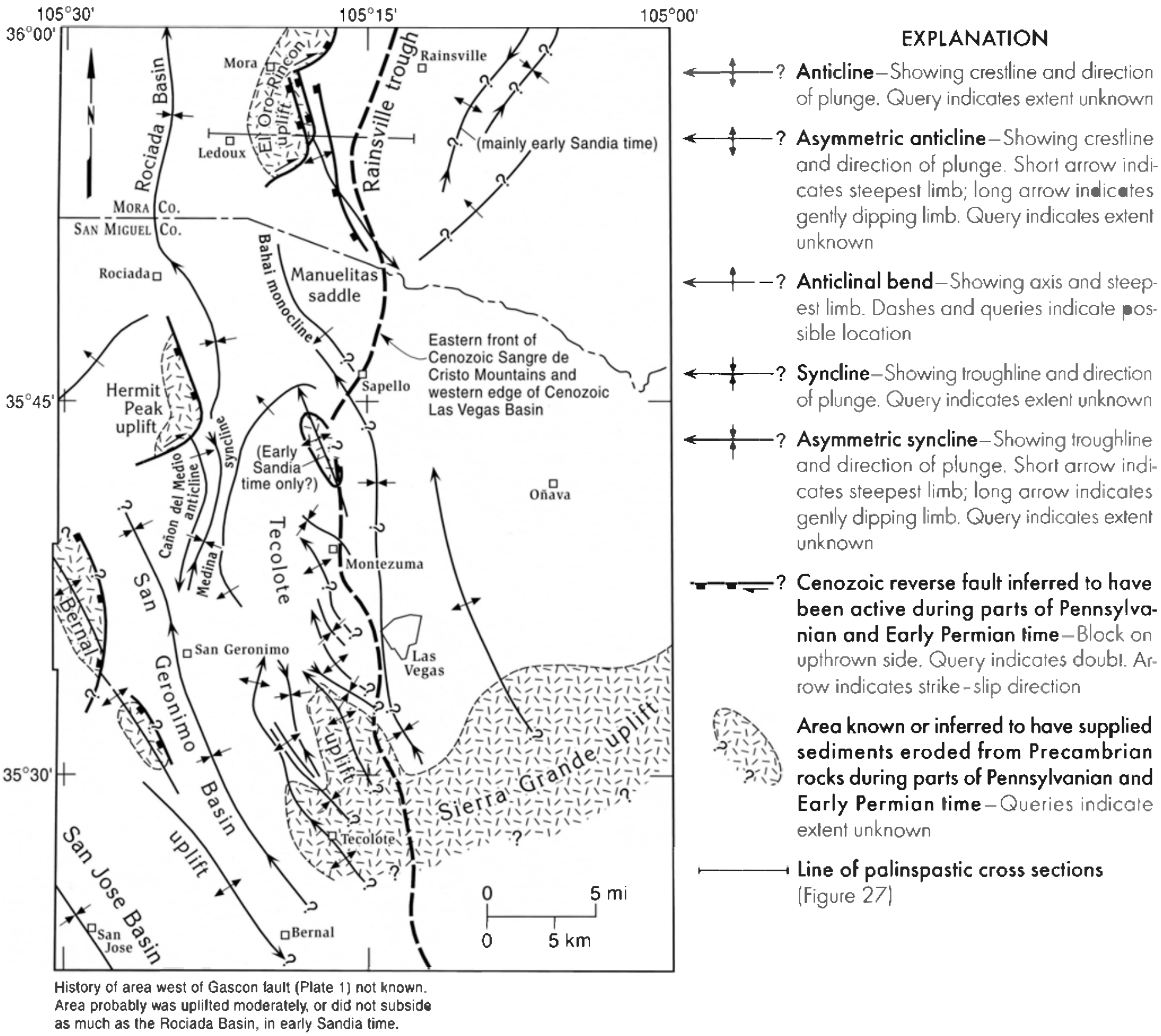


FIGURE 71—Paleotectonic diagram of southeastern part of Sangre de Cristo Mountains and adjacent part of Las Vegas Basin showing principal local geologic structures known and inferred to have developed in Pennsylvanian and Early Permian time. Faults that may have been active are shown without palinspastic reconstruction. Present eastern front of mountains shown for orientation

change from those of the southern, Pecos shelf. The Morrowan through upper Desmoinesian rocks preserved in the Rociada Basin are mostly marine shale and thin limestone, but they contain fine-grained to conglomeratic sandstone. The shale and part of the sandstone probably had sources in the Brazos and Sierra Grande uplifts, but some coarse clastics on the eastern margin of the Rociada Basin were derived from the El Oro–Rincon uplift. The mainly marine Morrowan through upper Desmoinesian rocks of the Manuelitas saddle contain thick feldspathic conglomeratic sandstones also derived from the El Oro–Rincon uplift. The partly marine upper Desmoinesian through Virgilian rocks of the basin and saddle contain alluvial-fan deposits and other coarse, feldspathic clastics derived from the Hermit Peak and El Oro uplifts and probably the Sierra Grande uplift. Wolfcampian nonmarine rocks of the saddle are 1,500–2,000 ft (460–610 m) thick and were derived partly from intrabasinal uplifts but mainly from multiple sources in the uplifts that bounded the main basins.

North of the Manuelitas saddle Morrowan through Wolfcampian rocks thicken rapidly into the Rainsville trough where they are about 10,000 ft (3,050 m) thick. In Morrowan and early Atokan the Rainsville trough may have been coextensive with the Taos trough, and the mainly marine shale, limestone, and sandstone probably were derived mainly from the basin-margin uplifts to the west, north, and east (Fig. 4). Beginning in Atokan, and continuing until Wolfcampian, the El Oro–Rincon intrabasinal uplift was elevated episodically to separate most of the deep part of the earlier basin into the eastern Rainsville trough and the western Rociada Basin and Taos trough. Precambrian rocks of the eastern part of the El Oro–Rincon uplift shed fans of micaceous, feldspathic to arkosic clastics south onto the Manuelitas saddle and east into the Rainsville trough where they mingled with mixed marine-nonmarine sediments derived mainly from the Sierra Grande uplift to the east. The El Oro–Rincon uplift restricted Atokan sediment dispersal so that organic-rich shale was deposited west of the uplift in the eastern part of the Taos trough. In that area the shaly Atokan sediments were derived from the Brazos uplift and uplifts north of the Taos trough. In Wolfcampian, the El Oro–Rincon uplift probably was buried, as were the intrabasinal uplifts at the south, by nonmarine sediments derived from outside the area.

Throughout Pennsylvanian time sedimentation was rapid enough to mainly keep up with subsidence of the shelf and major basins, as shown by repeated sequences of marine and nonmarine rocks. Despite repeated basin filling and repeated tectonic emergence of intrabasinal and basin-margin uplifts, marine rocks of all the series of the Pennsylvanian and the lowest Permian (lower Wolfcampian) are present, indicating that connections were maintained with seas to the south and west. The seemingly rapid southward retreat of the earliest Wolfcampian sea across much of northern New Mexico may have been a result of epeirogeny or eustatic sea-level changes followed by nonmarine sedimentation in various basins that still were subsiding. By the end of Wolfcampian, the basins were filled and sediments had lapped back across parts of basin-margin uplifts as the orogenic cycle was completed. A rapid readvance of the Leonardian (Yeso) sea back across northern New Mexico was a result of epeirogeny or eustatic sea-level change, or both.

In the area of this report the Paleozoic intrabasinal uplifts have a right-stepping echelon pattern (Fig. 71). Isopachs and stratigraphic relations along the Bernal and Tecolote uplifts show that they were southwest-tilted, basement-cored blocks that had anticlinal culminations near their eastern margins and parallel asymmetric synclines on their eastern flanks. Depositional hiatuses marked by intraformational and interformational angular unconformities occur on the crests and high on the flanks of the uplifts, but sedimentation was nearly continuous in the deep parts of the flanking synclinal basins. The Hermit Peak and El Oro–Rincon uplifts have been modified greatly by Cenozoic tectonic activity, and Middle and Upper Pennsylvanian and Permian rocks have been eroded from their western flanks, precluding the determination of whether local angular unconformities once existed there. Nevertheless, their present west-tilted structural configurations allow for that possibility, and both uplifts have northerly trending paleostructural and depositional troughs on their eastern and western flanks.

Paleozoic faulting seems necessary to have kept the Precambrian basement rocks of several uplifts shallow enough to recurrently supply sediments to the adjacent deeply subsided local basins. Palinspastic reconstruction suggests that the eastern flanks of these uplifts were broken by reverse faults (Fig. 27), but we are not able to distinguish possible Paleozoic faults from the Cenozoic faults, and it is likely that precursors of the Cenozoic Hermit Peak and El Oro faults, part of the Sapello fault (Plate 1), and unnamed faults at the east side of the present Rincon Range (Plate 2) were active in Paleozoic time.

The general geometry of the Paleozoic intrabasinal uplifts and synclines suggests they were produced by regional compression oriented northeasterly. The right-echelon pattern suggests coupling forces and local shallow to deep-seated, right-lateral shearing of basement rocks partly in response to transpression.

A general correspondence between Paleozoic and Cenozoic (Laramide) anticlines and synclines is apparent (Plates 1, 4), especially in the southern half of the area, but the greater Cenozoic deformation has bridged gaps by faulting between the Paleozoic uplifts, and the Paleozoic synclines in the eastern part of the mountains and northeast of Hermit Peak were uplifted, tilted, and faulted. The Laramide compressional forces were oriented similarly to those of the Paleozoic and reactivated structural features at least as old as Pennsylvanian.

East of the mountains, subsurface data are too scanty for detailed comparisons of Paleozoic and Cenozoic structures, but the Cenozoic Las Vegas Basin coincides generally with the eastern part of the Paleozoic Basin. At least part of the Cenozoic Ocate anticline (Plate 2) in the northern part of the Las Vegas Basin seems to be situated on a low, Pennsylvanian intrabasinal anticline.

The Precambrian basement south of Hermit Peak and Sapello seems to have been "welded", in Proterozoic time, into a tectonic unit that later deformed differently from the basement farther north. The Precambrian metamorphic rocks of the Paleozoic Bernal and Tecolote uplifts are folded sharply, migmatized, and intruded by granitic plutons, but these rocks are not known well enough to determine whether there is a direct relation of their local structure to Paleozoic and Cenozoic structure. This southern area of welded basement is the site of the relatively thin Paleozoic Pecos shelf facies and also has less Cenozoic structural relief than the northern part of the area.

The Precambrian rocks of Hermit Peak are parts of an asymmetric east-verging anticline or dome whose east limb was the site of multiple plutonic intrusions ranging from ultrabasic to granitic (Fig. 5). This area of Precambrian uplift and intrusion was rejuvenated along the west-dipping Hermit Peak fault in Paleozoic and Cenozoic times.

North of Hermit Peak the Precambrian folds are more open and are less intruded by plutonic rocks. The Precambrian structure near Rociada probably is a northwesterly trending synclinal basin in the area of part of the Paleozoic Rociada Basin. The Precambrian El Oro anticline plunges north and south and has an overturned east limb similar to the Paleozoic and Cenozoic faulted anticlines of the same area. North of Mora, Precambrian rocks of the Rincon Range are folded into large, northerly trending, east-verging anticlines whose partly known axes generally parallel the Paleozoic El Oro–Rincon uplift and the Cenozoic faulted anticlines on the eastern margin of the mountains (Plate 2).

SPECULATIONS AND IMPLICATIONS FOR REGIONAL INTERPRETATION OF ANCESTRAL ROCKY MOUNTAINS PALEOTECTONICS

By Elmer H. Baltz

Figure 72 is a highly speculative isopach map of the mixed marine-nonmarine Pennsylvanian rocks of north-central New Mexico that integrates stratigraphic data and paleotectonic features of the southeastern part of the Sangre de Cristo Mountains into a regional picture. The isopached interval includes also the thin (0–60 ft; 0–18 m) Lower Permian (lower Wolfcampian) marine rocks of the Alamitos Formation in the southeastern part of the Sangre de Cristo Mountains, but it excludes the nonmarine rocks of the lower part of the Sangre de Cristo Formation that may be Late Pennsylvanian (Virgilian) in the Rainsville trough. The excluded nonmarine rocks, as inferred from outcrops in the Mora River area, are 500–700 ft (150–215 m) thick. On the map, eroded parts of the Pennsylvanian rocks have been restored hypothetically in the high parts of the Sangre de Cristo Mountains, but palinspastic restorations were not made.

Parts of Figure 72, especially to the north, present new possible paleotectonic interpretations that are highly speculative because Pennsylvanian lithostratigraphic and biostratigraphic units have not been mapped there, and the details of stratigraphic relations and structure are poorly understood. The new interpretations are hypotheses that may explain some problems of stratigraphy and paleotectonics and are offered to stimulate further investigations.

Figures 4 and 72 show the Taos trough extending northwest of Taos into the area of a pronounced negative gravity anomaly in the Neogene San Luis Basin (Plate 2), and they show the Paleozoic uplift southwest of Taos as trending northwest and connecting with the ancestral Brazos uplift at a gravity high (Plate 2) between Precambrian rocks at Cerro Azul and the present Picuris Mountains. The figures show a hypothetical intrabasinal uplift north of Taos and also show the hypothetical San Luis(?) uplift as continuing northwest from the Cimarron arch to separate the Taos and Rainsville troughs from the Central Colorado Basin of Pennsylvanian time. These interpretations differ from previous interpretations in two major respects: (1) most previous interpretations show the Pennsylvanian and Permian basins of northern New Mexico and central Colorado as bounded on the west by a single, north-trending, Paleozoic uplift that was part of the Uncompahgre uplift of southwestern Colorado; and (2) previous interpretations show the Pennsylvanian–Permian basins extending northward in New Mexico without interruption into the Central Colorado Basin. Figure 73 illustrates a previous general concept of the paleotectonic setting of north-central New Mexico. The following parts of this report summarize and discuss various data and interpretations from the literature to provide the bases for the interpretations of Figures 4 and 72.

Ancestral Brazos uplift

General concepts

Melton (1925a, b) established the concept of a major sediment-shedding uplift west of the deep basin in which Pennsylvanian and Lower Permian rocks of the Sangre de Cristo Mountains were deposited in Colorado. He called this the San Luis uplift, which was thought to be in the subsurface of the present San Luis Basin of the Rio Grande depression. Later workers (Read and Wood, 1947; Brill, 1952; Sutherland, 1963; Baltz, 1965; Mallory, 1972a, b, 1975) inferred that Melton's postulated Paleozoic uplift and the Precambrian rocks of the western Sangre de Cristo Mountains south of Taos, New Mexico were southeastern parts of the Paleozoic and Mesozoic Uncompahgre uplift of Colorado. They included the area of the Cenozoic Brazos uplift (Plate 2) of New Mexico also with the Uncompahgre uplift.

The northwest-trending Cenozoic Brazos uplift west of the Rio Grande depression in New Mexico (Plate 2) clearly was the site of a Late Pennsylvanian–Early Permian and Triassic–Jurassic uplift (Dane, 1948; Muehlburger, 1967; Smith et al., 1961) that shed sediments southwestward. In latest Cretaceous and early Tertiary time the ancestral Brazos uplift became the western part of a broad Laramide geanticline (or anticlinorium) that included the present Sangre de Cristo uplift (Baltz, 1967, p. 19–20, 85–87). In Neogene time the part of the geanticline west of the Sangre de Cristo Mountains in New Mexico and Colorado was tilted east and its eastern part foundered along normal faults to form the San Luis Basin of the Rio Grande depression (Baltz, 1965, 1978; Tweto, 1979b, 1983). The repeated uplifting and erosion of the ancestral Brazos uplift have rendered most of its Pennsylvanian and Permian history unverifiable except near its northwest margin. Much of the northeastern part of the uplift is concealed by Tertiary volcanic rocks and sediments of the San Luis Basin.

In the western part of the Sangre de Cristo Mountains in New Mexico direct stratigraphic evidence of the existence of Paleozoic uplifts is scanty. Evidence of the low, Paleozoic Cañoncito uplift is clear northeast of Lamy (Fig. 72) where Pennsylvanian rocks and the Sangre de Cristo Formation both are much thinner on the uplift than in adjacent parts of the basin to the east (Read et al., 1944; Booth, 1976). Several miles north of there thin remnants of Mississippian and Pennsylvanian rocks are present in a narrow north-trending faulted block within the Precambrian, but younger rocks are absent (Budding, 1972). North of this block Paleozoic and younger rocks are absent entirely from the high western part of the mountains as far north as the Rio Arriba–Taos County line, suggesting the presence of a Paleozoic uplift but precluding direct evidence of it.

In the foothills along the western base of the Sangre de Cristo Mountains, Mississippian rocks and thin remnants of the Sandia Formation (Morrowan and Atokan) and the Porvenir Formation (Desmoinesian) crop out sporadically from south of Santa Fe to the vicinity of Rio Nambe (Spiegel and Baldwin, 1963; Miller et al., 1963; Baltz, 1978, fig. 3). These rocks may have been on the western margin of the Cañoncito uplift, as shown in Figure 72, but the original thicknesses of the Pennsylvanian rocks of the foothills are not known because they are overlain unconformably by Miocene to Quaternary sediments on the east margin of the Neogene Española Basin (Plate 2). From about Rio Nambe northward to about 2 mi (3 km) northeast of Cerro Piñon (Fig. 72) Paleozoic rocks are absent from the foothills, but pebble to boulder conglomerates with Precambrian, Mississippian, and Pennsylvanian clasts occur at the base and in the lower part of the Tertiary sediments, indicating that Paleozoic rocks were deposited at places in the western part of the mountains at least that far north.

In the foothills at Rio Nambe and a little farther south, Sutherland and Harlow (1973, fig. 50) found that Desmoinesian rocks (which I assign to the Porvenir Formation) lie on Morrowan or thin Atokan(?) rocks (which

I assign to the Sandia Formation). Sutherland and Harlow (1973, p. 111) believed that Atokan rocks had been cut out, or mainly cut out, by an east-directed thrust fault. I did not find evidence for the thrust fault during detailed remapping of the area of Sutherland and Harlow's (1973) figure 50. The outcrops on Rio Nambe illustrated by Sutherland and Harlow (1973, fig. 20) are broken by several small Neogene normal faults, but shale beds can be traced across the feature they delineate as a thrust fault, and massive bioclastic limestone of the Porvenir Formation, about 10 ft (3 m) above the postulated fault, lies on a slightly angular unconformity cut on the Sandia Formation. Stratigraphically higher limestones of the Porvenir contain large amounts of fine to coarse quartz sand that suggests a source terrane of Precambrian rocks. These rocks contain the early Desmoinesian fusulinid *Beedeina portalensis* (collection f10315) and are equivalent to the lower part of the Porvenir Formation. About 0.5 mi (0.8 km) southeast of Nambe Falls the Sandia contains thick coarse-grained to conglomeratic sandstones and sandy limestones that suggest an uplifted source of Precambrian rocks that was not far distant in Early Pennsylvanian time. I interpret the outcrops near Rio Nambe and farther south to be the lower Desmoinesian part of the Porvenir Formation lying unconformably on the Morrowan or lowest Atokan part of the Sandia Formation near the western margin of the Cañoncito uplift or the southern margin of the ancestral Brazos uplift (Fig. 72).

The primary evidence of major sources of first-cycle Paleozoic sediments east of the present Rio Grande is the lithology and facies distribution of Pennsylvanian and Permian rocks of the western part of the Sangre de Cristo Mountains. Highly arkosic and conglomeratic rocks of the Alamitos and Sangre de Cristo Formations in the southwestern part of the mountains are thought (Sutherland, 1963, p. 43–44) to have been derived mainly from Precambrian granitic rocks west of the Pecos–Picuris fault in northern Santa Fe County and southeastern Rio Arriba County (the ancestral Brazos uplift in Fig. 72). Morrowan through Desmoinesian quartzose and arkosic clastics of the Taos trough also are believed to have been derived from Precambrian metamorphic and granitic rocks west of the Pecos–Picuris fault in Rio Arriba and southeast Taos Counties (Sutherland, 1963, p. 41–42).

Pecos–Picuris fault

In New Mexico, in the western part of the Sangre de Cristo Mountains south of Taos, Montgomery (*in* Miller et al., 1963, p. 16–18) showed that Precambrian rocks are offset in right-lateral sense by a north-trending high-angle fault called the Pecos–Picuris fault. This fault, consisting locally of several closely spaced parallel faults, extends from the Picuris Mountains to south of the latitude of Pecos (Moench and Robertson, 1980), and it probably connects at the south with the Deer Creek fault (Plate 2; Fig. 72) of Budding (1972) and Booth (1976, 1977). According to Montgomery, Precambrian strike-slip movement on the Pecos–Picuris fault was about 23 mi (37 km). Montgomery noted that post-Pennsylvanian, probably Laramide or younger, vertical movements also occurred on the fault.

Sutherland (1963, p. 39-44) reasoned that the Pecos-Picuris fault had vertical displacements also during Pennsylvanian time and that the Precambrian rocks west of the fault north of the Santa Fe County line were the southern part of the Uncompahgre uplift and were the principal sources of coarse clastics for the entire basinal area to the east until Late Pennsylvanian and Early Permian time. Sutherland (1963, p. 40) pointed out that an inferred north-south line, extending the trend of the Pecos–Picuris fault northward beneath the Cenozoic deposits of the San Luis Basin, projects into a hypothetical north-south line within the San Luis Basin in Colorado that Mallory (1960) inferred might be the eastern edge of the Uncompahgre uplift there. Later, Mallory (1972b, fig. 1) called this hypothetical boundary, in its entirety in both states, the Pecos–Picuris fault. Baars and Stevenson (1984) and other writers also utilized this concept.

The Pecos–Picuris and Deer Creek faults are shown in Figure 72 as the eastern boundary of Paleozoic uplifts south of Taos, New Mexico, but the northern uplift is considered in this report as being part of the nearby ancestral Brazos uplift, rather than being part of the ancient Uncompahgre uplift of Colorado. Paleozoic movements on the Deer Creek fault and the nearby Apache Canyon fault are likely because Pennsylvanian rocks and the Sangre de Cristo Formation on the Cañoncito uplift are much thinner than they are in parts of the basin that are immediately adjacent to the east (Booth, 1976). Northwest of Pecos probable local unconformities within Pennsylvanian rocks occur adjacent to and east of the Deer Creek fault, and the Sangre de Cristo Formation locally laps onto Precambrian rocks east of the fault (R. H. Moench, U.S. Geological Survey, unpub. mapping and oral comm., 1986). A northwesterly trending Late Pennsylvanian anticline east of the fault probably is transected by the fault. Farther north, Cenozoic deformation and erosion have affected the western part of the Sangre de Cristo Mountains to the degree that direct stratigraphic evidence of a Paleozoic high immediately west of the Pecos–Picuris fault is scanty. Pennsylvanian rocks are shown to be present immediately west of the fault near the Rio Arriba–Taos County line (Miller et al., 1963, plate 1), suggesting that the ancestral Brazos uplift did not extend that far north, or that it was crossed by a westerly trending syncline south of the Picuris Mountains (Fig. 72).

The inclusion of the Picuris Mountains (Fig. 72) in an area of Paleozoic uplift is likely but problematic. Morrowan and Atokan rocks of Sutherland's (1963) Flechado Formation east of the Picuris Mountains are thick shales with interbedded conglomerates and minor amounts of limestone. These rocks are folded sharply, are overturned at places, and are faulted (Baltz and Read, 1956, p. 79; Sutherland and Harlow, 1973, p. 122–124). The Pennsylvanian rocks are overlain with sharp angular unconformity by basal conglomerates of the Picuris Formation (Montgomery, 1953) of Oligocene or Miocene age, indicating that the deformation mainly is Cenozoic, probably Laramide. The Picuris Mountains were uplifted strongly during deposition of the Picuris Formation and later (Montgomery, 1953, p. 82–83). The published evidence clearly confirms only Cenozoic stages of deformation, although Paleozoic highlands of the Brazos uplift may not have been far away, as indicated partly by the presence of chert pebbles and cobbles and other sedimentary rock fragments as well as clasts of Precambrian rocks in the lower part of the Pennsylvanian at places east of the Picuris uplift and the Pecos–Picuris fault.

Sutherland (1963, fig. 10) found that, in the easternmost part of Rio Arriba County and the southern part of Taos County, rocks of Morrowan through Desmoinesian age (his Flechado Formation) thicken rapidly northward from the Pecos shelf into the Taos trough and contain large proportions of thick, coarse to conglomeratic, quartzose sandstone that was deposited as alluvial fans and deltaic deposits that interfinger easterly with marine deposits. The coarse clasts in these rocks are reported to be lithologically similar to Precambrian metasedimentary rocks in the Picuris Mountains. Sutherland (1963, p. 41, figs. 16–18) postulated that, in Early Pennsylvanian time, Precambrian metasedimentary rocks equivalent to those of the Picuris Mountains were also present farther south, mainly in northernmost

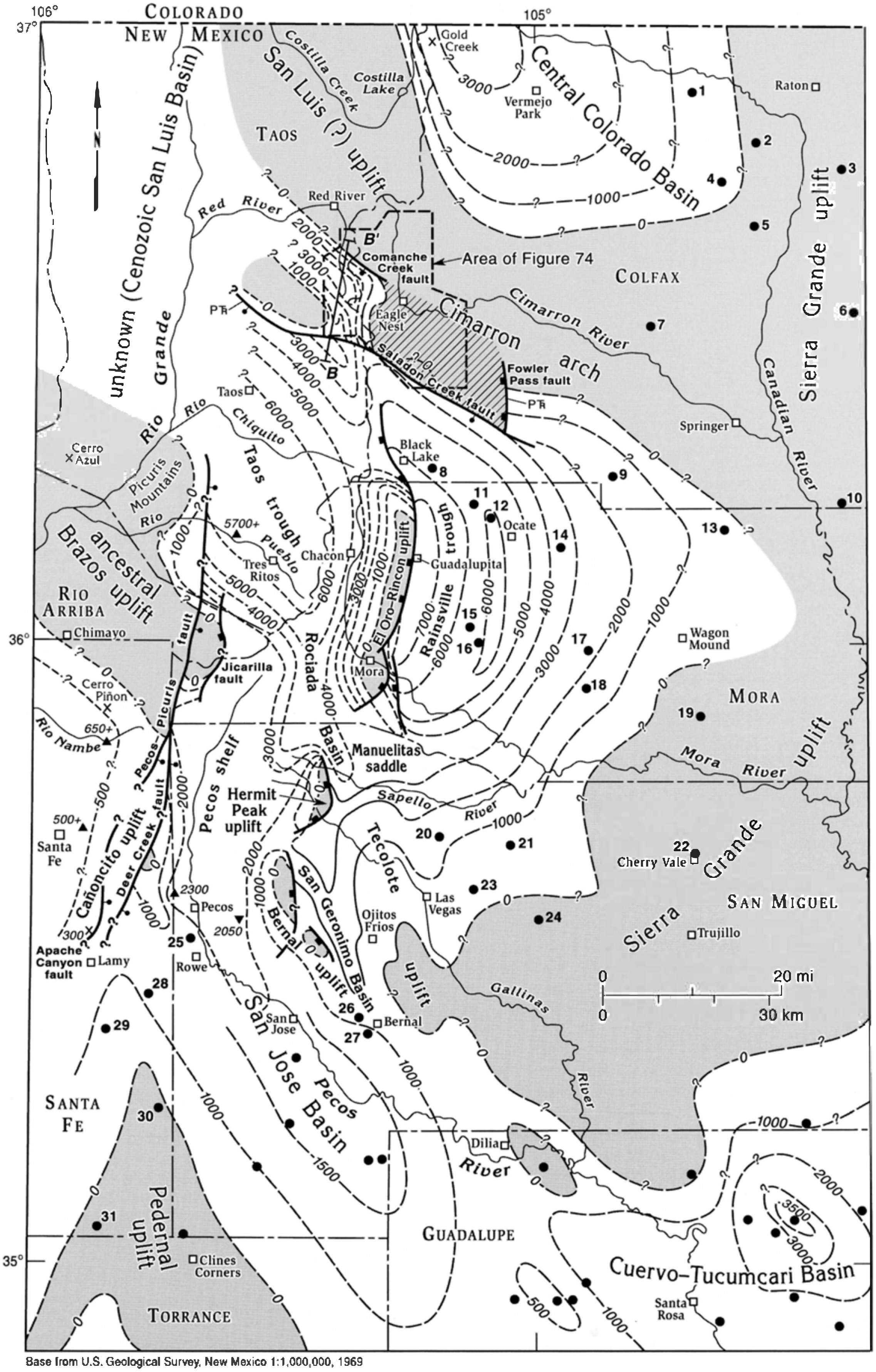


FIGURE 72—Map of north-central New Mexico showing late Paleozoic tectonic features and isopachs of combined thicknesses of Sandia, Porvenir, and Alamitos Formations and their mixed marine-nonmarine equivalents. Isopached rocks are mainly Pennsylvanian but include thin Permian (early Wolfcampian age) marine rocks of upper part of the Alamitos Formation present at places west and southwest of Las

EXPLANATION

—3000——? **Isopach**—Thickness in feet; interval 1,000 ft (about 300 m) except places to the southwest where interval is 500 ft (150 m). Isopach is solid line in outcrop areas where data (from Plate 4) are relatively abundant; short dashed in outcrop areas where upper part of Pennsylvanian rocks is eroded and original thickness is inferred; long dashed where Pennsylvanian rocks are in subsurface. Queried where location is highly uncertain

? **Cenozoic reverse fault inferred to have been active in parts of Pennsylvanian and early Permian time**—Blocks on upthrown side; queries indicate possibly active fault and fault segment. Palinspastic restoration not made

? **Cenozoic high-angle fault inferred to have been active in parts of Pennsylvanian and Permian time**—Bar and ball on downthrown side; queries indicate possibly active fault and fault segment

P₸ ? **Cenozoic fault inferred to have been active in Permian time and, possibly, early to middle Triassic time**—Bar and ball on downthrown side; queries indicate segments where persistence of fault is not certain

Southern Cimarron Mountains block inferred to have been uplifted mainly in Permian and, possibly, early to middle Triassic time

B B′ **Line of stratigraphic diagram** (Figure 77)

●2 **Well drilled to Pennsylvanian or Precambrian rocks**—Number refers to wells in list

▲5700+ **Locality of section and thickness (ft) from Sutherland (1963) and Sutherland and Harlow (1973)**—Plus symbol indicates partial thickness where top of Pennsylvanian rocks is eroded

▼2050 **Locality of section and thickness (ft) from Read and others (1944)**

x300 **Locality of measurement and thickness (ft) from Booth (1976)**

WELLS

Colfax County

1. **Continental Oil Co. No. 2** *St. Louis, Rocky Mtn. and Pacific R.R.*
   Sec. 26 T31N R21E. Total depth 7,268 ft (2,215 m); bottomed in Precambrian rocks
2. **Continental Oil Co. No. 1** *St. Louis, Rocky Mtn. and Pacific R.R.*
   Sec. 24 T30N R22E. Total depth 5,185 ft (1,580 m); bottomed in Precambrian rocks
3. **Condron No. 1** *Moore*
   Sec. 10 T29N R24E. Total depth 4,075 ft (1,242 m); bottomed in Precambrian rocks
4. **Continental Oil Co. No. 4** *St. Louis, Rocky Mtn. and Pacific R.R.*
   Sec. 17 T29N R22E. Total depth 4,709 ft (1,435 m); bottomed in Precambrian rocks
5. **Continental Oil Co. No. 1** *Maxwell*
   Sec. 11 T28N R22E. Total depth 2,947 ft (898 m); bottomed in Precambrian rocks
6. **Kates No. 1-A** *Souble*
   Sec. 35 T27N R24E. Total depth 2,520 ft (768 m); bottomed in Precambrian rocks
7. **American Manufacturing Co. No. 1** *W.S. Ranch*
   Sec. 1 T26N R20E. Total depth 3,825 ft (1,166 m); bottomed in Precambrian rocks
8. **True Oil Co. No. 21-25** *Medina*
   Sec. 25 T24N R16E. Total depth 9,140 ft (2,786 m); bottomed in Precambrian rocks
9. **McDaniel Oil Lease Trust No. 1** *McDaniel and Son*
   Sec. 32 T24N R20E. Total depth 5,200 ft (1,585 m); bottomed in Pennsylvanian(?) rocks
10. **California Oil Co. No. 1** *Floersheim-State*
    Sec. 15 T23N R24E. Total depth 2,556 ft (779 m); bottomed in Precambrian rocks

Mora County

11. **Continental Oil Co. No. 1** *Mores-Duran*
    Sec. 14 T23N R17E. Total depth 7,765 ft (2,367 m); bottomed in Precambrian (?) rocks
12. **True Oil Co. No. 34** *Arguello*
    Sec. 24 T23N R17E. Total depth 8,667 ft (2,642 m); bottomed in Precambrian rocks
13. **Shell Oil Co. No. 1** *Shell-State*
    Sec. 35 T23N R22E. Total depth 5,040 ft (1,536 m); bottomed in Precambrian rocks
14. **Shell Oil No. 1** *Mora Ranch*
    Sec. 5 T22N R19E. Total depth 9,690 ft (2,954 m); bottomed in Precambrian rocks
15. **Amoco Production Co. "B" No. 1** *Salman Ranch*
    Sec. 21 T21N R17E. Total depth 8,950 ft (2,727 m); bottomed in Precambrian rocks
16. **Amoco Production Co. "A" No. 1** *Salman Ranch*
    Sec. 3 T20N R17E. Total depth 10,133 ft (3,088 m); bottomed in Precambrian rocks

Mora County *(cont.)*

17. **Union Land and Grazing Co. No. 1** *Fort Union*
    Sec. 2 T20N R19E. Total depth 4,070 ft (1,241 m); bottomed in Pennsylvanian rocks and Tertiary igneous sills
18. **Cities Service Co. No. 1** *Fort Union*
    Sec. 33 T20N R19E. Total depth 5,836 ft (1,779 m); bottomed in Pennsylvanian(?) rocks and Tertiary igneous sills
19. **Shamrock Oil Co. No. 1** *McArthur*
    Sec. 12 T19N R21E. Total depth 3,240 ft (988 m); bottomed in Precambrian rocks

San Miguel County

20. **J.D. Hancock No. 1** *Sedberry*
    Sec. 25 T17N R16E. Total depth 5,131 ft (1,564 m); bottomed in Precambrian rocks
21. **Continental Oil Co. No. 1** *Shoemaker-Reed*
    Sec. 28 T17N R18E. Total depth 4,519 ft (1,377 m); bottomed in Precambrian rocks
22. **Southwest Drilling Co. No. 1** *Conchas*
    Sec. 34 T17N R21E. Total depth 3,512 ft (1,070 m); bottomed in Precambrian rocks
23. **Continental Oil Co. No. 1** *Leatherwood-Reed*
    Sec. 15 T16N R17E. Total depth 3,911 ft (1,192 m); bottomed in Precambrian rocks
24. **Phillips Petroleum Co. No. 1** *Leatherwood*
    Sec. 2 T15N R18E. Total depth 2,772 ft (845 m); bottomed in Precambrian rocks
25. **Tex Austin No. 1** *Fee*
    Sec. 16 T15N R12E. Total depth 1,835 ft (559 m); bottomed in Precambrian(?) rocks
26. **Rockwell No. 1** *Des Morios*
    Sec. 33 T14N R15E. Total depth 552 ft (168 m); bottomed in Precambrian rocks. Porvenir Formation is at surface
27. **Santa Fe Petroleum Co. No. 1** *State*
    Sec. 3 T13N R15E. Total depth 1,727 ft (526 m); bottomed in Pennsylvanian rocks

Santa Fe County

28. **Richfield No. 2** *Lee*
    Sec. 14 T14N R11E. Total depth 2,725 ft (831 m); bottomed in Precambrian rocks
29. **Toltec No. 1** *Eaton*
    Sec. 2 T13N R10E. Total depth 2,165 ft (660 m); bottomed in Precambrian rocks
30. **Adkins No. 1** *Basher*
    Sec. 23 T12N R11E. Total depth 977 ft (298 m); bottomed in Precambrian rocks
31. **Kelsey Clients No. 1** *Crowe Butte*
    Sec. 26 T10N R10E. Total depth 1,052 ft (321 m); bottomed in Precambrian rocks

Vegas. Isopachs (except south and southeast of Eagle Nest) represent thickness at beginning of deposition of nonmarine sediments of the Sangre de Cristo Formation (mainly Late Pennsylvanian time to the north, earliest Permian time to the south). Southeastern part of area (unnumbered wells) adapted from Foster et al. (1972, fig. 7).

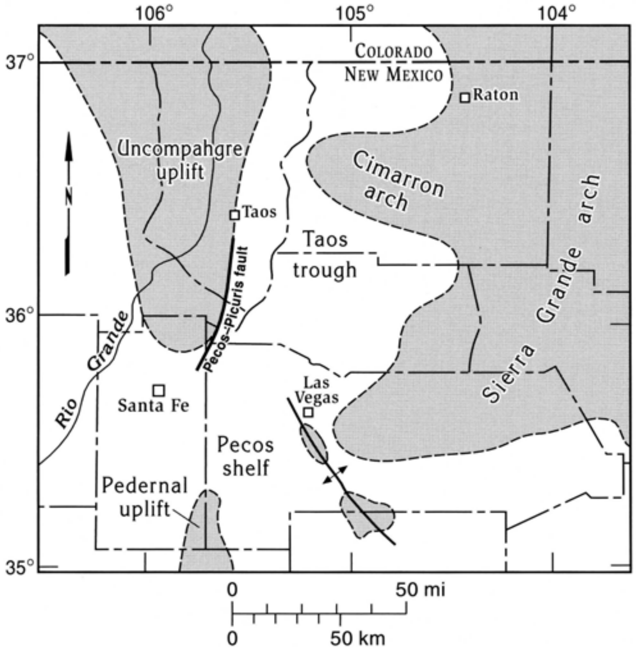


FIGURE 73—Pennsylvanian tectonic setting of north-central New Mexico, as envisioned by Casey (1980a). For setting as envisioned for the present report, see Fig. 4.

Santa Fe County and eastern Rio Arriba County, west of the Pecos–Picuris fault. This source was postulated to account for the metasedimentary detritus that comprises much of the Flechado Formation in adjacent parts of the Taos trough. Continuing Pennsylvanian uplift and erosion of the block west of the fault was thought to have caused stripping of the metasedimentary rocks south of the Picuris Mountains, eventually exposing underlying granitic batholiths that were the sources of arkoses of the Alamitos and Sangre de Cristo Formations preserved south of the vicinity of Pecos.

An alternative hypothesis that might partly account for the abrupt appearance of thick beds of coarse metasedimentary detritus of the Flechado Formation in southeastern Rio Arriba County (between sections 40 and 26 of Sutherland, 1963, figs. 7, 10) is suggested by the presence of an uplifted block of Precambrian metasedimentary rocks (plate 1 of Miller et al., 1963) between the Pecos–Picuris and Jicarilla faults (Fig. 72; Plate 2). The Precambrian Ortega Quartzite is widely exposed in this block. Apparently, these rocks east of the Pecos–Picuris fault were not considered to be sediment sources by Sutherland (1972) because he considered the Jicarilla fault to be Laramide. However, in view of the relation of some Pennsylvanian and Cenozoic structures established in the southeastern part of the mountains, this block between the two faults also might be a Paleozoic and Cenozoic structure. Section 40 of Sutherland and Harlow (1973, p. 106–109) indicates that the upper part of the La Pasada Formation just east of the Jicarilla fault includes conglomerates of quartzite pebbles but also includes limestone pebbles and cobbles and shale pebbles. This suggests proximity to the southern part of an area of uplifted older Pennsylvanian rocks as well as Precambrian rocks. At section 26 (Sutherland and Harlow, 1973, p. 102–104), in southernmost Taos County about 6 mi (9.5 km) northeast of section 40, the upper part of the equivalent Flechado Formation is mostly coarse-grained sandstone and pebbly conglomerate in units 15–114 ft (4.5–34 m) thick that may be fans derived also from the Precambrian metasedimentary rocks in the block between the Pecos–Picuris and Jicarilla faults. According to the interpretation in Figure 4 (this report), the extensive Precambrian metasedimentary terranes of the Brazos uplift west of the present Rio Grande also could have supplied quartzose sediments to the western part of the Taos trough in Early and Middle Pennsylvanian.

At the north edge of the Picuris Mountains, Precambrian rocks are dropped along the Neogene Embudo fault (Plate 2) and are buried deeply by Neogene rocks and sediments of the San Luis Basin. The extent of the Pecos–Picuris fault is not known north of the Embudo fault. The Pecos–Picuris fault may splay into other faults or may be terminated by some other structural mechanism, such as passing into northwest-trending Precambrian thrust faults. At any rate, the pronounced negative-gravity anomaly (Cordell and Keller, 1984) in the vicinity of Taos (Plate 2) suggests that a buried northern continuation of a Paleozoic uplift is not present north of the Picuris Mountains.

East and southeast of Taos outcropping thick Morrowan through Desmoinesian rocks of the deep part of the Taos trough are terminated abruptly at the west side of the Sangre de Cristo uplift by Neogene normal faults (Plate 2) that throw the Pennsylvanian rocks against Cenozoic volcanic rocks and sediments of the San Luis Basin. This is the only place in New Mexico where Precambrian rocks do not crop out to form the western backbone of the present Sangre de Cristo uplift. Even in the Cenozoic embayment south of the Picuris Mountains (Plate 2), Precambrian rocks are exposed at places beneath a veneer of Tertiary sediments. All these relations suggest that the Neogene faults near Taos cut transversely across the early Tertiary relic of the Taos trough and that Pennsylvanian rocks of the northwestern part of the trough may be buried by Cenozoic deposits in the area of pronounced low gravity in the San Luis Basin near and west of Taos.

Just (1937, p. 49) reported that, west of the San Luis Basin, the Tertiary Carson Conglomerate, which lies on Precambrian rocks of the Brazos uplift, consists primarily of clasts of Precambrian and Tertiary volcanic rocks but that, at unspecified localities, it contains clasts of black chert "presumably weathered from the Magdalena Formation." He suggested that the Magdalena once covered or occurred near the Petaca area (Fig. 4 of the present report). The Carson is now generally classified as the Los Pinos Formation of Oligocene and Miocene age in this region (May, 1984, p. 132). The report of Just (1937) is the only evidence known to me of the possible existence of Pennsylvanian rocks on the Brazos uplift, except on its northwestern margins (Muehlburger, 1967; Smith et al., 1961). If Just's presumption is correct, the chert clasts might have been derived from a Tertiary-uplifted western part of the Taos trough, but it must be emphasized that none of the more recent literature has mentioned possible Pennsylvanian detritus in Tertiary rocks and sediments of this region.

In the northern part of the Sangre de Cristo Mountains in Colorado, great thicknesses of bouldery conglomerate of the Crestone Conglomerate Member of the Sangre de Cristo Formation provide good evidence of a nearby major Late Pennsylvanian(?) and Early Permian uplift (Bolyard, 1959). At places northeast of the Great Sand Dunes National Monument, the Crestone Conglomerate Member laps onto Precambrian rocks within the Sangre de Cristo uplift (Johnson, 1969), indicating a late Paleozoic uplift within the range rather than concealed in the Neogene San Luis Basin to the west. De Voto et al.(1971) suggested that this uplift near Crestone, Colorado, was a west–northwest-trending fault block within the Paleozoic Central Colorado Basin, possibly an eastward projection of the Uncompahgre uplift (De Voto and Peel, 1972, p. 302, 309). However, Lindsey et al. (1986) indicated that Precambrian rocks of the Uncompahgre uplift are allochthonous within the western part of the Sangre de Cristo Mountains in Colorado, having been transported an unknown distance eastward in Laramide thrust plates.

In conclusion, I do not believe that the present incomplete data and the varying local interpretations compel a regional interpretation that, north of the Picuris Mountains in New Mexico, the sole source of Pennsylvanian and Early Permian first-cycle sediments was the eastern margin of a single, north-trending, Uncompahgre structural block bounded in its entirety in New Mexico and Colorado by the Pecos–Picuris fault. The presently known structural and stratigraphic complexity suggest a more complex paleotectonic and paleogeographic situation.

Taos trough

The first biostratigraphic study of the area of the Taos trough was reported in 1945 by J. A. Young, Jr., in an unpublished doctoral dissertation. He measured a series of generalized stratigraphic sections extending eastward from outcrops of the Precambrian south and north of Taos to the upper part of Cieneguilla Creek north of Black Lake, thus embracing all, or nearly all, the Pennsylvanian rocks of the region. He (p. 18) reported that the composite Pennsylvanian section exceeds 7,500 ft (2,280 m) in thickness. Young named three formations and described their faunas. His units are, in ascending order, the Cortado, Cieneguilla, and Osha Formations, all of which he considered to be of probable Middle Pennsylvanian (Desmoinesian) age. (See Fig. 2 of the present report.) Inasmuch as Young's report was not published, his terminology did not become part of the formal nomenclature of the region. Nevertheless, he provided valuable data and stratigraphic concepts that have been useful to later investigators.

Young (1945) found that the mixed marine and nonmarine rocks of his Cortado and Cieneguilla Formations disappear northward from the Palo Flechado Pass–Cieneguilla Creek area north of Black Lake, and at Six Mile Creek about 3 mi (5 km) southwest of Eagle Nest a nonmarine facies of his Osha Formation lies on Precambrian rocks. Young (1945, p. 81) believed that the sediment-shedding Uncompahgre highland lay within the present Sangre de Cristo Mountains in New Mexico and extended as far east as Wheeler Peak, about 8.5 mi (14 km) west of Eagle Nest and north of the area of thick Pennsylvanian rocks. His concept of a northern highland is similar to that in Figure 72 of the present report. Young (p. 28) ascribed a north-south facies change in his Cortado Formation to a source of abundant clastic detritus at the north. The cyclothemic rocks of his Cortado and Cieneguilla Formations were interpreted to be offshore bars and lagoonal, deltaic, and floodplain deposits, and his sections of these units were interpreted to be a west-east transect of the seaward margins of the shore zone south of the Uncompahgre highland. His Osha Formation that rests on Precambrian rocks southwest of Eagle Nest was interpreted to be a nonmarine delta south of the Uncompahgre highland. (Young's Osha now is assigned mainly to the Sangre de Cristo Formation. See Figure 2.)

The general interpretations of Sutherland (1963) and Casey (1980a, b), concerning marine and nonmarine depositional environments of the Pennsylvanian rocks in the Taos trough, were similar to those of Young (1945), but these later investigators placed the Uncompahgre uplift west of the present Sangre de Cristo Mountains. Casey (1980a, b) suggested that some of the Pennsylvanian terrigenous sediments were derived from the Cimarron arch to the northeast and the Sierra Grande uplift to the east.

Students from the University of Texas made detailed studies of Pennsylvanian (upper Atokan and Desmoinesian) lithofacies in parts of the Taos trough, as discussed in following paragraphs. The rocks studied correspond in age to the upper part of the Sandia Formation and part of the Porvenir Formation of the southeastern part of the mountains. According to Houle (1980, p. 51 52) paleocurrent directions of the Atokan fluviatile rocks east of Taos show south, southeast, and southwest directions of sediment transport, and, near Rio Chiquito, a dominant south-southwest direction. Coxe (1981, fig. 13, p. 92) reported that paleocurrent directions of lower Desmoinesian fluviatile rocks near Rio Chiquito show a strong south-southeasterly direction of sediment transport. Therefore, the paleocurrent directions suggest Atokan–Desmoinesian sources northwest, north, and northeast of the deep central part of the trough.

According to McBryde (1979, p. 90–91, 127, 129–131), paleocurrent features in lower to middle Desmoinesian fluviatile rocks at Tres Ritos (Fig. 72) and farther east indicate a predominant northward direction of transport, and at places northwesterly directions. McBryde (1979, p. 90–91) assumed that the primary source of sediments was the Uncompahgre uplift to the west and reasoned that the measured directions might be consonant with an easterly flow. On the other hand, the measured northerly and northwesterly directions of sediment transport, taken at face value, suggest that some first-cycle clastics were derived from the direction of uplifted Precambrian metasediments between the Pecos–Picuris and Jicarilla faults (Fig. 72) and the nearby granitic rocks west of the Pecos–Picuris fault.

Alsop (1982, figs. 18, 20, 23, 25) found that, southeast of Tres Ritos, paleocurrent directions are predominantly southerly and southwesterly. Most of the strata that Alsop studied are equivalent in age to the lower part of the Desmoinesian Porvenir Formation, as shown by the fusulinid *Beedeina arizonensis* (f10150 and f10151) we found in carbonate rocks along New Mexico Highway 518 just east of the Taos–Mora County line. The thick shales east of the county line and stratigraphically below the fusulinid-bearing rocks are not an easterly deep-basin facies of the Desmoinesian rocks as was supposed by Alsop and by Casey (1980b, fig. 26 and secs. 82–83), but, instead are equivalent to the Atokan upper part of the Sandia Formation. Alsop (1982, p. 129) assumed that the clastic sediments of this area were derived primarily from the west from the Uncompahgre uplift and, secondarily from the Sierra Grande uplift, but the current directions, taken at face value, suggest sources to the north or northeast.

Casey (1980b) summarized his work and the other University of Texas work on the Atokan–middle Desmoinesian rocks and concluded that areas to the west (Uncompahgre uplift), east (Sierra Grande uplift), and northeast (Cimarron arch) of the Taos trough all were sources of terrigenous clastics. He noted (1980b, p. 169–176) that lower Desmoinesian or uppermost Atokan rocks east of Taos contain conglomerates whose clasts range up to small boulder size; most of the large clasts are Precambrian metamorphic rocks, but some clasts are chert, Pennsylvanian sandstone, and silicified corals. These conglomerates become finer to the south and southeast, indicating a nearby northerly source of uplifted older Pennsylvanian rocks as well as Precambrian metavolcanic and plutonic igneous rocks. In Figure 72 this source area is interpreted to be an intrabasinal uplift north of Taos where Precambrian rocks of these kinds are present (Clark and Read, 1972, plate 1; Reed et al., 1983). Other data supporting the interpretation of an intrabasinal uplift north of Taos are presented later in this report.

The lithology of Desmoinesian sandstones of the Palo Flechado Pass area on the northeast side of the Taos trough was said by Casey (1980b, p. 176–177) to reflect an overwhelmingly granitic and gneissic source that he placed in the Cimarron arch. However, data from the northern part of the Rainsville trough, discussed earlier in the present report, suggest that Precambrian rocks of the Cimarron arch did not supply much first-cycle detritus at this time. An alternative source of granitic detritus would be the broad granitic terrane northwest of Eagle Nest (Clark and Read, 1972, plate 1) on the southeastern part of the San Luis(?) uplift shown in Figure 72. This detritus could have reached the northeastern part of the Taos trough through the structural sag north of the El Oro–Rincon uplift.

The data from facies analysis and paleocurrent determinations in the Taos trough are consistent with results of the present study of the southeastern part of the mountains in that they suggest multiple sediment-source areas were recurrently active in parts of Pennsylvanian time. The data also provide evidence of uplifts north of the Taos trough in Atokan and Desmoinesian time. The Missourian, Virgilian, and Early Permian history of the Taos trough is unknown because rocks of these ages are not preserved except, possibly, in the southwestern part, south of Rio Pueblo, where arkoses were assigned to the Sangre de Cristo Formation by Sutherland (1963, fig. 10). The Late Pennsylvanian coarse clastics in the western part of the Rainsville trough are interpreted in the present report to have been derived mainly from the eastern parts of the El Oro–Rincon uplift and to intermix with first- and second-cycle detritus from the Sierra Grande uplift and, possibly, the Cimarron arch. From Atokan to Early Permian time, the recurrently active El Oro–Rincon uplift probably was a barrier that prevented or inhibited the spread of sediments from eastern sources into the Taos trough.

Cimarron arch and southern part of Cimarron Mountains

The Cimarron arch is a northwest-trending Paleozoic and, probably Early Triassic, feature whose existence is inferred partly from scanty well data (Fig. 72) and gravity data (Plate 2). Surface stratigraphic evidence of the northwest part of the arch is present in the Cimarron Mountains southeast of Eagle Nest, but the complex Paleozoic through Cenozoic history is not understood completely.

The part of the Cimarron Mountains southeast of Eagle Nest shown in Figure 74 is a northwesterly plunging, Laramide anticline (Ray and Smith 1941; Smith and Ray, 1943) with an upfaulted core of Precambrian rocks. The Laramide uplift is bounded on the east and northeast by a synclinal bend in Cretaceous and lower Tertiary rocks on the southwestern flank of the Cenozoic Raton Basin (Plate 2). The uplift is bounded on the west by a generally synclinal structure that has been tilted east and downfaulted along its eastern margin in Neogene time (Clark and Read, 1972, p. 83). The tilted syncline underlies the Moreno Valley (Fig. 75). The Precambrian rocks of the uplift are truncated on the south by the southeasterly trending Saladon Creek fault (of Smith and Colpitts, 1980) and its southeastward extension (called the Lost Cabin fault by Wanek et al., 1964), which juxtapose the Precambrian rocks against Permian rocks of the northwest spur of the Cenozoic Las Vegas Basin (Plate 2).

The central core of the Laramide Cimarron Mountains uplift was raised along the southeast-trending Fowler Pass reverse fault that bends into a south trend (Plate 2) and becomes the southeast boundary of the uplift east of the area of Figure 74. The Fowler Pass fault is older than Oligocene or Miocene dacite porphyry bodies that intrude parts of the fault and its latest movements are younger than Cretaceous rocks that are folded east of the south-trending part of the fault (east of area Fig. 74). The vertical separation on the fault is probably only several hundred feet near Cimarron River (Goodknight, 1976, p. 138), but may be several thousand feet along the south-trending segment near Rayado Creek (Wanek et al., 1964). The south-trending segment of the Fowler Pass fault at Rayado Creek is a reverse fault that dips west at about 60° (Simms, 1965, p. 58).

The Saladon Creek fault extends southeastward beneath Neogene volcanic rocks, merges with or truncates the Lost Cabin fault (Fig. 74), and probably extends southeastward (Wanek et al., 1964) to join the south-trending segment of the Fowler Pass fault beneath the volcanics. The relatively straight trace suggests that the dip of the fault is steep. Data from the True Oil Co. well (no. 8, Fig. 72) indicate that Pennsylvanian rocks and the Pennsylvanian and Permian Sangre de Cristo Formation south of the Saladon Creek fault are about 9,000 ft (2,740 m) thick. Smith and Colpitts (1980, p. 14) estimated that the total stratigraphic separation on the fault might be 10,000–12,000 ft.

The age and history of the Saladon Creek fault are not understood well, nor is its northwestern extent known west of Moreno Valley. Smith and Colpitts (1980, p. 14) classified the fault as being younger than Laramide age. Their map shows that movement along the segment east of Cieneguilla Creek (Fig. 74) is younger than part of the Neogene volcanics in their "slump block", but farther east the fault is at least partly concealed by the volcanics. Farther southeast, Wanek et al. (1964) also show local fault contacts between the Neogene volcanics and the Precambrian, but elsewhere show the fault concealed by part of the volcanics. Therefore, it appears likely that the last displacements on the Saladon Creek fault are Pliocene and partly coeval with the volcanics.

In the Cimarron Mountains the primary evidence of the Paleozoic Cimarron arch is a relatively thin (100–200 ft; 30-60 m) section of the Pennsylvanian and Permian Sangre de Cristo Formation that lies with sedimentary contact on Precambrian rocks just north of Cimarron River west of the Palisades (Fig. 74). South of the river a few outcrops show that the Sangre de Cristo was deposited on the Precambrian in that area (Wanek et al., 1964).

Near the southeast end of the Cimarron Mountains, at Rayado Creek about 13 mi (21 km) southeast of Cimarron River, the south-trending segment of the Fowler Pass fault throws Precambrian rocks against the Sangre de Cristo Formation whose entire thickness is not known. According to Simms (1965, p. 12) the exposed part there is about 3,500 ft (1,070 m) thick. This southeastward thickening of the Sangre de Cristo suggests that the area east of the Fowler Pass fault was the south limb of the Cimarron arch in Permian time and probably also in Pennsylvanian time (Fig. 72).

As shown in Figure 74, Upper Triassic rocks of the Dockum Group lie on the Sangre de Cristo Formation north of Cimarron River, but just west of the Palisades, the Triassic rocks lap eastward across the Sangre de Cristo to lie with sedimentary contact on Precambrian rocks (Wanek et al., 1964). On the west side of the Cimarron Mountains, near Eagle Nest dam and farther south, remnants of the Dockum Group lie on Precambrian rocks (Wanek and Read, 1956, p. 82–83; Clark and Read, 1972, p. 45; Goodknight, 1976, p. 137–138). However, Smith and Colpitts (1980, p. 2–3; R. M. Colpitts, written comm., 1986) found thin remnants of probable Mississippian and Pennsylvanian rocks on the Precambrian in the southwest part of the Cimarron Mountains not far north of the Saladon Creek fault (Fig. 74). If this is correct, the presence of these rocks suggests that, at least in Early Pennsylvanian time, the southern part of this area was the north limb of the Rainsville trough.

The first published interpretation of the complex

Paleozoic and Mesozoic stratigraphic relations of the vicinity of Eagle Nest was made by L. C. Graton (*in* Lindgren et al., 1910, p. 93–94). Graton reported that, near Comanche Creek west of the Moreno Valley (Fig. 74), conglomeratic red beds then called "Jura–Trias" (now, the Sangre de Cristo Formation) rest directly on Precambrian rocks, but that farther south Carboniferous strata (the Pennsylvanian Magdalena Group of present usage) are present between the red beds and the Precambrian. He reported that, near the head of Cimarron Canyon, Carboniferous, Triassic, and Jurassic rocks are absent and the then-called Dakota(?) Sandstone is on the Precambrian. (The Dakota(?), as then assigned in this area, apparently included rocks now classified as the Jurassic Entrada Sandstone and Morrison Formation as well as the Cretaceous Dakota of present usage.) Graton concluded that "If the Carboniferous and Jurassic or Triassic were once present they can have been removed from under the Dakota(?) sandstone only by a faulting almost parallel to the stratification, and the character of the faulting which is known to have occurred seems certainly to preclude this supposition. It is probable, therefore, that a portion of this region was an island of Precambrian rocks during Jurassic and Triassic time, and that a still larger area had been exposed during Carboniferous time."

Wanek and Read (1956, p. 82–83) interpreted the central block of Precambrian rocks in the Cimarron Mountains to be a nearly recumbent, east-verging, Laramide anticline bounded on the east by the west-dipping Fowler Pass reverse fault. They postulated that the Fowler Pass fault passes downward into a flatter thrust at depth. The Precambrian rocks west of the Fowler Pass fault were interpreted to be a diapirlike core of the anticline. Wanek and Read (1956) revived the idea of faulting nearly parallel to stratification that Graton had mentioned and rejected. They envisioned the upper boundary of the Precambrian core as a flat, west-dipping underthrust fault that cut gently across the overlying sedimentary rocks to bring the core or "plunger" into contact with overlying Triassic, Jurassic, and Cretaceous rocks at various places on the west limb of the core and beneath the Moreno Valley. The south side of the Precambrian core was said to be an approximately east-trending, unnamed major tear fault which, presumably, is the Saladon Creek fault of Plate 2 and Figure 74 of the present report. Their "plunger" concept is illustrated in Robinson et al. (1964, fig. 113, p. 116).

Baltz (1965, p. 2049, fig. 4) suggested, as an alternative to the "plunger" hypothesis of Wanek and Read (1956), that Laramide deformation in the Cimarron Mountains may have occurred on a Paleozoic positive area, an idea similar to the earlier conclusion of Graton (*in* Lindgren et al., 1910). In the northern part of the Las Vegas Basin, Pennsylvanian rocks at the Continental Oil Co. no. 1 Mares-Duran well (no. 11, Fig. 72) northwest of Ocate are more than 5,000 ft (1,500 m) thick, and the Sangre de Cristo Formation in that vicinity is probably about 3,500 ft (1,070 m) thick. Baltz suggested that the absence of the Pennsylvanian from most of the Cimarron Mountains and the northward thinning and local pinchout of the Sangre de Cristo at places in the mountains was the result of a Paleozoic uplift that he called the Cimarron arch. Additional evidence of the Cimarron arch is that the Permian Yeso Formation, Glorieta Sandstone, and Bernal Formation, all about 650 ft (200 m) thick at Mora River and farther north, are not present on the arch. These rocks wedge out northward depositionally, or they have been truncated by an unconformity at the base of the Upper Triassic Dockum Group. The Dockum Group, itself, thins northward from about 1,100 ft (335 m) near Ocate (Bachman, 1953) to 340 ft (105 m) and less in the Eagle Nest area (Clark and Read, 1972, p. 46). This thinning suggests additional uplift in the Cimarron Mountains (Baltz, 1965, p. 2058–2059) in latest Triassic or Early Jurassic time.

The southern margin of the Cimarron Mountains is concealed by Pliocene and Pleistocene basalts (O'Neill and Mehnert, 1988) so that stratigraphic and structural relations between the mountains and the Las Vegas Basin cannot be seen. However, the relatively abrupt thinning of Paleozoic rocks suggested to Baltz (1965, fig. 4) that the southern margin of the mountains is a major northwest-trending fault or zone of faults of Pennsylvanian or Early Permian inception that was recurrently active also in Mesozoic and Cenozoic times. This is the (then unnamed) Saladon Creek fault.

Clark and Read (1972, p. 45, 90–91) noted that the Upper Triassic Dockum Group on the northeast side of the Cimarron Mountains is in normal (sedimentary) contact with underlying Precambrian rocks, and they concluded (p. 90–91) that a low arch in the vicinity of Cimarron extended into the Eagle Nest area in Middle to Late Pennsylvanian time and that some strata may have thinned over this arch. Nevertheless, they (p. 89–90) continued to reason that underthrusting of Precambrian rocks west of the Fowler Pass fault and under the Moreno Valley caused some of the thinning of various stratigraphic units above the Precambrian, in a manner similar to that envisioned by Wanek and Read (1956). (See eastern part of section 1, Fig. 75 of the present report.)

Goodknight (1976) found additional outcrops of rocks he assigned to the Dockum Group lying on Precambrian rocks in the western part of the Cimarron Mountains, and he reported that he found no evidence of flat faults between the Triassic and the Precambrian. He considered the mountains to occupy the approximate site of the late Paleozoic Cimarron arch. He concluded that the Fowler Pass fault probably is an upthrust rather than being a downward-flattening major overthrust as envisioned previously by Wanek and Read (1956).

Some aspects of the geologic history of the southern Cimarron Mountains that I interpret from the published mapping and stratigraphic studies are summarized as follows. At least the southwestern part of the present Cimarron Mountains was part of the Rainsville trough in Early and Middle Pennsylvanian time. The dominantly shaly facies of the Lower and Middle Pennsylvanian rocks in the subsurface of the northern part of the Rainsville trough south of the Cimarron Mountains contains some coarse clastics that may have been derived from the rising northwest-trending Cimarron arch and from the San Luis(?) uplift.

In Late Pennsylvanian and Early Permian time the southern part of the present Cimarron Mountains may have begun to develop independently from the Cimarron arch as a northeast-verging anticline or fault block bounded by precursors of the Saladon Creek and Fowler Pass faults (Fig. 72). The Sangre de Cristo Formation south of the Saladon Creek fault contains pebbles of Precambrian rocks and Pennsylvanian limestone and sandstone (Smith and Colpitts, 1980, p. 3) probably derived from the block during stripping of the sedimentary cover and exposure of the Precambrian core in Late Pennsylvanian and Early Permian time.

The area immediately east of the southern part of the Fowler Pass fault was an area of Late Pennsylvanian and Early Permian deposition on the south flank of the Cimarron arch as shown by the thickening of the Sangre de Cristo Formation southeastward from Cimarron River to Rayado (just southeast of the area of Fig. 74). Simms (1965, p. 12) described the Sangre de Cristo Formation in the Rayado area as micaceous arkosic conglomerates with interbeds of "extremely arkosic" sandstone and red micaceous arkosic shale. The feldspar clasts are angular and unweathered, and

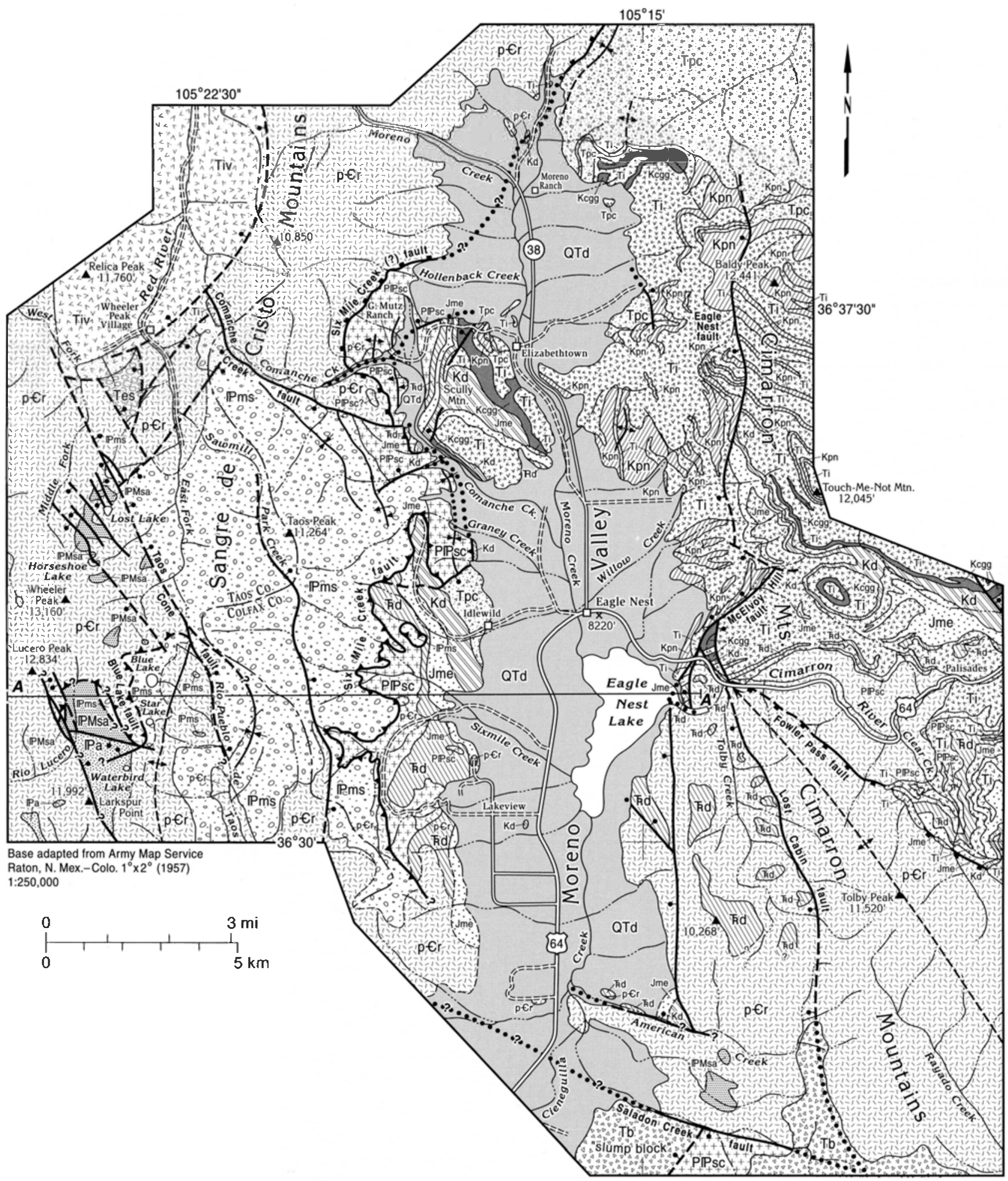
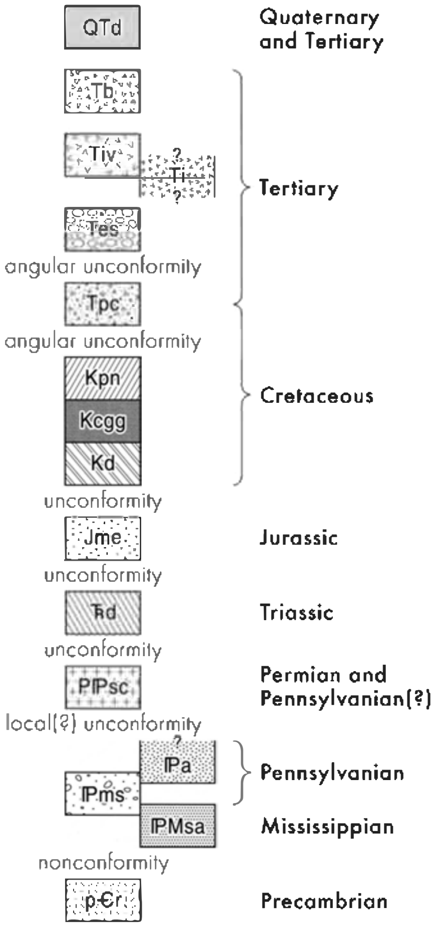


FIGURE 74—Bedrock geologic map of Wheeler Peak–Eagle Nest–Cimarron River area. Compiled from Clark and Read (1972, plate 1), Goodknight (1973, fig. 2), Reed et al. (1983), Smith and Colpitts (1980, fig. 1), and Wanek et al. (1964). Dashed contacts of area adjacent to southern part of Moreno Valley adapted from Dane and Bachman (1965). Area of map shown in Figure 72.

CORRELATION OF UNITS



MAP SYMBOLS

Contacts, faults, anticlines, and synclines are shown by solid lines where accurately located at map scale, dashed lines where approximately located, dotted lines where shown concealed by Quaternary and Tertiary units, and question marks where probable

- **Contact**
- **Normal fault**—Bar and ball on downthrown side
- **High-angle reverse fault**—Blocks on upthrown side
- **Low-angle thrust fault**—Triangles on overthrust side
- **Anticline**—Showing crestline and direction of plunge
- **Anticline with overturned limb**—Showing crestline
- **Syncline**—Showing troughline
- A A′ **Line of cross section** (Fig. 75)

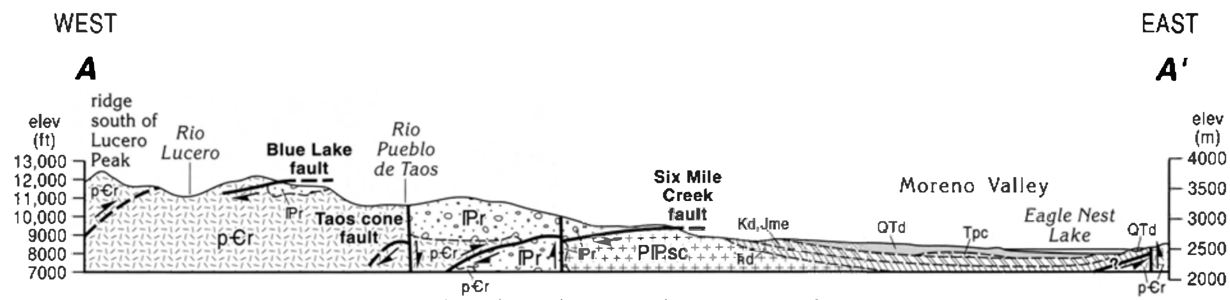
DESCRIPTION OF UNITS

- QTd **Unconsolidated deposits (Pleistocene and Pliocene)**—Alluvium, alluvial fans, and terrace gravels of Moreno Valley
- Tb **Basalt flows (Pliocene and Miocene?)**
- Tiv **Intrusive igneous rocks, volcanic rocks, and volcaniclastic rocks, undivided (Miocene)**
- Ti **Intrusive igneous rocks (Miocene or Oligocene)**—Sills and dikes in Paleocene, Mesozoic, and Paleozoic rocks northwest, north, and southeast of Eagle Nest
- Tes **Prevolcanic sediments and rocks (Oligocene or Eocene)**—Poorly indurated reddish- to greenish-gray shale, sandstone, and conglomerate in fault block between East and Middle Forks of Red River
- Tpc **Poison Canyon Formation (Paleocene)**—West of Eagle Nest, may include lower part of Paleocene and Upper Cretaceous Raton Formation
- Kpn **Pierre Shale and Niobrara Formation, undivided (Upper Cretaceous)**
- Kcgg **Carlile Shale, Greenhorn Limestone, and Graneros Shale, undivided (Upper Cretaceous)**
- Kd **Dakota Sandstone (Lower? and Lower Cretaceous)**
- Jme **Morrison Formation (Upper Jurassic) and Entrada Sandstone (Middle Jurassic), undivided**
- TRd **Dockum Group (Upper Triassic)**
- PℙSc **Sangre de Cristo Formation (Lower Permian and Upper Pennsylvanian?)**
- ℙa **Alamitos(?) Formation (Upper? and Middle Pennsylvanian)**—Remnants on divide between Rio Lucero and Rio Pueblo de Taos in southwestern part of map area
- ℙms **Equivalents of Madera Group (Upper and Middle Pennsylvanian) and Sandia Formation (Middle and Lower? Pennsylvanian), undivided**
- ℙMsa **Lower part of Sandia Formation (Lower? Pennsylvanian) and Arroyo Peñasco Group (Mississippian), undivided**—Erosional remnants northeast and south of Wheeler Peak and in southern part of Cimarron Mountains
- p€r **Precambrian igneous and metamorphic rocks, undivided (Early Proterozoic)**

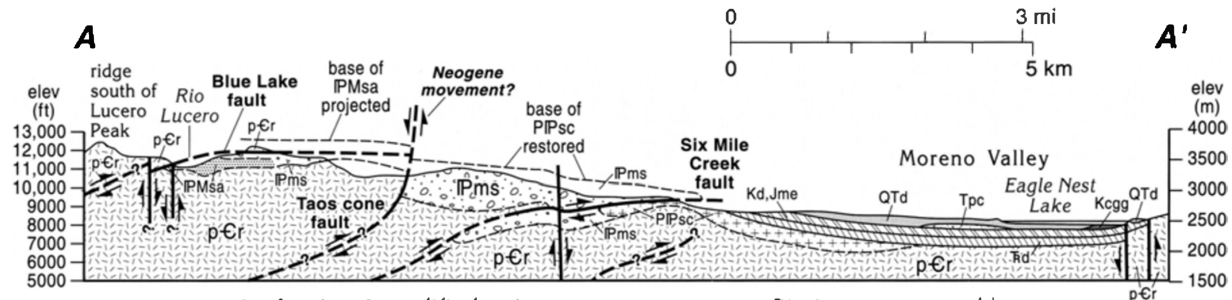
pebbles and cobbles of granite gneiss occur in some beds. These characteristics suggest proximal and medial parts of fans derived from the Precambrian igneous and metamorphic rocks of the Cimarron Mountains that were rising along the precursor of the southeast part of the Fowler Pass fault.

In the western part of the Cimarron Mountains, the nearness of outcrops of the Upper Triassic Dockum Group to the Saladon Creek fault suggest that the fault was active in Permian time during the cutting of the unconformity on the Precambrian at the base of the Dockum Group. In Late Triassic time, most or all of the area of the Cimarron Mountains probably was buried by the Dockum Group whose sediments mainly are shaly (Robinson et al., 1964, fig. 86, plate 2) and do not suggest a nearby major source of first-cycle clastics. However, this area was structurally higher than the region to the south in Late Triassic or Early Jurassic time because the Dockum Group is only about a third as thick as the Santa Rosa Sandstone and Chinle Formation of the Dockum Group in the Cenozoic Las Vegas Basin. Therefore, it is possible that part of the displacements on the Saladon Creek fault occurred as late as Triassic time.

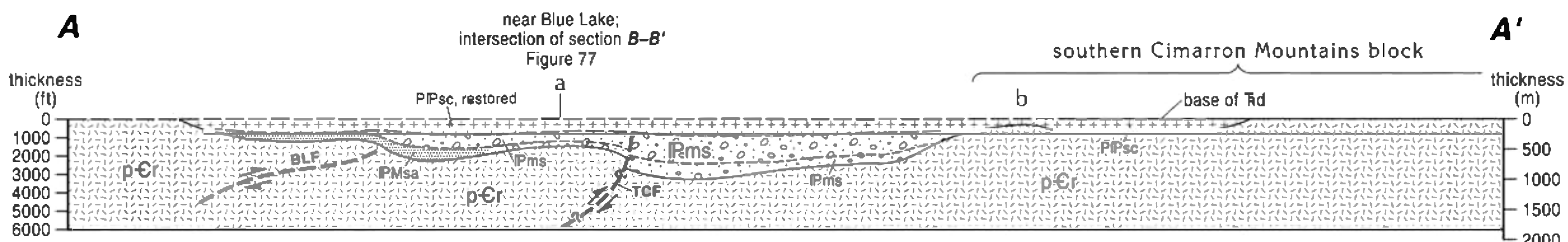
The precursor of the Saladon Creek fault is shown (Fig.



1. From Clark and Read (1972, plate 1), part of section *A–A'*



2. Section 1 modified to interpret structure near Rio Lucero mapped by Reed et al. (1983), and to show paleostructural interpretations discussed in this report.



3. Palinspastic reconstruction of section 2 showing hypothetical relations at beginning of deposition of Dockum Group (Ћd). Short dashes represent bedding; long dashes represent restored contacts; a and b, anticlines discussed in text; BLF, restored position of Cenozoic Blue Lake fault; TCF, precursor(?) of Taos cone fault.

FIGURE 75—Cross section and palinspastic diagram, Rio Lucero–Eagle Nest Lake area. Line of section shown in Figure 74. On cross section 1, IPr is undivided Pennsylvanian rocks. Other symbols are explained in Figure 74. Section 1 does not correspond exactly with the map because of midifications by the author.

72) extending northwest across the area of the present Moreno Valley as the boundary of Precambrian rocks on the north and Pennsylvanian rocks on the south, a condition that may be similar to the present structure (Plate 2) of that area. By this interpretation, the Paleozoic–Mesozoic southern Cimarron Mountains block also extended west of the Moreno Valley (Figs. 72, 75). Clark and Read (1972, plate 1) and Dane and Bachman (1965) showed that, southwest of Eagle Nest, small inliers of Precambrian rocks are overlain, variously, by the Sangre de Cristo Formation, the Upper Triassic Dockum Group, and the Middle Jurassic Entrada Sandstone (Fig. 74 of the present report). Clark and Read (1972, p. 90–91) interpreted the contacts of the Precambrian with the various overlying sedimentary rocks as a flat underthrust fault at the top of their postulated "plunger" of the Cimarron Mountains. They reasoned (1972, p. 90) that, to explain the contacts as depositional, "...too many unrecorded coincidental events of local deposition, warping, and erosion through late Paleozoic and Mesozoic times would be required. The alternative explanation is by mechanical means." They cited evidence from thin sections that the sedimentary rocks at places along the contacts have mortar structure and alinement of softer materials in response to shear, thereby suggesting a flat fault between the sedimentary rocks and the underlying Precambrian.

Nevertheless, the relations in the Cimarron Mountains east of Moreno Valley, where Permian and Triassic rocks lie in depositional contact on the Precambrian, suggest that the outcrops west of the valley also represent residual hills ("b" in sec. 3, Fig. 75) on the southern Cimarron Mountains block that were overlapped by relatively thin sedimentary sequences of Permian, Triassic, and Jurassic ages. Slight shearing at places along the contacts of the Precambrian rocks and sedimentary rocks at places may be expected because of Laramide folding and faulting, and does not prove the existence of flat underthrust faults.

The amount of Cenozoic displacement on most of the Saladon Creek fault appears to have been relatively small, as suggested by the relations of the fault to the Neogene volcanics at the south end of the Cimarron Mountains. Laramide movement occurred on the southeastern part of the Fowler Pass fault, and the blocks north and south of the Saladon Creek fault rose at least partly in unison during Laramide orogeny. Therefore, the southeastern part of the Fowler Pass fault may cut across the Saladon Creek fault and be a continuation of the structure of the folded eastern margin of the Laramide Ocate anticline of the Las Vegas Basin (Plate 2). The eastern part of the anticline is underlain at least locally by a west-dipping reverse fault (wells 2 and 3, Plate 3) that dies out upward into folded rocks at the surface. The Saladon Creek and Fowler Pass faults are covered by Neogene volcanics south of the Cimarron Mountains, and nothing is known to me from the published literature that would cast additional light on the relations.

The Cimarron arch separates the Rainsville trough from the Paleozoic Central Colorado Basin (Fig. 72) as shown by the northward thickening of the Sangre de Cristo Formation into the Central Colorado Basin at the surface and in the subsurface. For example, at Gold Creek (Fig. 72) near the front of the Sangre de Cristo Mountains northwest of Vermejo Park, the base of the Sangre de Cristo Formation is faulted against Precambrian rocks but the Sangre de Cristo is more than 5,700 ft (1,735 m) thick (A. A. Wanek, unpub. measured section, 1957). Pennsylvanian rocks older than the Sangre de Cristo are not present at the surface in New Mexico north of the exposures west of Eagle Nest (Fig. 74), but in Colorado, beginning a short distance north of the State line, northward-thickening Lower and Middle Pennsylvanian rocks occur in Laramide thrust-faulted slices in the Sangre de Cristo Mountains (Johnson, 1969; Tweto, 1979a). These rocks were deposited in the Paleozoic Central Colorado Basin, which probably is the same basin in which thin sections of Pennsylvanian marine rocks occur at two wells west and southwest of Raton (Foster, 1966). The isopachs of Pennsylvanian rocks northwest of Vermejo Park (Fig. 72) are based on thicknesses measured at the surface in Colorado by Brill (1952).

To the east the Cimarron arch probably connects in the subsurface with the Paleozoic Sierra Grande uplift. This is suggested by scanty well data and by a poorly defined southeast-trending gravity anomaly south of Cimarron River (Plate 2). Andreasen et al. (1962, fig. 4, p. 357) inferred from gravity and magnetic data that a northeast-trending structural depression, on the top of the Precambrian, lies between the northwestern part of the Cimarron arch and Springer, New Mexico, but the later gravity map of Cordell and Keller (1984) does not indicate a transverse basinal feature across the gravity high that probably represents the buried Cimarron arch.

Paleozoic basin and uplifts west of Eagle Nest

West of Moreno Valley (Fig. 74), and west of the Paleozoic and Triassic southern Cimarron Mountains block, Pennsylvanian rocks are at least 2,900 ft (885 m) thick, and possibly as much as 5,000 ft (1,500 m) thick (Clark and Read, 1972, p. 36). The Pennsylvanian rocks are lithologically similar to those of the Taos trough and the Mora River area. They are predominantly shale that contains interbeds of coarse-grained to conglomeratic sandstone and arkose and relatively minor amounts of limestone. Shales of about the lower two-thirds are gray. The upper third contains much greenish-gray and red shale and micaceous siltstone, some arkosic limestone, and pebbly arkoses that are a few feet to as much as 200 ft (60 m) thick.

These rocks of a formerly deep Paleozoic structural basin (Fig. 72) have been uplifted, tilted east, and thrust eastward across Permian and Mesozoic rocks in a plate above the Cenozoic low-angle Six Mile Creek fault (Figs. 74, 75). Palinspastic reconstruction of the Paleozoic basin depends partly on interpretation of this fault and the fault farther north that is labeled the Six Mile Creek(?) fault in Figure 74.

Clark and Read (1972, p. 84–85) indicated that, southwest of Scully Mountain, the slip on the Six Mile Creek fault is about 9,000 ft (2,700 m) but, on the west side of Scully Mountain, the fault dies out in steeply dipping beds of the Sangre de Cristo Formation. They considered the fault possibly younger than the thick Cenozoic intrusives of Scully Mountain. The leading edge of the fault at places dips east 10–34° suggesting that it might be a gravity slide from the high part of the mountains to the west, but such an origin was considered unlikely by Clark and Read (1972, p. 85) because sedimentary contacts of the Pennsylvanian and Precambrian rocks are exposed at places within the plate indicating it is rooted, structurally. The east tilting may be the result of Neogene uplift of the central part of the Sangre de Cristo Mountains after the displacement occurred on the fault. A possibility not discussed by Clark and Read is that detachments might have occurred within the Pennsylvanian rocks above the Precambrian, as suggested by the sharp local crumpling of these rocks south of the Comanche Creek fault (Fig. 74).

Reed et al. (1983) suggested that the Six Mile Creek fault is the downfaulted eastern part of the Blue Lake fault, a flat thrust that is exposed in the high part of the mountains south of Wheeler Peak (Fig. 76). Their interpretation requires that, between the Taos Cone fault and an unnamed normal fault to the east, the contact of Pennsylvanian and

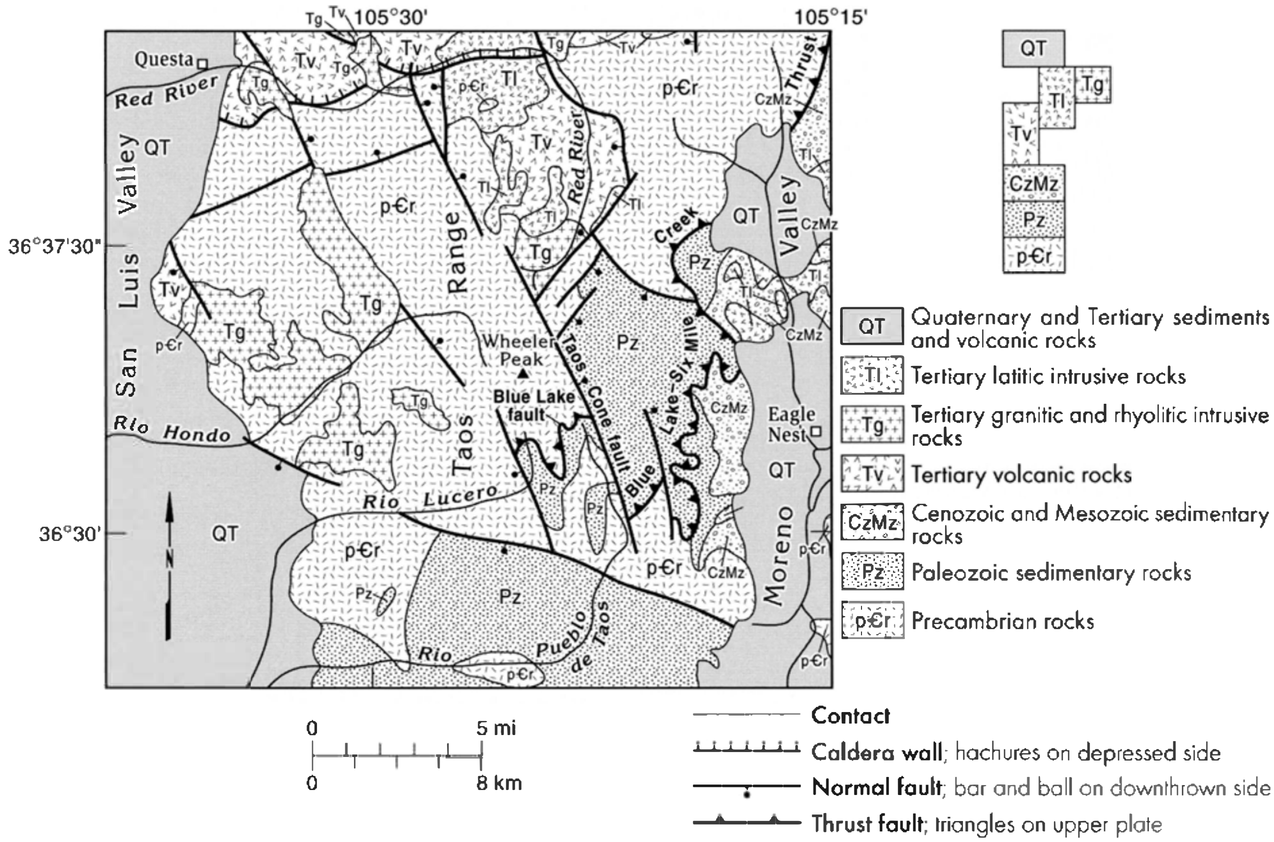


FIGURE 76—Generalized map of part of Taos Range of Sangre de Cristo Mountains showing principal geologic and tectonic features as interpreted by Reed et al. (1983). Adapted from Reed et al. (1983, part of fig. 2).

Precambrian rocks is a part of the Blue Lake thrust fault rather than being a sedimentary contact as mapped by Clark and Read (1972, plate 1, p. 85). The interpretation of Reed et al. (1983) also indicates that the southernmost part of the plate above the Six Mile Creek fault is Pennsylvanian rocks thrust over Precambrian. Apparently, additional detailed investigations are needed to resolve the differing interpretations. Figure 74 of the present report shows the interpretation of Clark and Read (1972, plate 1) east of Taos Cone fault. The palinspastic reconstruction of the eastern part of the Pennsylvanian basin (sec. 3, Fig. 75) probably would be similar using either interpretation, although some thick Pennsylvanian rocks would have been originally farther west than shown if the Blue Lake and Six Mile Creek faults actually are parts of the same fault.

Definitive evidence of the structure responsible for the western termination of the Paleozoic–Triassic southern Cimarron Mountains block is now concealed by the Six Mile Creek thrust plate. The western margin of the block might have been a northwest-plunging anticline or anticlinal bend, as suggested at "b" in section 3 (Fig. 75), or the western margin might have been faulted down to the west. The internal stratigraphy of the Pennsylvanian rocks of the thrust plate has not been determined; therefore, it is not known whether there are unconformities or facies relations that would bear on the paleostructural relation of the eastern margin of the Paleozoic basin to the southern Cimarron Mountains block.

The restoration of the western part of the Paleozoic basin (sec. 3, Fig. 75) is based mainly on a lithologic correlation of dominantly red sedimentary rocks that lie on the Precambrian near Larkspur Point and Waterbird Lake on the drainage divide between Rio Lucero and Rio Pueblo de Taos. These rocks, assigned to the Alamitos(?) Formation in Figure 74, occur south of anticline "a" in section 3 (Fig. 75). Figure 77 is a north–south diagram through the area of outcrop of the Alamitos(?) Formation.

Gruner (1920, p. 738–740) reported that the sedimentary rocks near Larkspur Point are arkoses and thick red conglomerates interbedded with sandy fossiliferous limestones and grayish-green to red shales. Conglomerate in the lower part of this section contains angular and platy clasts of gray slate, green chlorite schist, and gray quartz schist ranging in size up to angular boulders 3–4 ft (0.9–1.2 m) in diameter. Conglomerates higher in the sequence contain limestone pebbles in fossiliferous limestone matrices. The explanation for Gruner's (1920, plate XIII) map is not explicit, but the area of closely spaced patterning of Carboniferous rocks on the map, compared with his text description, indicates that outcrops of these rocks extend along the drainage divide from about 1 mi southwest of Larkspur Point northeastward to the vicinity of Blue Lake.

Clark and Read (1972, p. 34 and section 1, p. 135–136) also described the rocks east and north of Larkspur Point (IPa in Fig. 74) and assigned them questionably to the Late Pennsylvanian or Early Permian because of their dominant red color. Clark and Read (1972, p. 34) concluded as had Gruner (1920, p. 741), that the boulder conglomerates indicate a nearby source, especially because Precambrian chlorite schist, similar to the sedimentary clasts, is present beneath the conglomerates and also is present farther west where sedimentary rocks are absent. My interpretation of this probable westerly source of the coarse Precambrian clastics is shown in Figure 72 by the zero isopach northeast of Taos.

The rocks near Larkspur Point that were described by Gruner (1920) and Clark and Read (1972) are assigned in this report to the Alamitos(?) Formation because they are partly marine and because the greenish-gray and red colors of the shales are similar to those of the Alamitos Formation farther south in the Sangre de Cristo Mountains. Red and purple shales and interbedded arkoses and marine limestones occur also in the upper part of the Pennsylvanian section east of the Taos Cone fault. Clark and Read (1972, p. 42) pointed out a possible correlation of these upper rocks with the upper arkosic limestone member (now, Alamitos Formation) of their Madera Formation to the south. Although fossil data are scarce, two species of brachiopods in the upper part of the Pennsylvanian sequence west of Eagle Nest suggest a Late Pennsylvanian (Missourian) age and support a correlation of some of these rocks with the Alamitos Formation. Clark and Read (1972, p. 38–39 and map 1) reported the occurrence of *Neospirifer latus* (loc. 582) and *Echinaria semipunctata* (loc. 561, 444) in the Eagle Nest area. These brachiopods occur also in the Missourian part of the type section of the Alamitos (Sutherland and Harlow, 1973, p. 13, 75). For all these reasons, the Alamitos(?) Formation of the Larkspur Point–Waterbird Lake area is shown as equivalent to Missourian and upper Desmoinesian rocks in the basinal areas of Figure 77.

The presence of a probable equivalent of the Alamitos Formation lying on the Precambrian near Larkspur Point and Waterbird Lake implies angular unconformities between these rocks and the nearby thick older Pennsylvanian rocks in the Taos trough and the Paleozoic basin west of Eagle Nest (Fig. 77). This suggests that the large anticline west of the Taos Cone fault may be a Paleozoic structure rejuvenated in Cenozoic time. If the Larkspur Point–Waterbird Lake area and the Precambrian rocks to the west were uplifted recurrently in Pennsylvanian time, they probably were the sources of the Precambrian and Pennsylvanian clasts of coarse conglomerates in the upper Atokan and Desmoinesian rocks of the north limb of the Taos trough that were reported by Houle (1980), Coxe (1981), and Casey (1980b) as previously discussed in this report. The palinspastic reconstruction of Figure 75 suggests that, in Cenozoic time, the west limb of the Paleozoic basin and the Paleozoic uplift to the west were transported eastward at least 2.5 mi (4 km) on the plate above the Blue Lake fault. In this interpretation the east-dipping remnants of Mississippian and Pennsylvanian rocks north of the trace of the Blue Lake fault (Fig. 74) were formerly on the west limb of the basin.

The original northward extent of the Paleozoic basin is not known because all the Morrowan through Desmoinesian Pennsylvanian rocks of the Six Mile Creek thrust plate terminate abruptly at the northwest-trending Comanche Creek fault (Fig. 74). However, an Early to Middle Pennsylvanian basin margin southwest of the fault (Fig. 77) is suggested by outcrops southeast of Wheeler Peak Village where Pennsylvanian rocks are in depositional contact with Precambrian rocks (Clark and Read, 1972, p. 34; J. C. Reed, Jr., oral comm., 1983). Clark and Read (1972, p. 34) found *Fusulina* sp. (now, *Beedeina* sp.) in limestone less than 100 ft (30 m) above the Precambrian. The position of this Desmoinesian fusulinid in the lower part of the Pennsylvanian was reconfirmed later by K. F. Clark (oral comm., 1986). Therefore, Morrowan and Atokan rocks equivalent to the Sandia Formation either are very thin or are absent southwest of upper Comanche Creek (Fig. 77).

About 1.5 mi (2.4 km) south–southwest of the locality of the Desmoinesian fusulinids, J. C. Reed, Jr. (oral comm., 1983), found a thick succession of east-dipping coarse-grained to conglomeratic sandstones and interbedded gray shales west of the East Fork of Red River in an area shown as mainly Precambrian rocks by Clark and Read (1972, plate

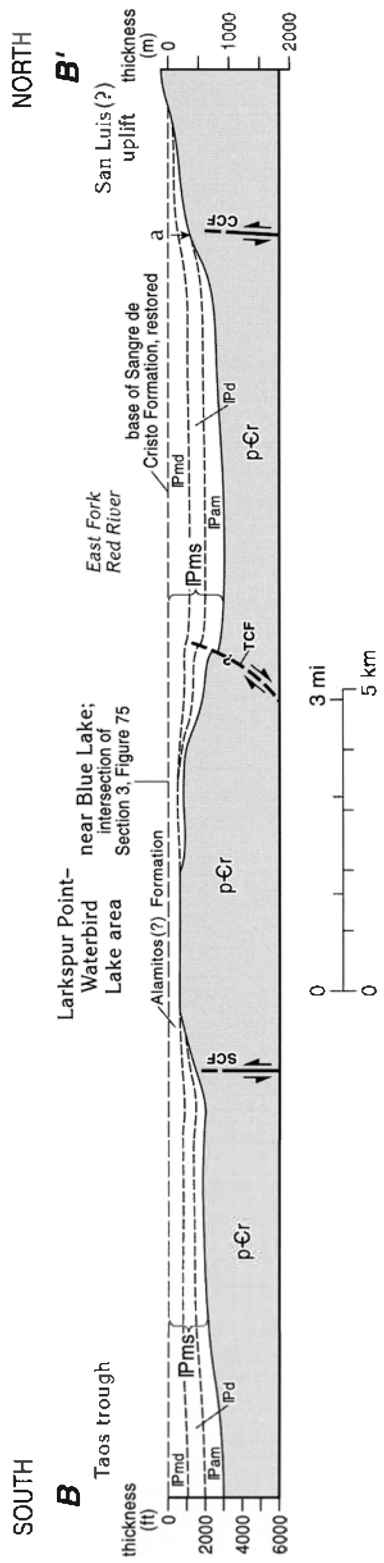


FIGURE 77—Hypothetically restored Pennsylvanian rocks west of Eagle Nest. Line of section shown in Figure 72. IPms, Madera Group and Sandia Formation undivided; locally may include Mississippian rocks. IPmd, Missourian(?) and upper Desmoinesian rocks; IPd, Desmoinesian rocks; IPam, Atokan and Morrowan and locally Mississippian rocks; p€r, Precambrian rocks. SCF, precursor of Saladon Creek fault; CCF, precursor of Comanche Creek fault; TCF, precursor(?) of Taos cone fault. Arrow at "a", position of Desmoinesian fusulinids (collection 452 of Clark and Read, 1972) about 1 mi (1.6 km) southeast of Wheeler Peak Village.

1). I observed these sedimentary rocks in reconnaissance and judged their lithology to be similar to the Morrowan and Atokan Sandia Formation of areas to the south. Although fossils have not been reported from these rocks, they probably are a southward-thickening wedge of pre-Desmoinesian rocks, as shown in Figure 77. Clark and Read (1972, p. 42) also suggested that equivalents of the Sandia Formation may be present farther south.

Comanche Creek area

The Cenozoic Comanche Creek fault northwest of Eagle Nest (Fig. 74) throws Precambrian granitic rocks on the north against Pennsylvanian (Desmoinesian and probable Missourian) rocks and the Sangre de Cristo Formation on the south. The Pennsylvanian rocks south of the fault are the northernmost outcropping rocks of that age in New Mexico (except for whatever part of the Sangre de Cristo Formation may be Late Pennsylvanian). The next outcrops of Pennsylvanian rocks to the north in the Sangre de Cristo Mountains are about 1 mi (1.6 km) north of the Colorado–New Mexico border (Johnson, 1969).

A patch of poorly exposed red beds on the Precambrian north of the Comanche Creek fault and west of Scully Mountain was assigned questionably to the Sangre de Cristo Formation by Clark and Read (1972, plate 1). A little farther north, folded beds of the Sangre de Cristo lie on the Precambrian in an inlier on the north side of Comanche Creek, but Wanek and Read (1956, p. 93) and Clark and Read (1972, p. 89–90) interpreted the contact there as a Cenozoic underthrust on a local "plunger" of Precambrian rocks. Parts of the basic studies of Clark and Read (1972) can be reinterpreted to indicate that a relict Paleozoic uplift is present in the vicinity of Comanche Creek as shown in Figures 72 and 77. This uplift would have been a northwestern extension of the Cimarron arch and also a part of the San Luis(?) uplift. The southwest margin of the uplift may have been an anticlinal bend that was broken by a precursor of the Comanche Creek fault that was active recurrently in Late Pennsylvanian and Early Permian time.

Clark and Read (1972, p. 87) reasoned that the Comanche Creek fault (to which they did not apply a name) is a nearly vertical Laramide tear fault that bounds an eastward salient of the Blue Lake thrust fault and connects with the curved high-angle fault northwest of Scully Mountain that they called the Blue Lake fault, also. (I have labeled this curved fault the Six Mile Creek(?) fault in Fig. 74.) Clark and Read suggested that right-lateral, strike-slip displacement on the Comanche Creek fault is 2,000–3,000 ft (600–900 m).

East of Wheeler Peak Village (Fig. 74), Clark and Read (1972, p. 86–87) connected the northwestern part of the Comanche Creek fault with a southwest-trending, high-angle and locally east dipping fault that they considered to be a thrust. This fault is downthrown to the east and was considered to be part of the south-trending Taos Cone fault which Clark and Read mapped as mainly concealed by Quaternary deposits near the East Fork of Red River. At the south, the high-angle Taos Cone fault terminates the Blue Lake thrust fault northeast of Blue Lake, (Fig. 74). Clark and Read (1972, p. 86–87) wrote that the Blue Lake thrust becomes vertical at its juncture with the Taos Cone fault and that a later normal fault dropped the block east of the Taos Cone fault.

Later mapping by Reed et al. (1983) determined that Pennsylvanian rocks are present, although poorly exposed, west of the East Fork of Red River in areas shown as Precambrian by Clark and Read (1972, plate 1). North of the junction with the Blue Lake fault, Reed et al. (1983) mapped the Taos Cone fault as a northwest-trending normal fault considerably west of the trace shown by Clark and Read (1972). The trace of the Taos Cone fault, as now mapped by Reed et al. (1983, and Fig. 74 of this report), makes it unlikely that a high-angle thrust fault connects the Blue Lake fault and the Comanche Creek fault in the manner conceived by Clark and Read (1972). The Comanche Creek fault (Fig. 74), therefore, probably is not a Laramide tear fault connecting parts of a Blue Lake thrust plate.

If the Precambrian rocks west of the Six Mile Creek fault near the Taos-Colfax County line are part of the Blue Lake plate, the thrust would be broken by the younger Taos Cone fault and would be below the Pennsylvanian rocks east of Taos Cone fault, as suggested by Reed et al. (1983). In this case, the segment of thrust fault mapped (Fig. 76) just east of Taos Cone fault would be younger (Paleozoic) rocks thrust over older (Precambrian) rocks, rather than the older-over-younger situation on the Blue Lake fault west of Taos Cone fault. An alternative suggestion is that the Blue Lake thrust underlies a Laramide age, structurally high plate of Precambrian rocks that was broken near its eastern leading edge and dropped down to the *west* by younger movement on the Taos Cone fault. Although the apparent main displacement on the Taos Cone fault is down to the east, Pennsylvanian rocks east of the fault are at higher altitudes than the base of the Precambrian rocks of the Blue Lake plate a short distance north of the intersection of the Taos Cone and Blue Lake faults (north of secs. 1 and 2, Fig. 75). This relation could be interpreted to indicate Neogene down-to-the-west displacement on the Taos Cone fault during formation of the Rio Grande rift. (See sec. 2, Fig. 75.) Northwest-trending faults, displaced down to the west, are present near Horseshoe and Lost Lakes west of the Taos Cone fault (Fig. 74). A similar style is exhibited in the southeastern part of the Sangre de Cristo Mountains (Plate 1) where, between Mora and Sapello, the eastern parts of easterly-directed thrusts are broken by down-the-west Pliocene(?) to Pleistocene normal faults in the Quebraditas fault zone (Baltz and O'Neill, 1986).

Taken at face value, the outcrops of the Sangre de Cristo lying on the Precambrian north of the Comanche Creek fault indicate the presence of a Paleozoic uplift. This is indicated also by the onlap of Desmoinesian rocks onto Precambrian rocks southeast of Wheeler Peak Village ("a" in Fig. 77). Clark and Read (1972, p. 89–90) presented some thin-section evidence that movement and grinding of rock materials occurred along the contact of the Precambrian and the Sangre de Cristo at the inlier just north of Comanche Creek. However, the well-exposed contact appears to be sedimentary, and slight concentric shearing during Laramide folding of the Precambrian and Sangre de Cristo also could have caused the microscopic features they described. The nearness of the southern outcrop of the Sangre de Cristo Formation(?) of the uplift to the older Pennsylvanian rocks in the basin suggests a faulted margin in the position of the Comanche Creek fault. Therefore, this fault probably was recurrently active in Middle or Late Pennsylvanian and part of Permian time. The lower part of the Sangre de Cristo from Comanche Creek north contains thick beds of subangular to subrounded, pebbles and boulders of Precambrian rocks (Clark and Read, 1972, p. 43); the clasts indicate a nearby source area, probably the San Luis(?) uplift to the west, that had rugged relief and from which Pennsylvanian rocks were absent. Sediments of the Sangre de Cristo derived from this source buried the eastern part of the uplift near Comanche Creek.

Clark and Read (1972, p. 44) reported that the Sangre de Cristo Formation at their locality 8 north of Comanche Creek may be as much as 5,300 ft (1,615 m) thick. However, most of the Sangre de Cristo at their section is concealed by

Quaternary colluvial deposits and by alluvium in Comanche Creek where the structure is not known. May et al. (1977, loc. 1, plate 1) measured a section of the lower part of the Sangre de Cristo west of the alluvial valley of Comanche Creek and west-northwest of the G. Mutz Ranch. Near the middle of their section, two fault-bounded outcrops of granitic gneiss occur, and the basal part of the Sangre de Cristo apparently is repeated twice. It appears that the structure of the Sangre de Cristo Formation north of Comanche Creek may be more complex than is presently mapped, and the formation on the Paleozoic uplift possibly is much thinner than the 5,000 ft reported by Clark and Read.

In summary, the complex structural and stratigraphic relations near Comanche Creek may be the combined results of Paleozoic and Cenozoic deformation. The high-angle, Six Mile Creek(?) fault north of Comanche Creek may be a rooted, upthrust splinter of the Laramide Six Mile Creek thrust fault. The style of the Six Mile Creek(?) fault is different from the southern segment because the thrust passes northward out of sedimentary rocks of the Paleozoic basin and cuts across the Comanche Creek fault into Precambrian rocks of the San Luis(?) uplift that were structurally high before Laramide deformation. Neogene rejuvenation of the Comanche Creek fault is indicated because it displaces Tertiary intrusive rocks and appears to displace the Six Mile Creek fault.

San Luis (?) uplift

From near Comanche Creek to about 1 mi (1.5 km) north of the New Mexico–Colorado border Lower and Middle Pennsylvanian mixed marine-nonmarine rocks are absent from the Sangre de Cristo Mountains. However, in Colorado, Lower and Middle Pennsylvanian rocks are present continuously in the mountains for 60 mi (95 km) north of the border and are present even in fault slices in the high western part near Sierra Blanca (Johnson, 1969; Tweto, 1979a; Lindsey et al., 1986). The absence of Pennsylvanian rocks (other than whatever part of the Sangre de Cristo Formation is Pennsylvanian) from the mountains in northernmost New Mexico suggests that at least part of that area was the northwest-trending continuation of the Paleozoic Cimarron arch. This continuation is shown in Figures 4 and 72 as the San Luis(?) uplift because it may be the southeastern part of the San Luis uplift that Melton (1925a, b) originally postulated as the western source of coarse Pennsylvanian and Permian clastics of the Sangre de Cristo Mountains in Colorado. If so, the San Luis(?) uplift of Figure 72 extended northwest in the area of the Neogene San Luis Basin probably as the buried uplift as indicated by a large high-gravity anomaly near the Colorado–New Mexico border between the Rio Grande and 106° longitude (Fig. 4; Plate 2). This uplift extends northward in the subsurface of the San Luis Basin in Colorado as shown by a major gravity anomaly (Keller et al., 1984) that is marked locally by Neogene faults. Drill holes north of Alamosa, Colorado, show that Eocene(?) sedimentary rocks lie on the Precambrian rocks of the uplift (Baltz, 1965, p. 2072; Tweto, 1979b, p. 40–42), indicating that it also was part of the previously discussed Laramide geanticline that, prior to Neogene time, included areas west of the Rio Grande as well as the Sangre de Cristo uplift. The area of the postulated Paleozoic San Luis(?) uplift in Colorado was interpreted by Tweto (1979b, p. 41; 1983, Fig. 1) to be the southeastern part of the ancient Uncompahgre highland. The eastern and western margins of the Paleozoic uplift, within the San Luis Basin, are not known.

In the high parts of the Sangre de Cristo Mountains in New Mexico northwest of Eagle Nest, small patches of arkosic sandstone, conglomerate, and greenish-gray to red shale are present here and there beneath Miocene volcanic rocks and lying on Precambrian rocks. A few of these patches were assigned questionably to the Pennsylvanian and Permian Sangre de Cristo Formation by McKinlay (1956) and were shown as Pennsylvanian by Dane and Bachman (1965). Clark and Read (1972, p. 43, 52–57) considered them more likely to be Tertiary. McKinlay (1956, p. 12) considered other outcrops of gray to red sandstone, shale, and conglomerates beneath Tertiary volcanics to be probably Tertiary and equivalent to the Vallejo Formation of Upson (1941) in the adjacent part of Colorado. In the Wheeler Peak–Latir Peak area west and northwest of Eagle Nest all these patches of rocks were assigned to the early Tertiary (Eocene or Oligocene) by Reed et al. (1983), and similar patches near the drainage divide west of Vermejo Park also are considered early Tertiary by C. L. Pillmore (oral comm., 1982). The clasts of these sedimentary rocks were derived entirely from Precambrian sources (Reed et al., 1983). They probably were deposited near the end of Eocene time in valleys or shallow structural depressions on residual highlands of the Laramide geanticline (Baltz, 1978, p. 223–224) after early Tertiary sediments had filled the adjacent Laramide Raton and San Juan Basins.

Outcrops of arkosic sandstone and red shale about 5 mi (8 km) south of Costilla Lake in New Mexico (Fig. 72) were mapped by McKinlay (1956) and Dane and Bachman (1965) as the Sangre de Cristo Formation and still are considered to be part of that formation on lithologic bases. The outcrops are surrounded mainly by Precambrian rocks, and McKinlay (1956) suggested they are a fenster in a Laramide thrust plate However, P. W. Lipman (oral comm., 1982) found that the structure is more complex than envisioned by McKinlay, and that the Sangre de Cristo probably reached its present structural and topographic situation partly because of late Cenozoic faulting related to the Rio Grande rift. The base of the Sangre de Cristo is not exposed, and it is not known whether Pennsylvanian rocks are present beneath the Sangre de Cristo. These outcrops indicate that a Permian depositional basin extended west of the hypothetical margin shown for Pennsylvanian rocks in Figure 72, but the available evidence does not permit an interpretation as to whether the Sangre de Cristo lapped onto the Precambrian of the San Luis(?) uplift, or whether the Sangre de Cristo was deposited in the Central Colorado Basin and was overridden by a Laramide thrust plate

About 1 mi (1.5 km) north of the Colorado–New Mexico border, Pennsylvanian mixed marine-nonmarine rocks reappear along the east front of the Sangre de Cristo Mountains in sedimentary contact with Precambrian rocks, but mainly in thrust-fault contact with the Sangre de Cristo Formation (Johnson, 1969). The rocks in Colorado were classified by Tweto (1979a) as the Minturn Formation of Middle Pennsylvanian age. About 12 mi (19 km) north of the Colorado border, the Kerber Formation of Early and Middle Pennsylvanian age (Tweto, 1979a) wedges in above the Precambrian and below the Minturn Formation. The Pennsylvanian rocks are reported to be about 3,000 ft (915 m) thick at Whiskey Creek Pass about 14 mi (22 km) north of the Colorado border (Brill, 1952). Farther north at Crestone Peak, Pennsylvanian rocks are thick in the deep part of the Central Colorado Basin (Bolyard, 1959, p. 1904, 1919–1920). The northward wedge in of the Lower and Middle Pennsylvanian Kerber Formation below the Minturn and the general northward thickening of the Pennsylvanian rocks into the Central Colorado Basin suggest that an uplift, or at least a low arch, existed south of the New Mexico–Colorado border in Pennsylvanian time. The Pennsylvanian rocks in Colorado contain coarse grained to conglomeratic first-cycle sediments that are generally thought to have been derived from the San Luis–Uncompahgre uplift to the west. Conceivably, some of these sediments may have been derived also from the San Luis(?) uplift (of this report) to the south and southwest, but no published data on the lithologies of the southernmost Pennsylvanian rocks exist to evaluate this possibility.

Direct evidence of the Late Pennsylvanian–Permian existence of the San Luis(?) uplift is present only where bouldery conglomerates of the Sangre de Cristo lie on the Precambrian near Comanche Creek northwest of Eagle Nest, New Mexico. Other evidence mainly is the thickening of the Sangre de Cristo northward from the Cimarron arch. For about 10 mi (16 km) north of the Moreno Valley (Fig. 74; Plate 2) the Cenozoic structural boundary of the Sangre de Cristo uplift and the Raton Basin in New Mexico is a north–northeast-trending reverse fault (Clark and Read, 1972) that throws Precambrian rocks against the Cretaceous Dakota Sandstone and rocks as young as the Paleocene Poison Canyon Formation, thereby concealing Paleozoic rocks and eliminating possible evidence of the San Luis(?) uplift. However, in northernmost New Mexico, a northerly trending reverse or thrust fault juxtaposes the Precambrian and the steeply dipping Sangre de Cristo Formation (Dane and Bachman, 1965). At Gold Creek (Fig. 72) northwest of Vermejo Park and several miles south of the Colorado border, the Sangre de Cristo Formation is at least 5,700 ft (1,735 m) thick (A. A. Wanek, unpub. section, 1957). About 14 mi (22 km) north of the Colorado border, at Whiskey Creek Pass in the Sangre de Cristo Mountains, Brill (1952, p. 821) measured about 9,500 ft (2,895 m) of rocks assigned to the Sangre de Cristo, which lie gradationally on Pennsylvanian (Desmoinesian) rocks. The Sangre de Cristo at Whiskey Creek Pass is faulted and folded internally (Johnson, 1969) and may not be as thick as thought by Brill (1952). Nevertheless, the Sangre de Cristo clearly thickens northward into the Paleozoic Central Colorado Basin from the exposures on the Cimarron arch.

If a thick sequence of Pennsylvanian rocks had existed in the area shown as the San Luis(?) uplift in Figure 72, some record of its former existence might be expected in the lithology of the Sangre de Cristo Formation, but such evidence mainly is lacking. The thick beds of bouldery conglomerate in the lower part of the Sangre de Cristo north of Comanche Creek appear to have been derived from the nearby Precambrian terrane of the San Luis(?) uplift. No clasts containing Paleozoic fossils were reported in the Sangre de Cristo north of Comanche Creek by Clark and Read (1972) or by May et al. (1977), although both reports indicate that some conglomerates are calcareous. May et al. (1977, plate 1, sec. 1) reported sedimentary-rock fragments in several conglomerate beds, indicating that some Paleozoic rocks existed in the source area. If these are fragments of Pennsylvanian rocks, their likely sources were the margins of the Pennsylvanian basin west of Eagle Nest.

To the north, at Gold Creek the basal part of the Sangre de Cristo is cut out by a fault. The part exposed is predominantly coarse sandstone and arkosic sandstone with thin to thick red and green shale interbeds and contains numerous pebble to cobble conglomerates and some boulder conglomerates, all composed of clasts of Precambrian rocks (A. A. Wanek, unpub. stratigraphic section, 1957). The coarseness of the conglomerates suggests sources nearby at the west. A few thin conglomerates of limestone pebbles and cobbles probably represent intraformational unconformities and reworking of limestone beds of the Sangre de Cristo; conceivably, some of the limestone clasts were derived from Pennsylvanian rocks formerly to the west, but no fossils were found to confirm the age of the clasts.

At the Whiskey Creek Pass section in Colorado, the Sangre de Cristo Formation lies transitionally on Desmoinesian rocks within the Central Colorado Basin and is similar lithologically to the Sangre de Cristo farther south except that, generally, the conglomerates may not be as coarse as those in New Mexico. The section of the Sangre de Cristo described by Brill (1952, p. 853–859) shows that the formation contains thin beds of limestone and limestone nodules scattered throughout, but it is not reported to contain recognized sedimentary detritus that would indicate a source terrane that included Pennsylvanian rocks.

On the other hand, previous writers (Read and Wood, 1947; Brill, 1952, plate 3; Baltz, 1965; Clark and Read, 1972, fig. 8; Mallory, 1972a, fig. 4) inferred that a basin containing Pennsylvanian rocks did exist in the area of the northernmost part of the mountains in New Mexico and that the Sangre de Cristo Formation was derived from the Precambrian of the Uncompahgre uplift farther west. In that case, the Sangre de Cristo would not necessarily contain Pennsylvanian detritus, and both the Sangre de Cristo and older Pennsylvanian rocks would have been eroded from the area of the mountains after Permian time.

The thin layer of Upper Triassic rocks on the east side of the Sangre de Cristo Mountains in northern New Mexico and southern Colorado is predominantly fine- to medium-grained sandstone and shale that contain some thin, bedded limestone. Thin lenses of pebbles of quartz, chert, and limestone occur commonly near the base and, at some places, at higher stratigraphic positions (Johnson and Baltz, 1960; Robinson et al., 1964; Clark and Read, 1972; Pillmore and Laurie, 1976, p. 47–48). Some of the chert and limestone pebbles appear to have been derived by erosion and channeling of limestones within the Triassic; other pebbles are similar to limestone of the unconformably underlying Sangre de Cristo Formation (Clark and Read, 1972, p. 46). Fossils have not been reported in the pebbles. Similarly, the fine- to medium-grained sandstones, shales, and thin limestones of the Jurassic formations are not known to contain the kinds of clasts that would suggest nearby sources of Paleozoic rocks. Sources of Triassic and Jurassic sediments of north-central New Mexico generally are thought to have been the Brazos uplift (Muehlburger, 1967) and the Uncompahgre (MacLachlan, 1972; Tweto, 1983) and Wet Mountains uplifts of Colorado. Onlapped upper parts of the Sangre de Cristo Formation on the Cimarron arch, the southern Cimarron Mountains block, and the San Luis(?) uplift also may have been sources of at least parts of the Triassic sediments.

The Lower Cretaceous Dakota Sandstone on the east side of the Sangre de Cristo Mountains and in the adjacent Raton and Las Vegas Basins is composed mainly of fine to coarse quartzose sands. The lower part, probably equivalent to the Purgatoire Formation of Colorado, is fluviatile sandstone that commonly contains lenses and scattered pebbles of white to gray chert. Sediment transport directions in the southern and eastern parts of the Raton Basin are east to southeast (Asquith and Gilbert, 1976) and, in the Las Vegas Basin, easterly (Bejnar and Lessard, 1976). The mature sands of the Dakota are second cycle and probably were transported for considerable distances. Bejnar and Lessard (1976) reported that some chert pebbles in the Las Vegas Basin contain bryozoans and fusulinids from a source terrane of silicified Paleozoic limestone. The probable sources of Dakota sediments are the Upper Jurassic Morrison Formation and patches of Pennsylvanian rocks on the Brazos and Uncompahgre uplifts and their margins.

The lithologies of Triassic, Jurassic, and Lower Cretaceous rocks on the east front of the Sangre de Cristo Mountains north of Eagle Nest do not suggest that major Mesozoic orogenic events occurred nearby that would have caused uplift and stripping of thousands of feet of Permian and Pennsylvanian rocks from the area shown as the San

Luis(?) uplift of Figure 72. In Late Cretaceous time the entire region was buried deeply by sediments derived from areas far to the southwest and west. Therefore, if a Pennsylvanian–Permian Basin had existed in the Sangre de Cristo Mountains in northernmost New Mexico, its destruction would have occurred in latest Cretaceous–early Tertiary time, and evidence of its former existence would be expected in rocks of those ages.

The oldest rocks of the Cenozoic Raton Basin whose stratigraphy and lithology directly reflect Laramide uplift of the Sangre de Cristo Mountains are the Raton Formation of Late Cretaceous and Paleocene age and the laterally mainly equivalent Paleocene Poison Canyon Formation. In the westernmost part of the Raton Basin the basal conglomerate of the Raton lies with angular unconformity on rocks as old as the Upper Cretaceous Pierre Shale (Johnson et al., 1956).

Lee (*in* Lee and Knowlton, 1917, p. 66–167) examined the Raton Formation and underlying rocks in detail throughout most of its outcrop area in the Raton Basin. He reported that the basal conglomerate of the Raton at most places consists of quartz and chert pebbles of undetermined provenance. The basal conglomerate in the southwestern part of the basin east of Eagle Nest was described by Wanek (1963) as coarse-grained sandstone containing granules and subangular to subround pebbles of granite, gneiss, and quartzite. Along the western rim of the basin west and northwest of Vermejo Park and in southern Colorado, Lee (Lee and Knowlton, 1917, p. 58, 148–156) found that the conglomerate contains cobble-size clasts at places. He reported that, on Vermejo Creek and farther north, the conglomerate contains clasts of Cretaceous rocks, the Sangre de Cristo Formation, Precambrian rocks, and cherty limestone and chert that contain crinoids, brachiopod shells, and horn corals. The fossiliferous clasts could have been derived only from Pennsylvanian rocks, and their relative abundance suggests that Pennsylvanian rocks formerly were present in the uplifted area west and northwest of Vermejo Park as they still are in the immediately adjacent part of Colorado. Therefore, the Late Pennsylvanian or Early Permian southern margin of the Central Colorado Basin probably lay west and northwest of Vermejo Park (Fig. 72). Pennsylvanian rocks may exist in the subsurface of the western part of the Raton Basin in northernmost New Mexico where they may have been overridden by Laramide faults. No palinspastic restoration is made in Figure 72; thus, the hypothetical zero isopach of Pennsylvanian rocks represents a Laramide-deformed boundary. The original edge of the Paleozoic basin probably lay farther west and had a more northwesterly trend.

To the south, west of Eagle Nest, in the area of Figure 74, sandstone, shale, and conglomerate probably equivalent to the basal part of the Raton Formation lie unconformably on the Dakota Sandstone. These rocks were mapped as the lower part of the Poison Canyon Formation by Clark and Read (1972, p. 51–52). West and north of Eagle Nest the Poison Canyon at the west margin of the Raton Basin is an arkosic conglomeratic facies that contains pebbles, cobbles, and boulders of Precambrian quartzite, granite, and gneiss. Clark and Read (1972, p. 52) reported that part of these clasts appear to have been derived from the granitic Precambrian block west of their Blue Lake fault (the Six Mile Creek(?) fault in Fig. 74 of the present report) north of Eagle Nest. Farther north, and to the east in the Raton Basin, much of the Poison Canyon consists of coarse arkosic sandstone and pebble conglomerates (Wanek, 1963). Part of this material might be second-cycle material reworked from the Sangre de Cristo Formation, but the bouldery conglomerates on the west, and probably most of the sediments, were derived from Precambrian terranes (Johnson et al., 1956, p. 131). None of the literature reports recognized clasts of Pennsylvanian rocks. These factors indicate that the Precambrian basement was exposed in the rising mountains in northern New Mexico after the initial Laramide uplift and erosional stripping of Mesozoic rocks and whatever onlapped parts of the Sangre de Cristo Formation that existed in that area. Probably, there were no Pennsylvanian rocks present in the area labeled the San Luis(?) uplift in Figures 4 and 72 because they were never deposited there or were eroded in Late Pennsylvanian time.

Sierra Grande uplift

The Paleozoic structure of the Sierra Grande uplift of northeastern New Mexico is poorly known because of the sparsity of wells drilled to the basement on parts of the uplift. Pennsylvanian rocks are known to be absent from many places (Figs. 72, 78) where the (mainly) Wolfcampian Sangre de Cristo Formation lies on Precambrian rocks. At most places the Sangre de Cristo is less than 500 ft (150 m) thick, and locally it is absent. The probable southern margin of the Cimarron arch is marked by a poorly defined high-gravity anomaly trending southeast from the Cimarron Mountains to south of Springer (Plate 2). Farther southeast, a prominent, broad, high-gravity anomaly (Keller and Cordell, 1983) on the Sierra Grande uplift extends southeast to the area of the Paleozoic Bravo dome near the Texas–New Mexico boundary. In this southeast-trending area, shown by an anticlinal axis in Figure 78, well data show the Sangre de Cristo is absent and the Precambrian is overlain by younger Permian (Leonardian) rocks (Roberts et al., 1976, figs. 6, 8) except at Bravo dome where thin Wolfcampian clastic rocks lie on the Precambrian. This area apparently is a broad structural culmination represented by late Wolfcampian residual hills of the Sierra Grande uplift.

Southwest of the culmination the Sierra Grande uplift is relatively narrow and has broadly scalloped margins with the Rainsville trough and the Cuervo–Tucumcari Basins as shown on isopach maps of the Pennsylvanian rocks (Roberts et al., 1976, figs. 4, 5; Foster et al., 1972, fig. 7; Krisle, 1959). The northeastern edge of the Cuervo–Tucumcari Basin may be a major northwest-trending Late Pennsylvanian or Permian fault or fault zone (Fig. 78) as suggested by probable offset of the basement rocks near Tucumcari (Foster et al., 1972, fig. 10), by relatively abrupt northeastward termination of Pennsylvanian rocks, and by rapid southwest thickening of Wolfcampian clastic rocks, which are about 3,500 ft (1,070 m) thick in the northeast part of the basin. The trend of the probable fault or fault zone is uncertain because of differing interpretations of structure-contours of the top of Precambrian rocks (Krisle, 1959). Probably, other Paleozoic faults exist on the uplift or its margins (Foster et al., 1972, p. 17), but evidence of their existence and trends is not definitive. Nevertheless, the narrowness and the scalloped margins of the southwestern part of the uplift suggest that it might have originated in Pennsylvanian time as northwesterly trending fault blocks, or anticlines, and intervening basins analogous to the uplifts and basins exposed at the southeastern margin of the Sangre de Cristo Mountains (Fig. 72).

Sutherland (1963, p. 44) suggested that the western margin of the Sierra Grande uplift did not develop until Late Pennsylvanian or Permian time and that the eastward disappearance of Pennsylvanian rocks (of the Rainsville trough) may have resulted from post-depositional erosional truncation rather than from onlap. The Shell Oil Co. no. 1 Mora Ranch well (no. 14, Fig. 72), drilled on the east limb of the Paleozoic basin after Sutherland's report, provides additional information on the nature of the eastward thinning of

Pennsylvanian rocks. At this well the Sangre de Cristo Formation is about 3,400 ft (900 m) thick; the Alamitos and Porvenir Formations are about 1,500 ft (460 m) in combined thickness; the Sandia Formation is about 1,800 ft (550 m) thick; and Mississippian rocks are absent. The thicknesses and lithologies of the Sangre de Cristo, Alamitos, and Porvenir at the well are similar generally to those rocks near the east front of the mountains (Plate 3), but the Sandia at the well is much thinner than the more than 5,000 ft (1,500 m) of Sandia exposed at Mora River. The northeastward thinning of the Sandia indicates that the eastern limb of the basin was structurally much higher than the Rainsville trough in Morrowan and Atokan time, a situation analogous to the probable Morrowan and Atokan margin of the San Luis(?) uplift and the basin northwest of Eagle Nest (Fig. 77). Therefore, it is likely that at least parts of the Cimarron arch and the Sierra Grande uplift were emergent at times in the Pennsylvanian and were sources of fine to very coarse sands and other sediments of the Sandia at the Shell well and sources also of the sediments of the younger formations. Subsurface data east and north of the Shell well are not adequate to determine the stratigraphic nature of the wedgeout of the Pennsylvanian or the thinning of the Sangre de Cristo Formation onto the uplifts.

East of the Sierra Grande uplift, on the west margin of the Dalhart Basin (Fig. 78), pre-Pennsylvanian rocks and several hundred feet of black shale and interbedded sandstones of probable Morrowan and Atokan age (Roberts et al., 1976, fig. 4, 7) wedge out westward beneath granite wash, arkosic sandstones, and sandy limestones of probable Desmoinesian through Wolfcampian ages. All these rocks grade eastward into shelf facies of the Dalhart Basin in which carbonate rocks are common or predominant. Adjacent to the Bravo dome Pennsylvanian and Permian granite wash and sandstones wedge out eastward and southeastward into shelf deposits of the Palo Duro Basin (Roberts et al., 1976, fig. 4; Handford and Dutton, 1980). All these relations suggest that the eastern parts of the Sierra Grande uplift and the Bravo dome were emergent sources of coarse clastics in much, if not all, of Pennsylvanian and Early Permian time.

Part of the history of the southwestern part of the Sierra Grande uplift and its relation to the Cuervo–Tucumcari Basin are uncertain. Foster et al. (1972, p. 15) noted that gray shale and interbedded arkose and arkosic conglomerate in the lower part of the Pennsylvanian section in the basin are similar to the Pennsylvanian rocks exposed in the Sangre de Cristo Mountains west of Mora, but they pointed out (p. 15) that, without supporting paleontologic data, correlation of these rocks with those of the Cuervo–Tucumcari Basin is problematic. They pointed out that, if these sediments in the Cuervo–Tucumcari Basin were an eastward-thinning wedge of Lower Pennsylvanian gray shales and arkoses derived from the Uncompahgre uplift, the Sierra Grande is younger than the Uncompahgre. In that case, the Sierra Grande uplift would have been the source of only the younger Pennsylvanian and Permian coarse, arkosic, red sediments of the Cuervo–Tucumcari Basin. However, data from the southeastern part of the area of this report (Figs. 18, 20, 32) indicate that the Sandia Formation thins southward depositionally onto the north flank of the Sierra Grande uplift and the southern parts of the Tecolote and Bernal uplifts, showing that these areas were active in Morrowan and Atokan, and that at least part of the Sierra Grande shed sediments to the north throughout Pennsylvanian. Therefore, it may have been a source of presumed Early Pennsylvanian sediments of the Cuervo–Tucumcari Basin also. The Pedernal uplift, known to have been recurrently active through Pennsylvanian and Early Permian (Kottlowski, 1961), also seems likely to have supplied some terrigenous sediments to the Cuervo–Tucumcari Basin and to the San Jose Basin and the Pecos shelf.

Origin of ancestral Rocky Mountain uplifts and basins

Figure 78 shows the major Pennsylvanian tectonic features of the area of this report (Fig. 72) in relation to other Pennsylvanian Ancestral Rockies uplifts and basins. West of the area of Figure 78, the Uncompahgre uplift plunges northwest and dies out in eastern Utah. To the north, the Frontrange uplift dies out in southern Wyoming, and to the south the Pedernal uplift broadens and extends southward entirely across New Mexico. The Amarillo–Wichita uplift plunges southeast but, along the same trend, faulted basins and the parallel Arbuckle uplift in Oklahoma and Texas intersect and interrupt a southwest-trending segment of the Paleozoic Ouachita fold and thrust belt beneath Mesozoic rocks and Cenozoic sediments of the Gulf Coastal Plain (Flawn et al., 1961, p. 171–172).

All the features illustrated in Figure 78 were tectonically active also in Wolfcampian (Early Permian) time but, by the end of the Wolfcampian, sediments had mainly filled the basins and thin sedimentary beds lapped back across the Precambrian of most of the Defiance–Zuni, Peñasco, and Sierra Grande uplifts, the northern Pedernal uplift, the Cimarron arch, and (Dixon, 1967; MacLachlan, 1967) all but the eastern parts of the Amarillo–Wichita uplift. Large parts of the Uncompahgre, Frontrange, Wet Mountains–Apishapa, Brazos, and San Luis(?) uplifts probably were not covered by Wolfcampian sediments.

Precambrian ancestry of most of the major faults of the Ancestral Rockies has been postulated by various writers and is confirmed in places in south-central Colorado (Tweto, 1977, 1980b). Montgomery (1963) presented evidence for late Precambrian origin of the Pecos–Picuris fault in New Mexico. The Wichita uplift and Anadarko Basin have been interpreted as deformed parts of a late Precambrian to Middle Cambrian aulacogen, a rifted trough on the margin of the North American craton. This concept, as it applies to the geology of Oklahoma, was summarized by Wickham (1978a) and modified by Brewer et al. (1983, p. 113–114).

Regional-tectonic concepts

The generally similar Mississippian through Early Permian erosional and sedimentational histories of the northwesterly trending Ancestral Rockies uplifts and basins have suggested to many geologists that the system was produced by a regionally unified structural mechanism. The patterns of late Paleozoic folds and faults of the Texas Panhandle and Oklahoma were interpreted to indicate regionally distributed left-lateral shearing and left-lateral wrenching along high-angle faults (Nicholson, 1960, p. 53–54; Walper, 1970; Wickham, 1978a, p. 36). Walper (1970) included the Amarillo–Wichita uplift in what he called the Wichita megashear, which he considered to be a zone of major left-lateral displacements that extended northwest across New Mexico to include the Uncompahgre uplift and Paradox Basin in Colorado and Utah. Baars (1976) proposed that a curving, northwest alignment of basement fractures continues from the Uncompahgre uplift and Paradox Basin across the Western United States to the coast of Washington, and he called his entire proposed transcontinental alignment the Olympic–Wichita lineament. However, Baars (1976) and Stevenson and Baars (1986, fig. 2) indicated that strike-slip displacements in the Olympic–Wichita lineament, including the southeastern part, are right lateral, and that the Paradox Basin is pulled apart because of late Paleozoic east-west extension and divergent right-lateral wrenching along its margin with the Uncompahgre uplift.

Plate-tectonic concepts also have been applied to analysis of the northwesterly trending structures of Figure 78 and to other late Paleozoic uplifts and basins of the Western United States. Sales (1968, p. 2019, 2023–2024) proposed that the Ancestral Rockies and the Laramide Rockies foreland structures both were produced by eastward subduction of Pacific oceanic crust beneath the Cordilleran geosyncline that caused the geosyncline to be tectonically thickened enough to transmit compressional forces eastward to the Colorado Plateau. The cratonic crust in Colorado was thought to have been broken up along east- and west-dipping upthrusts because of east yielding at the eastern margin of the Colorado Plateau. Sales (p. 2024) suggested that, south of the Colorado Front Range, eastward yielding was accomplished by left-lateral wrench on the Wichita lineament.

Later plate-tectonic explanations (Casey, 1980a, b; Kluth and Coney, 1981; Kluth, 1986) have postulated that tectonic forces were applied to the craton at the east and southeast from the area of the Ouachita fold and thrust belt. The "S"-shaped Ouachita belt is a late Paleozoic craton-margin orogen that rims the Gulf Coastal Plain from Mississippi to west Texas and Mexico. The parts that are exposed in Oklahoma and Arkansas and in the Marathon region of west Texas are northerly verging folded and thrust salients thought to be connected by a lengthy, northwest-concave segment that is buried by Mesozoic rocks and Cenozoic sediments of the Gulf Coastal Plain (Flawn et al., 1961, p. 165). By analogy of its facies with Appalachian facies and structural zones, the buried part of the Ouachita belt is thought to verge northwesterly toward the craton (Flawn et al., 1961, plate 2). Wickham (1978b) briefly summarized evidence which suggests that the northerly verging Ouachita Mountains part of the belt is on a former continental margin that was deformed by a collision of the North American plate with an island arc or another continent.

Casey (1980a, b) suggested that a collision of the North American plate with an island arc or South America along the Ouachita belt caused the southwestern part of the North America craton to be shoved northwestward away from the rest of the main part of the craton, creating right-lateral shear couples along the Uncompahgre–Wichita trend and tensional features on other divergent Ancestral Rockies trends, such as the Frontrange uplift. Using this concept, Casey suggested that the Taos and Rainsville troughs of the area of this report (Taos trough of his usage) was a northwest-tilted rhomboid depression that may have been similar to a pull-apart basin. According to Casey, the basin formed in an area of tension between the Pecos–Picuris fault and unspecified faults of a northwest-trending Uncompahgre "lineament" along the south side of the Cimarron arch. He reasoned that tensional stresses responsible for vertical movements do not necessarily require large-scale lateral movements on through-going wrench faults and suggested that basin subsidence was accelerated by sediment loading. He suggested also that the Sierra Grande uplift was broadly arched by compressional stress in a right-lateral wrench system.

Kluth and Coney (1981) compared the timing of depositional events in late Paleozoic Basins of the Western United States with deformational events of the Ouachita belt. They concluded, as had Casey (1980a, b), that an assumed collision with South America along an irregular margin caused the southwestern part of the North American craton to be shoved northwestward, creating changing complex patterns of stress that acted on pre-existing weak zones in the crust during southwestward-progressing suturing of the continents along the Ouachita belt.

In discussing the plate-tectonic hypotheses of Kluth and Coney (1981), Goldstein (1981) pointed out that late Paleozoic continental collision at the south margin of the North American craton had not been proven and that there are noncollisional models for the Ouachita belt. Warner (1983) briefly discussed rock-mechanics problems of transmitting stresses across a deforming, weak, continental-margin zone into the deep interior of the continent. Concerning kinematics of Ancestral Rockies deformation, Warner (1983) pointed out that wrenching by distributive shear during northwestward pushing of the craton would produce horizontal greatest and least principal stresses, with the direction of tectonic transport being subparallel to the axes of the uplifts. Warner (1983, p. 121) wrote: "One is at some loss to understand how uplift of northwest-trending basement blocks by dominantly vertical movements along marginal faults could have resulted from such a stress system." Warner concluded that, by analogy with the Laramide Rockies, under thrusting consistent with eastward-directed compression is a mechanism preferable to that suggested by Kluth and Coney (1981).

Kluth (1986) expanded on the plate-tectonic model of Kluth and Coney (1981). Kluth (1986, p. 361) reiterated the interpretation that Ancestral Rockies deformation was produced in response to the events that produced the Ouachita–Marathon orogeny because he believed that Pennsylvanian time was a period of relative quiescence along the western plate margin of North America. He (p. 362–363) interpreted the marginal faults of some of the mountain blocks of the Ancestral Rockies as having both vertical and horizontal motions. Wrenching and translation were postulated to have been caused by distributive shear in a large area of the craton because there is no evidence for large-scale through-going megashears with great displacement in Pennsylvanian or pre-Pennsylvanian rocks. Kluth postulated changing patterns of stress during southwestward continent-continent suturing, and suggested that a northward component of stress, set up by plate collision in the Marathon region of Texas, resulted in vertical movements along the Uncompahgre and Amarillo–Wichita uplifts.

Tectonic styles

As illustrated by the various differing concepts, the structural mechanisms that produced the Ancestral Rockies are not clear, largely because basic details of local late Paleozoic structural style are poorly known or are conjectural. Formerly, the main boundary faults of the Wichita uplift were generally thought to be high angle and to have large components of left-lateral slip, but deep seismic profiles and well data have been interpreted by Brewer et al. (1983, p. 113, fig. 2) to indicate that the Mountain View and Meers faults (Fig. 78) at the north side of the uplift are thrusts dipping 30-40° southwest. They suggested a total of 15 ± 5 km (6–12 mi) of Pennsylvanian crustal shortening. According to Brewer et al. (1983, p. 114), a compressional stress in parts of Pennsylvanian time could have been north–northeast and south–southwest perpendicular to the uplift but, in Late Pennsylvanian, left-lateral oblique slip may have occurred in the parts of the system. Elsewhere, east of the present Rocky Mountains, very little is known about the late Paleozoic style of the Sierra Grande and Apishapa uplifts and their margins other than the existence of the Freezeout Creek fault zone on the east side of the Apishapa uplift and the Apishapa fault to the north. According to Tweto (1980a, p. 7) the Paleozoic Apishapa fault probably originated in Precambrian time, but its Paleozoic style is not reported.

Near longitude 105°, in the vicinity of the present Rocky Mountains and farther south, the asymmetry of uplifts and basins begins to change from that farther east where the steep, faulted parts of the Amarillo–Wichita and Apishapa

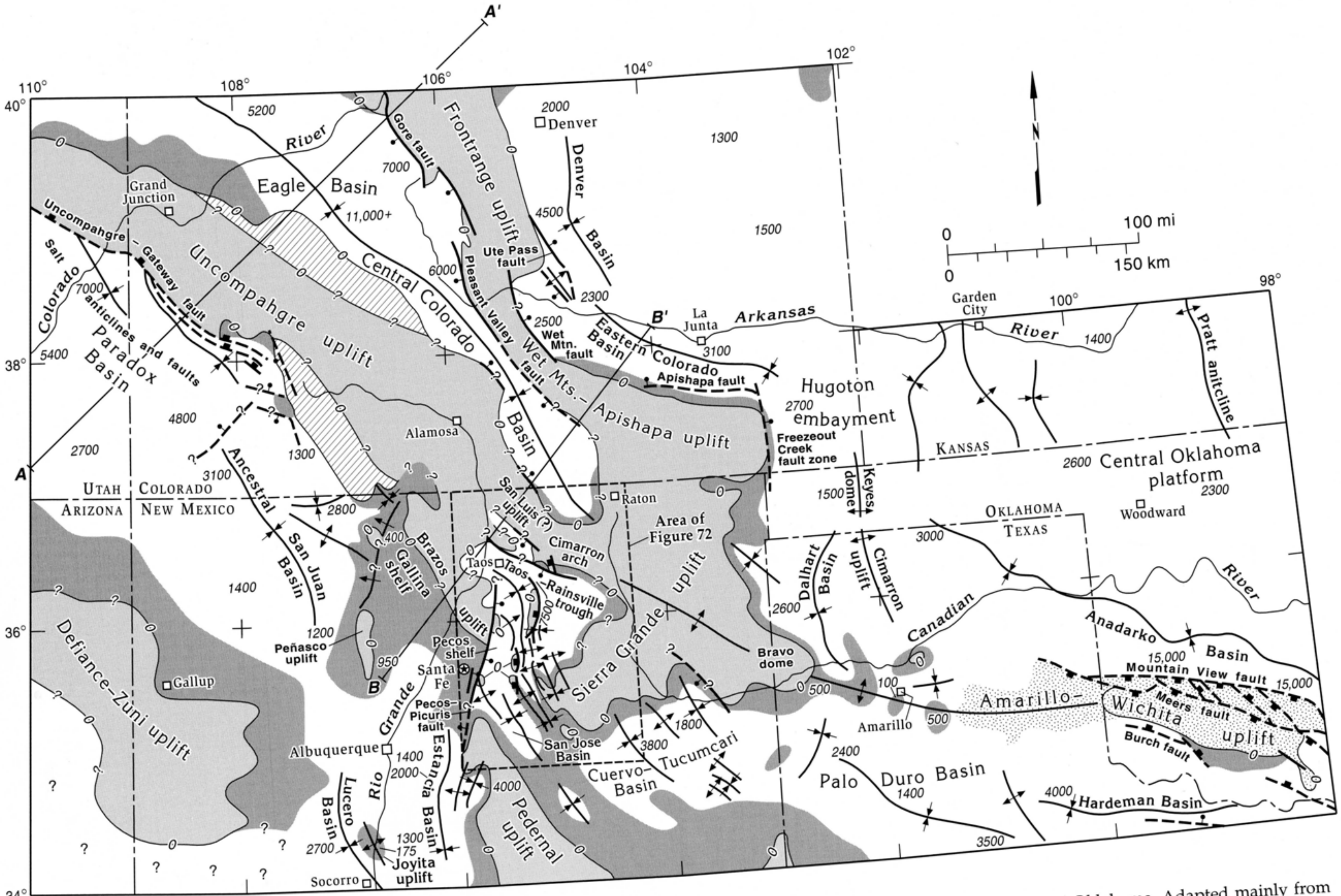


FIGURE 78—Principal late Paleozoic tectonic features of southern Colorado, northern New Mexico, and adjacent parts of Texas and Oklahoma. Adapted mainly from McKee and Crosby (1975, plate 11), Foster et al. (1972), Roberts et al. (1976), Kottlowski (1961), De Voto (1980), and other sources cited in text. Palinspastic restorations not made.

DESCRIPTION OF UNITS

Area where Pennsylvanian rocks are thin and are absent locally because of recurrent uplift of older Paleozoic and Precambrian rocks in Pennsylvanian and Early Permian time. Pennsylvanian rocks are absent from most of the Wichita uplift east of 100°

Area of uplifted Precambrian rocks where Pennsylvanian rocks mainly were not deposited or were eroded before or during Early Permian (Wolfcampian) time. Boundary queried where poorly known or hypothetical

Area added to Uncompahgre uplift in early Mesozoic time (Tweto, 1983). Pennsylvanian and Permian rocks probably were present in some places before uplift and erosion in Triassic time

Area where Pennsylvanian rocks are equal to or less than 1,000 ft (300 m) thick

Area where Pennsylvanian rocks are more than 1,000 ft (300 m) thick

15,000 Local approximate thickness (ft) of Pennsylvanian rocks

FOLDS AND FAULTS ACTIVE IN PENNSYLVANIAN TO EARLY PERMIAN TIME

Anticlines and uplift axes—Dashed in area of local uplifts and basins

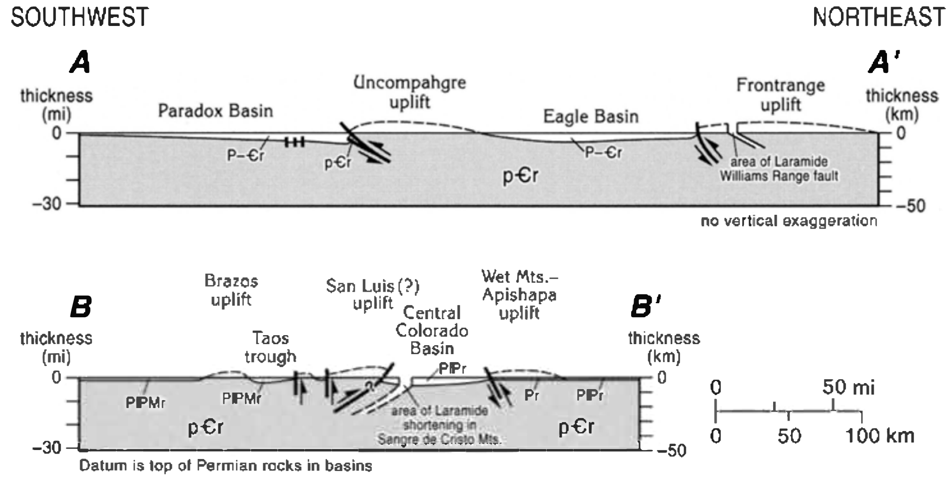
Anticlinal bend

Synclines and basin axes

Fault—Dashed where concealed; queried where uncertain. Bar and ball on downthrown side. Paleozoic style not certainly established

Probable reverse or thrust fault—Dashed where concealed. Blocks on upthrown side. Faults of Wichita uplift mainly after Brewer and others (1983, figures 1, 2). Faults on southwest margin of Uncompahgre uplift adapted from White and Jacobson (1983)

A — A' **Line of structural profile** (Figure 79)



sedimentary rocks:

- Pr—Post Wolfcampian Permian rocks of Wet Mountains-Apishapa uplift
- PIPr—Permian and Pennsylvanian rocks
- PIPMr—Permian, Pennsylvanian, and Mississippian rocks
- P–Ꞓr—In Paradox Basin, Permian through Devonian and Cambrian rocks; in Eagle Basin, Permian through Devonian, Ordovician, and Cambrian rocks

pꞒr—Precambrian crystalline basement rocks and other crustal rocks. Dashed lines above top of profiles are restored pre-Pennsylvanian tops of Precambrian rocks

FIGURE 79—Hypothetical structural profiles of Ancestral Rockies uplifts and basins. Lines of profiles shown in Figure 78. Profiles are lengthened to eliminate part of Laramide shortening. Reconstructed tops of Precambrian rocks (dashed lines) of uplifts are based on the assumption that cross-sectional areas of eroded rocks above the datum are about equivalent to cross-sectional areas of Permian and Pennsylvanian rocks of adjacent parts of basins on the profiles.

In *A–A'*, Uncompahgre uplift is assumed to have supplied all the late Paleozoic sediments of adjacent deep part of Paradox Basin and southwestern two-thirds of adjacent part of Eagle Basin. Frontrange uplift supplied sediments to Eagle and Denver Basins.

In *B–B'*, San Luis(?) uplift is assumed to have supplied about two-thirds of sediments of Central Colorado Basin. Wet Mountains–Apishapa uplift supplied sediments to both flanking basins but is buried by thin post-Wolfcampian Permian sediments from San Luis(?) uplift. Basin at southwest end of *B–B'* received sediments from Brazos and Peñasco uplifts.

uplifts face north–northeast. In Colorado, the narrow Wet Mountains uplift and Central Colorado Basin probably were bounded by faults on both sides. The Taos and Rainsville troughs in New Mexico are deepest on the north and may have been bounded partly by the Saladon Creek fault at the north, the Pecos–Picuris fault at the west, and by folded structures at the south. The Uncompahgre and Frontrange uplifts of Colorado were gently tilted upwarps that had fault-bounded fronts on their southeast sides but were upwarped only gently on their northeast sides (Tweto, 1980a, p. 6). The basinal areas in Colorado have been interpreted as grabens and half grabens with the major faults on their northeast sides (De Voto, 1980, p. 71).

In New Mexico the late Paleozoic Brazos uplift also may have had a southwest-facing monoclinal boundary. The Pedernal uplift, similar in some respects to the Uncompahgre uplift, was a huge upwarp that had a west-facing front, which may have been faulted, at least locally, in Pennsylvanian time (Bachman, 1975, p. 240), but the style of the faults is not known. The northeastern and eastern margins of the Pedernal uplift were shallow shelves on which Pennsylvanian and Lower Permian rocks thicken irregularly eastward.

The major late Paleozoic faults exposed along the Wet Mountains and Frontrange uplifts in the present Rocky Mountains in Colorado have been overprinted by Laramide and Neogene structure to the extent that most writers have not made direct statements concerning their Paleozoic styles, other than to observe that the faults mainly have Precambrian antecedents and that the vertical senses of displacements in late Paleozoic and Cenozoic times were the same. (See summaries in Tweto, 1977, 1980a, b; De Voto, 1980.) In cross sections, the faults generally are portrayed as vertical, or high-angle reverse, or normal (De Voto, 1980; Tweto, 1983). Tweto (1980b, p. 43) reported that the Gore fault and other northwest-trending faults of the Frontrange and Wet Mountains uplifts are essentially vertical zones on which strike-slip and vertical movements occurred in the Precambrian, but whose motions were largely dip slip in Phanerozoic time.

The boundary of the Central Colorado Basin and the eastern Uncompahgre uplift is obscure. Precambrian rocks of the western part of the Sangre de Cristo Mountains northeast of Alamosa were interpreted as a late Paleozoic intrabasinal uplift by De Voto and Peel (1972) and De Voto (1980, figs. 3–5 et al.), but Lindsey et al. (1986, p. 555) consider the Precambrian rocks to be fragments of the Uncompahgre uplift transported eastward by Laramide thrusts. Lindsey et al. (1986) noted that facies of the adjacent Sangre de Cristo Formation match the distribution of Precambrian source rocks and reported that Paleozoic or Laramide strike slip has not occurred along the fault boundary. They indicated (p. 558) that the Paleozoic eastern boundary of the Uncompahgre uplift was destroyed by the Laramide faulting, but the boundary probably was a normal or reverse fault system.

The southwestern late Paleozoic margin of the Uncompahgre uplift is concealed mainly by Mesozoic rocks and partly by Cenozoic volcanic rocks of the San Juan Mountains. The boundary of the uplift and the Paradox Basin is the buried late Paleozoic Uncompahgre and Gateway fault zones. Pennsylvanian and Permian rocks are 10,000–12,000 ft (3,050–3,650 m) in total thickness in the subsurface of the northern part of the Paradox Basin; however, locally in and near the fault zone, thin Permian rocks lie on the Precambrian and are truncated northeastward by Triassic rocks that lie on the Precambrian of the immediately adjacent parts of the uplift (Stone, 1977, p. 23: Frahme and Vaughn, 1983, p. 201; White and Jacobson, 1983).

Seismic profiles and well data from west of the Colorado River in Utah were interpreted by Frahme and Vaughn (1983, p. 209) to indicate that the Uncompahgre fault is a thrust that dips about 30° northeast. A well there completely penetrates the overhanging Precambrian rocks and bottoms in Cambrian rocks below the fault. They estimated that the vertical separation on the top of the Precambrian is about 20,000 ft (9,100 m) and the northeast–southwest shortening is about 6 mi (9.5 km). However, White and Jacobson (1983, p. 37–38) apparently used about the same data to interpret the fault as dipping 50–55° northeast and having about 14,400 ft (4,400 m) of displacement parallel to the fault plane.

White and Jacobson (1983) interpreted faults of the Gateway fault zone in Colorado also as dipping about 50° northeast. They indicated that, as the Paradox Basin shallows to the southeast, part of the displacement is transferred basinward from one fault to several northeast-dipping reverse faults and faulted anticlines. The interpretation of White and Jacobson (1983) differs from that of De Voto (1980, fig. 13) who illustrated the Gateway fault as nearly vertical, and from that of Stevenson and Baars (1986, figs. 10, 11) who indicated diagrammatically that the southwest margin of the Uncompahgre uplift is a complex zone of high-angle normal and reverse faults produced by right wrenching. Analogy with conditions on the Uncompahgre fault in Utah seems to provide the best evidence for White and Jacobson's interpretation of reverse faulting in the Gateway zone.

Southeast of the Paradox Basin the late Paleozoic margin of the Uncompahgre uplift and the relatively shallow ancestral San Juan Basin is unknown because Paleozoic rocks wedge out northward beneath Triassic and Jurassic rocks in areas where Precambrian basement was warped up and added to the margins of the uplift in Mesozoic time (Fig. 78). Southwest of Alamosa (Fig. 78), just north of the New Mexico line, Pennsylvanian rocks are present locally in the subsurface in folds truncated by Triassic and Jurassic rocks (J.W. Osterhoudt, as reported in Tweto, 1983) suggesting that, prior to Mesozoic deformation, Pennsylvanian depositional areas may have separated part of the Uncompahgre uplift from the ancestral Brazos uplift.

On the edge of the Brazos uplift southeast of Chama, New Mexico, Muehlburger (1967, p. 10–14) found partly marine Desmoinesian rocks, about 400 ft (120 m) thick, that include eastward-thinning, basal gravelly beds that were deposited on a possibly southwest-facing monoclinal flank of the uplift. These rocks are truncated by Triassic rocks that lap northeastward onto the Precambrian. Farther southeast nonmarine Desmoinesian or Missourian rocks overlain by Permian rocks crop out several miles southeast of the Precambrian of the uplift (Smith, Budding, and Pitrat, 1961, p. 5), but the margin of the uplift is concealed by younger rocks. The metamorphic and igneous rocks of the uplift were folded sharply in Precambrian time along northwesterly axes and are broken by lengthy, northwesterly trending, mainly high-angle, normal faults. The history of these faults is not known because of the lack of pre-Cenozoic rocks on the uplift. The faults seem to have had predominantly dip-slip Phanerozoic motions (Barker, 1958, p. 72–73; Muehlburger, 1967, p. 63). According to Wobus (1984, p. 197), faults of the Tusas Range (of the Brazos uplift) are generally high angle, cut both Precambrian and Tertiary rocks, and many likely were developed during evolution of the Rio Grande rift.

Interpretations of this report

The tectonic patterns of Ancestral Rockies basins and uplifts (Fig. 78) change markedly at about 103° longitude where the Sierra Grande and Apishapa uplifts rise across the entire basin-uplift system of Texas and Oklahoma. This is near the vaguely demarcated eastern edge of the early Paleozoic northern New Mexico–southern Colorado positive area from which rocks older than Mississippian are absent. (See plate 2 in Craig and Varnes, 1979; Ross and Tweto, 1980, p. 53–54.) Farther west, the structural grain of uplifts, basins, and folds is northwest and, at about 105° near the present Rocky Mountains, the grain is north–northwest. To the south in New Mexico, the trends of Paleozoic basins and uplifts are northerly also in the area between the present Great Plains and the Colorado Plateau that is marked now by basins and uplifts of the Rio Grande rift. In the eastern part of the present Colorado Plateau, the Ancestral Rockies trends again are northwest.

These changing patterns and trends suggest a northeastward shifting of the crust west of 103°, throughout Pennsylvanian and Early Permian time, with consequent upbuckling and downbuckling of various areas as a result of northeast–southwest compression. The Frontrange and the Wet Mountains–Apishapa uplifts appear to have been upthrust buttresses that resisted the shifting and compression and mitigated their effects on the Denver and Eastern Colorado Basins. To the northwest, where the Paradox and Eagle Basins are broad, northeast shortening occurred mainly by overthrusting or underthrusting on the southwest margin of the Uncompahgre uplift. To the southeast where the Uncompahgre uplift is wider, shortening may have occurred by upbuckling and lateral expansion of the uplift, such as happened also in the Triassic and Jurassic. Additional shortening may have occurred as a result of Late Pennsylvanian and Early Permian down forcing of the deep, narrow Central Colorado Basin between opposed possible reverse faults on the west and in the Pleasant Valley fault zone on the east (De Voto, 1980, fig. 17).

The late Paleozoic structure of the area of this report (Figs. 71, 72, 78) is interpreted to be the result of a northeast-oriented compressional force operating in a structurally transitional zone between the areas of the present Colorado Plateau and the present Great Plains. The Taos and Rainsville troughs and Pecos shelf were downbuckled and partly downfaulted, and the southern margin of this basinal area was deformed into northwest-trending anticlines and synclines. The San Luis(?) uplift and the Cimarron arch were buckled and partly faulted up between deep basins. The northeast compressional force seems to have been resolved into transpression that produced low right-echelon folds on the Tecolote uplift and right-oblique slip on reverse faults of other intrabasinal uplifts whose Precambrian structures were properly oriented. The Paleozoic styles of the northwest-trending Saladon Creek and Comanche Creek faults are not known, but they may have acted as upthrusts. The high-angle, Precambrian Pecos–Picuris fault, the Deer Creek fault, and other northerly trending faults of unknown history in the Santa Fe Range (Plate 2) are oriented to relieve stress by right shift that could have caused the Brazos uplift to encroach on the northwestern part of the Taos trough. However, there is presently no direct evidence that late Paleozoic strike slip did occur on these faults.

Figure 79 shows reconstructed profiles of uplifts and basins approximately as they might have been at the end of the Permian. The profiles, shown reduced in Figure 79, were reconstructed to estimate the amounts of regional crustal shortening if the deformation was compressional. The main assumptions for the reconstructions are given in the caption.

The areas of both profiles were affected by Cenozoic deformation that partly was taken into account palinspastically as shown. Other Cenozoic deformation was considered but was not used to restore the profiles. According to Heyman (1983, p. 46), Cenozoic arching of the Uncompahgre uplift south of Grand Junction produced 1–3 percent shortening of the top of the Precambrian basement in southeast–northwest direction. This regionally small amount of shortening, 0.33–1 mi (0.6–1.6 km), was not considered necessary for restoration because the depositional edges of Pennsylvanian and Permian rocks at the northeast side of the uplift are only an approximation (Tweto, 1977, 1983) at line *A–A'*. To the northeast, in the Eagle Basin, line *A–A'* crosses the Cenozoic Grand Hogback monocline and the uplifted eastern part of the Eagle Basin between the Cenozoic Sawatch and White River uplifts. Some regionally small Cenozoic shortening probably occurred on the monocline and on several broad open folds to the east. However, this was not taken into account palinspastically on the assumption that the basement and the projected top of the Permian in the Paleozoic basin would have been deformed about the same and that this deformation would not greatly affect estimation of the late Paleozoic shortening. Areas of evaporite flowage in the Eagle Basin (Tweto, 1977; Tweto et al., 1978) were not considered in the reconstruction of profile *A–A'*, nor were several Cenozoic normal faults.

The southwestern part of profile *B–B'* is drawn through poorly known areas of structural complexity in the Neogene Rio Grande rift. Some Neogene extension occurred obliquely to line *B–B'* where it crosses the edge of the Neogene San Luis Basin north of Taos, but some Laramide and possibly Neogene shortening probably occurred in the upbulged Sangre de Cristo uplift; therefore, the Cenozoic deformation is not considered palinspastically in profile *B–B'*. The position and style of late Paleozoic faults at the west margin of the narrow Central Colorado Basin are not known in this area, but the margin was assumed to be a thrust for hypothetical reasons discussed previously.

The amount of late Paleozoic shortening of the top of Precambrian rocks in line *A–A'* is only about 4 mi (6.5 km), which is about 2 percent. About half of the shortening occurs along the Gateway fault zone, as determined mainly from cross section *D–D'* of White and Jacobson (1983). The shortening in profile *B–B'* is about 7 mi (11 km), which is about 4.4 percent. These figures cannot be considered as accurate estimates of late Paleozoic shortening because of the many uncertainties in the data and the assumptions used to construct the profiles. Nevertheless, they may indicate at least the order of magnitude of shortening. The shortening along *B–B'* suggests that, if late Paleozoic right slip occurred on the Pecos–Picuris fault (a possibility not yet established), the amount need not have been more than 2–3 mi (3–4.8 km), and less, if the northerly trending faults in the Santa Fe Range to the west also participated in late Paleozoic strike-slip movements.

Conclusions

The tectonic patterns of Figure 78, and what is known of the structural styles of various elements, suggest a northeastward shift of intracratonic crust in the region west of about longitude 103° that began in Early Pennsylvanian time. By Late Pennsylvanian and Early Permian the rising Sierra Grande and Wet Mountains–Apishapa uplifts may have become buttressing elements that caused the main areas of compressional deformation and possibly some right wrenching to become concentrated in the north–south region adjacent to the present Rio Grande. This began a Phanerozoic structural differentiation of the Cenozoic Great Plains, Southern Rocky Mountains, and Colorado Plateau provinces.

The postulated northeast-oriented late Paleozoic regional compressional force associated with the shift does not fit well with plate-tectonic concepts that require compressional forces to have been applied at either the western or the southeastern margins of the craton. If a craton-marginal force was responsible for the shift it seems most likely to have been applied at the southwest.

On the other hand, it seems possible that an intraplate shift of a large segment of the craton might have caused compression in the crust, perhaps as a result of some mechanism, such as regionally minor horizontal and locally vertical movements of mantle, that carried or dragged the overlying crust. Whatever the cause, it may have been reactivated slightly in about the same direction in Triassic and Jurassic time, and also during Laramide orogeny when, according to some writers, the Colorado Plateau seems to have shifted slightly northeasterly, producing compressional structures in the eastern part of the plateau and in the Southern Rocky Mountains (Kelley, 1955, p. 66; Baltz, 1967, p. 85; Chapin and Cather, 1983, p. 51–53).

As pointed out by Tweto (1975, p. 36–37), the distinguishing characteristic of the Southern Rocky Mountain province (including adjacent eastern parts of the Colorado Plateau) is a Phanerozoic history of buoyancy relative to other parts of the continent. He concluded that this history, including differential buoyancy of large uplift and basinal tracts, must reflect inhomogeneity built into the continental plate at an early time. Whatever external forces were applied, there has been an evident local control of many tectonic features that date from the Paleozoic and Precambrian. A history of regional buoyancy applies also to the western part of the Great Plains that is underlain by the Apishapa and Sierra Grande uplifts and northern part of the Pedernal uplift and also the Zuni–Defiance uplift in the Colorado Plateau, all in the region of the pre-Mississippian northern New Mexico–southern Colorado positive area. Perhaps this entire intraplate region has been predisposed to behave nearly independently from tectonic events on distant continental-crustal margins.

References

Alsop, J. L., 1982, Shelf carbonates of the Madera Formation (Desmoinesian) of the late Paleozoic Taos trough, northern New Mexico: Unpublished MS thesis, University of Texas (Austin), 180 p.

Andreasen, G. E., Kane, M. F., and Zietz, I., 1962, Aeromagnetic and gravity studies of the Precambrian in northeastern New Mexico: Geophysics, v. 27, p. 343–358.

Armstrong, A. K., 1955, Preliminary observations on the Mississippian System of northern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 39, 42 p.

Armstrong, A. K., 1967, Biostratigraphy and carbonate facies of the Mississippian Arroyo Peñasco Formation, north-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 20, 80 p.

Armstrong, A. K., and Holcomb, L. D., 1967, Interim report on Mississippian Arroyo Peñasco Formation of north-central New Mexico: American Association of Petroleum Geologists Bulletin, v. 51, no. 3, p. 417–424.

Armstrong, A. K., and Mamet, B. L., 1974, Biostratigraphy of the Arroyo Peñasco Group, Lower Carboniferous (Mississippian), north-central New Mexico; *in* Siemers, C. T., Woodward, L. A., and Callender, J. R., (eds.), Ghost Ranch, central-northern New Mexico: New Mexico Geological Society, Guidebook 25, p. 145–158.

Armstrong, A. K., and Mamet, B. L., 1979, The Mississippian System of north-central New Mexico; *in* Ingersoll, R. V., Woodward, L. A., and James, H. L., (eds.), Santa Fe country: New Mexico Geological Society, Guidebook 30, p. 201–210.

Armstrong, A. K., Kottlowski, F. E., Stewart, W. V., Mamet, B. L., Baltz, E. H., Siemers, W. T., and Thompson, S., III, 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—New Mexico: U.S. Geological Survey Professional Paper 1110–W, p. W1–W27.

Asquith, G. B., and Gilbert, J. L., 1976, Proximal and distal braided alluvial facies in the lower braided interval of the Dakota Sandstone, northeastern New Mexico; *in* Ewing, R. C., and Kues, B. S , (eds.), Vermejo Park, northeastern New Mexico: New Mexico Geological Society, Guidebook 27, p. 153–155.

Baars, D. L., 1976, Colorado Plateau aulacogen; *in* Podwysocki, M. H., and Earle, J. L., (eds.), Proceedings of 2nd International Conference on Basement Tectonics: Basement Tectonics Committee, Inc., Denver, Colorado, p. 157–164.

Baars, D. L., and Stevenson, G. M., 1984, The San Luis uplift, Colorado and New Mexico—An enigma of the Ancestral Rockies: The Mountain Geologist: Rocky Mountain Association of Geologists, v. 21, p. 57–67.

Bachman, G. O., 1953, Geology of a part of northwestern Mora County, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map OM–137, scale 1:48,000.

Bachman, G. O., 1975, New Mexico; *in* Paleotectonic investigations of the Pennsylvanian System in the United States, Part I, Introduction and regional analyses of the Pennsylvanian System: U.S. Geological Survey, Professional Paper 853–L, p. 233–243.

Bachman, G. O., and Myers, D. A., 1969, Geology of the Bear Peak area, Doña Ana County, New Mexico: U.S. Geological Survey, Bulletin 1271–C, 46 p.

Baltz, E. H., 1965, Stratigraphy and history of Raton Basin and notes on San Luis Basin, Colorado–New Mexico: American Association of Petroleum Geologists Bulletin, v. 49, p. 2041–2075.

Baltz, E. H., 1967, Stratigraphy and regional tectonic implications of part of Upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico: U.S. Geological Survey, Professional Paper 552, 101 p.

Baltz, E. H., 1969, Interim report on Mississippian Arroyo Peñasco Formation of north-central New Mexico; Discussion: American Association of Petroleum Geologists Bulletin, v. 53, p. 1508–1518.

Baltz, E. H., 1972, Geologic map and cross sections of the Gallinas Creek area, Sangre de Cristo Mountains, San Miguel County, New Mexico: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I–673, 2 sheets, scale 1:24,000.

Baltz, E. H., 1978, Resumé of Rio Grande depression in north-central New Mexico; *in* Hawley, J. W., compiler, Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, p. 210–228.

Baltz, E. H., and Bachman, G. O., 1956, Notes on the geology of the southeastern Sangre de Cristo Mountains, New Mexico; *in* Rosenzweig, A., (ed.), Southeastern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, Guidebook 7, p. 96–108.

Baltz, E. H., and Myers, D. A., 1984, Porvenir Formation (new name) and other revisions of nomenclature of Mississippian, Pennsylvanian, and Lower Permian rocks, southeastern Sangre de Cristo Mountains, New Mexico: U.S. Geological Survey, Bulletin 1537–B, 39 p.

Baltz, E. H., and O'Neill, J. M., 1984, Geologic map and cross sections of the Mora River area, Sangre de Cristo Mountains, Mora County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I–1456, 2 sheets, scale 1:24,000.

Baltz, E. H., and O'Neill, J. M., 1986, Geologic map and cross sections of the Sapello River area, Sangre de Cristo Mountains, Mora and San Miguel Counties, New Mexico: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I–1575, 2 sheets, scale 1:24,000.

Baltz, E. H., and O'Neill, J. M., 1990, Third-day road log, form Angel

Fire to Las Vegas, via Black Lake, Guadalupita, Mora, Rociada, and Sapello; *in* Bauer, P. W., Lucas, S. G., Mawer, C. K., and McIntosh, W. C., (eds.), Tectonic development of the Southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, Guidebook 41, p. 67–96.

Baltz, E. H., and Read, C. B., 1956, Second day, Kearny's Gap and Montezuma via Mineral Hill and Gallinas Canyon, Las Vegas to Mora to Taos; *in* Rosenzweig, A., (ed.), Southeastern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, Guidebook 7, 1956, p. 49–81.

Baltz, E. H., and Read, C. B., 1960, Rocks of Mississippian and probable Devonian age in Sangre de Cristo Mountains, New Mexico: American Association of Petroleum Geologists Bulletin, v. 44, p. 1749–1774.

Barker, Fred, 1958, Precambrian and Tertiary geology of Las Tablas quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 45, 104 p.

Bauer, P. W., Lucas, S. G., Mawer, C. K., and McIntosh, W. C., (eds.), 1990, Tectonic development of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, Guidebook 41, 450 p.

Bejnar, C. R., and Lessard, R. H., 1976, Paleocurrents and depositional environments of the Dakota Group, San Miguel and Mora Counties, New Mexico; *in* Ewing, R. C., and Kues, B. S., (eds.), Vermejo Park, northeastern New Mexico: New Mexico Geological Society, Guidebook 27, p. 157–163.

Bolyard, D. W., 1959, Pennsylvanian and Permian stratigraphy in Sangre de Cristo Mountains between La Veta Pass and Westcliffe, Colorado: American Association of Petroleum Geologists Bulletin, v. 43, p. 1896–1939.

Booth, F. O., 1976, Geology of the Galisteo Creek area, Lamy to Cañoncito, Santa Fe County, New Mexico: Unpublished MS thesis, Colorado School of Mines, Golden, 122 p.

Booth, F. O., 1977, Geologic map of the Galisteo Creek area, Lamy to Cañoncito, Santa Fe County, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map MF–823, scale 1:12,000.

Brewer, J. A., Good, R., Oliver, J. E., Brown, L. D., and Kaufman, S., 1983, COCORP profiling across the southern Oklahoma aulacogen; overthrusting of the Wichita Mountains and compression within the Anadarko Basin: Geology, v. 11, p. 109–114.

Brill, K. G., Jr., 1952, Stratigraphy in the Permo–Pennsylvanian zeugogeosyncline of Colorado and northern New Mexico: Geological Society of America Bulletin, v. 63, p. 809–880.

Brown, C. E., 1984, Depositional environments of the Permo–Pennsylvanian Sangre de Cristo Formation, Coyote Creek district, Mora County, New Mexico; *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., (eds.), Rio Grande rift, northern New Mexico: New Mexico Geological Society, Guidebook 35, p. 115–122.

Budding, A. J., 1972, Geologic map of the Glorieta quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 24, scale 1:24,000.

Budding, A. J., 1979, Supplemental road log no. 2, Glorieta to Las Vegas; *in* Ingersoll, R. V., Woodward, L. A., and James, H. L., (eds.), Santa Fe country: New Mexico Geological Society, Guidebook 30, 1979, p. 44–49.

Budding, A. J., and Cepeda, J. C., 1979, Tectonics and metamorphism of the El Oro gneiss dome near Mora, north-central New Mexico; *in* Ingersoll, R. V., Woodward, L. A., and James, H. L., (eds.), Santa Fe country: New Mexico Geological Society, Guidebook 30, p. 159–164.

Cabot, E. C., 1938, Fault border of the Sangre de Cristo Mountains north of Santa Fe, New Mexico: Journal of Geology, v. 46, p. 88–105.

Callon, M. W., 1962, Las Vegas, New Mexico—The town that wouldn't gamble: Daily Optic, Las Vegas Publishing Co., Las Vegas, New Mexico; 352 p.

Campa, A. L., 1963, Treasure of the Sangre de Cristos—Tales and traditions of the Spanish Southwest: University of Oklahoma Press, Norman, 223 p.

Casey, J. M., 1980a, Depositional systems and paleogeographic evolution of the late Paleozoic Taos trough, northern New Mexico; *in* Fouch, T. D., and Magathan, E. R., (eds.), Paleozoic paleogeography of the west-central United States; Rocky Mountain paleogeography, Symposium 1: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 181–196.

Casey, J. M., 1980b, Depositional systems and basin evolution of the late Paleozoic Taos trough, northern New Mexico: Unpublished PhD dissertation, University of Texas (Austin), 236 p.

Cassity, P. E., and Langenheim, R. L., 1966, Pennsylvanian and Lower Permian fusulinids of the Bird Spring Group from Arrow Canyon, Clark County, Nevada: Journal of Paleontology, v. 40, p. 931–968, plates. 110–114.

Chapin, C. E., and Cather, S. M., 1981, Eocene tectonics and sedimentation in the Colorado Plateau–Rocky Mountain area; *in* Dickinson, W. R., and Payne, W. D., (eds.), Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 173–198.

Chapin, C. E., and Cather, S. M., 1983, Eocene tectonics and sedimentation in the Colorado Plateau–Rocky Mountain area; *in* Lowell, J. D., and Gries, R., (eds.), Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists Field Symposium, p. 33–56.

Clark, K. F., and Read, C. B., 1972, Geology and ore deposits of Eagle Nest area, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 94, 152 p.

Cordell, L., 1976, Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar; *in* Woodward, L. A., and Northrop, S. A., (eds.), Tectonics and mineral resources of southwestern North America: New Mexico Geological Society, Special Publication 6, p. 62–70.

Cordell, L., 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America Bulletin, v. 89, p. 1073–1090.

Cordell, L., and Keller, G. R., 1984, Regional structural trends inferred from gravity and aeromagnetic data in the New Mexico–Colorado border region; *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., (eds.), Rio Grande rift, northern New Mexico: New Mexico Geological Society, Guidebook 35, p. 21–23.

Coxe, C. L., 1981, Pennsylvanian (lower Desmoinesian) fluvial-deltaic depositional systems in the Taos trough, northern New Mexico: Unpublished MS thesis University of Texas (Austin), 108 p.

Craig, L. C., and Varnes, K. L., 1979, History of the Mississippian System—an interpretive summary; *in* Paleotectonic investigations of the Mississippian System in the United States; Part II, Interpretive summary and special features of the Mississippian system: U.S. Geological Survey, Professional Paper 1010, p. 371–406.

Dane, C. H., 1948, Geologic map of part of eastern San Juan Basin, Rio Arriba County, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 78, scale 1:62,500.

Dane, C. H., and Bachman, G. O., 1965, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.

Darton, N. H., 1922, Geologic structure of parts of New Mexico; *in* Contributions to economic geology, Part 2—Mineral fuels, 1921: U.S. Geological Survey, Bulletin 726, p. 173–275.

Darton, N. H., 1928a, "Red beds" and associated formations in New Mexico, with an outline of the geology of the state: U.S. Geological Survey, Bulletin 794, 356 p.

Darton, N. H., 1928b, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.

De Voto, R. H., 1980, Pennsylvanian stratigraphy and history of Colorado; *in* Kent, H. C., and Porter, K. C., (eds.), Colorado geology: Rocky Mountain Association of Geologists, 1980 symposium, p. 71–101.

De Voto, R. H., and Peel, F. A., 1972, Pennsylvanian and Permian stratigraphy and structural history, northern Sangre de Cristo Range, Colorado; *in* De Voto, R. H., (ed.), Paleozoic stratigraphy and structural evolution of Colorado, a symposium: Quarterly of the Colorado School of Mines, v. 67, p. 283–320.

De Voto, R. H., Peel, F. A., and Pierce, W. H., 1971, Pennsylvanian and Permian stratigraphy, tectonism, and history, northern Sangre de Cristo Range, Colorado; *in* James, H. L., (ed.), San

Luis Basin, Colorado: New Mexico Geological Society, Guidebook 22, 1971, p. 141–163.

Dixon, G. H., 1967, Northeastern New Mexico and Texas-Oklahoma panhandles, Chapter D; *in* Paleotectonic investigations of the Permian System in the United States: U.S. Geological Survey, Professional Paper 515, p. 61–80.

Dunbar, C. O., and Condra, G. E., 1927, The *Fusulinidae* of the Pennsylvanian System in Nebraska: Nebraska Geological Survey, Bulletin 2, 2nd ser., 135 p.

Dunbar, C. O., and Henbest, L. G., 1942, Pennsylvanian *Fusulinidae* of Illinois: Illinois State Geological Survey, Bulletin 67, 218 p.

Ferguson, C. A., Timmons, J. M., Pazzaglia, F. J., Karlstrom, K. E., Osburn, G. R., and Bauer, P. W., 1996, Geology of Sandia Park quadrangle, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Mines & Mineral Resources, Open-file Digital Map DM-1, 12 p. text, scale 1:12,000.

Fitzsimmons, J. P., Armstrong, A. K., and Gordon, M., Jr., 1956, Arroyo Peñasco Formation, Mississippian, north-central New Mexico: American Association of Petroleum Geologists Bulletin, v. 40, p. 1935–1944.

Flawn, P. T. , Goldstein, August, Jr., King, P. B., and Weaver, C. E., 1961, The Ouachita System: University of Texas, Bureau of Economic Geology Publication 6120, 401 p.

Foster, R. W., 1966, Oil and gas exploration in Colfax County; *in* Northrop, S. A., and Read, C. B., (eds.), Taos–Raton–Spanish Peaks Country, New Mexico and Colorado: New Mexico Geological Society, Guidebook 17, 1966, p. 80–87.

Foster, R. W., Frentress, R. M., and Riese, W. C., 1972, Subsurface geology of east-central New Mexico: New Mexico Geological Society, Special Publication 4, 22 p.

Frahme, C. W., and Vaughn, E. B., 1983, Paleozoic geology and seismic stratigraphy of the northern Uncompahgre front, Grand County, Utah; *in* Lowell, J. D., and Gries, R., (eds.), Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists Field Symposium, p. 201–211.

Frezon, S. E., and Dixon, G. H., 1975, Texas Panhandle and Oklahoma; *in* Paleotectonic investigations of the Pennsylvanian System in the United States, Part 1; Introduction and regional analyses of the Pennsylvanian System: U.S. Geological Survey, Professional Paper 853, p. 177–195.

Fullager, P. D., and Shiver, W. S., 1973, Geochronology and petrochemistry of the Embudo Granite, New Mexico: Geological Society of America Bulletin, v. 84, p. 2705–2712.

Galusha, Ted, and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Museum of Natural History Bulletin, v. 144, article 1, 125 p.

Goldstein, A. G., 1981, Comment on plate tectonics of Ancestral Rocky Mountains: Geology, v. 9, p. 387–388.

Goodknight, C. S., 1973, Structure and stratigraphy of the central Cimarron Range, Colfax County, New Mexico: Unpublished MS thesis, University of New Mexico, 85 p.

Goodknight, C. S., 1976, Cenozoic structural geology of the central Cimarron Range, New Mexico; *in* Ewing, R. C., and Kues, B. S., (eds.), Vermejo Park, northeastern New Mexico: New Mexico Geological Society, Guidebook 27, p. 137–140.

Gordon, C. H., 1907, Notes on the Pennsylvanian formations in the Rio Grande Valley: Journal of Geology, v. 15, p. 805–816.

Grambling, J. A., and Codding, D. B., 1982, Stratigraphic and structural relationships of multiply deformed Precambrian metamorphic rocks of the Rio Mora area, New Mexico: Geological Society of America Bulletin, v. 93, p. 127–137.

Griggs, R. L., 1964, Geology and ground-water resources of the Los Alamos area, New Mexico: U.S. Geological Survey, Water–Supply Paper 1753, 107 p.

Gruner, J. W., 1920, Geologic reconnaissance of the southern part of the Taos Range, New Mexico: Journal of Geology, v. 28, p. 731–742.

Handford, C. R., and Dutton, S. P., 1980, Pennsylvanian–Early Permian depositional systems and shelf-margin evolution, Palo Duro Basin, Texas: American Association of Petroleum Geologists Bulletin, v. 64, p. 88–106.

Harbour, R. L., 1970, The Hondo Sandstone Member of the San Andres Limestone of south-central New Mexico: U.S. Geological Survey, Professional Paper 700-C, p. C175–C182.

Hayes, P. T., 1957, Possible igneous origin of Turkey Mountain dome, Mora County, New Mexico: American Association of Petroleum Geologists Bulletin, v. 41, p. 953–956.

Hayes, P. T., 1964, Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey, Professional Paper 446, 69 p.

Henbest, L. G., 1946a, Correlation of the marine Pennsylvanian rocks of northern New Mexico and western Colorado [abs.]: Washington Academy of Science Journal, v. 36, p. 134.

Henbest, L. G., 1946b, Stratigraphy of the Pennsylvanian in the west half of Colorado and in adjacent parts of New Mexico and Utah [abs.]: American Association of Petroleum Geologists Bulletin, v. 30, p. 750–751.

Herrick, C. L., 1900, The geology of the White Sands of New Mexico: Journal of Geology, v. 15, p. 805–816.

Heyman, O. G., 1983, Distribution and structural geometry of faults and folds along the northwestern Uncompahgre uplift, western Colorado and Utah; *in* Averett, W. R., (ed.), Northern Paradox Basin–Uncompahgre uplift: Grand Junction Geological Society, 1983 Field Trip, p. 45–57.

Hills, R. C., 1899, Description of the El Moro quadrangle (Colorado): U.S. Geological Survey, Atlas, Folio 58.

Houle, J. A., 1980, Depositional systems, sandstone genesis, and cobble study in the lower Pennsylvanian Taos trough, northern New Mexico: Unpublished MS thesis, University of Texas (Austin), 128 p.

Johnson, H. D., 1979, Chapter 9, Shallow siliciclastic seas; *in* Reading, H. D., (ed.), Sedimentary environments and facies: Elsevier, New York, p. 207–258.

Johnson, J. H., 1929, Contributions to the geology of the Sangre de Cristo Mountains of Colorado: Colorado Scientific Society Proceedings, v. 12, no. 1, 21 p.

Johnson, R. B., 1959, Geology of the Huerfano Park area, Huerfano and Custer Counties, Colorado: U.S. Geological Survey, Bulletin 1071–D, p. D87–D119.

Johnson, R. B., 1969, Geologic map of the Trinidad quadrangle, south-central Colorado: U.S. Geological Survey, Miscellaneous Investigations Map I–558, scale 1:250,000.

Johnson, R. B., 1970, Geologic map of the Villanueva quadrangle, San Miguel County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ–869, scale 1:62,500.

Johnson, R. B., 1972, Geologic map of the North San Ysidro quadrangle, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ–1007, scale 1:24,000.

Johnson, R. B., 1973, Geologic map of the Pecos quadrangle, San Miguel and Santa Fe Counties, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ–1110, scale 1:24,000.

Johnson, R. B., 1974, Geologic map of the Apache Springs quadrangle, San Miguel County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ–1163, scale 1:62,500.

Johnson, R. B., 1975, Geologic map of the Rainsville quadrangle, Mora County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ–1276, scale 1:24,000.

Johnson, R. B., and Baltz, E. H., 1960, Probable Triassic rocks along eastern front of Sangre de Cristo Mountains, south-central Colorado: American Association of Petroleum Geologists Bulletin, v. 44, p. 1895–1902.

Johnson, R. B., Dixon, G. H., and Wanek, A. A., 1956, Late Cretaceous and Tertiary stratigraphy of the Raton Basin of New Mexico and Colorado; *in* Rosenzweig, A., (ed.), Southeastern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, Guidebook 7, p. 122–133.

Johnson, R. B., and Wood, G. H., Jr., 1956, Stratigraphy of Upper Cretaceous and Tertiary rocks of Raton Basin, Colorado and New Mexico: American Association of Petroleum Geologists Bulletin, v. 40, p. 701–721.

Just, E., 1937, Geology and economic features of the pegmatites of Taos and Rio Arriba Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 13, 73 p.

Keller, G. R., and Cordell, L., 1983, Bouguer gravity anomaly map of

New Mexico; *in* Geothermal Resources, of New Mexico: National Oceanic and Atmospheric Administration Scientific Map Series, scale 1:500,000.

Keller, G. R., Cordell, L., Davis, G. H., Peeples, W. J., and White, G., 1984, A geophysical study of the San Luis Basin; *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., (eds.), Rio Grande rift, northern New Mexico: New Mexico Geological Society, Guidebook 35, p. 51–57.

Kelley, V. C., 1955, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: University of New Mexico Publications in Geology, no. 5, 120 p.

Kelley, V. C., and Northrop, S. A., 1975, Geology of Sandia Mountains and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 29, 135 p.

Keyes, C. R., 1903, Geological sketches of New Mexico: Ores and Metals, v. 12, p. 48.

King, P. B., 1951, The tectonics of middle North America: Princeton University Press, 203 p.

Kluth, C. F., 1986, Plate tectonics of the Ancestral Rocky Mountains; *in* Peterson, J. A., (ed.), Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 353–369.

Kluth, C. F., and Coney, P. J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10–15.

Konishi, Kenji, and Wray, J. L., 1961, *Eugonophyllum*, a new Pennsylvanian and Permian algal genus: Journal of Paleontology, v. 35, p. 659–665.

Kottlowski, F. E., 1961, Pennsylvanian rocks in north-central New Mexico; *in* Northrop, S. A., (ed.), Albuquerque country: New Mexico Geological Society, Guidebook 12, 1961, p. 97–103.

Kottlowski, F. E., 1963a, Paleozoic and Mesozoic strata of southwestern and south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 79, 100 p.

Kottlowski, F. E., 1963b, Pennsylvanian rocks; *in* Spiegel, Zane, and Baldwin, Brewster, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey, Water-Supply Paper 1525, p. 28–32.

Kottlowski, F. E., 1975, Stratigraphy of the San Andres Mountains in south-central New Mexico; *in* Seager, W. R., Clemons, R. E., and Callender, J. F., (eds.), Las Cruces country: New Mexico Geological Society, Guidebook 26, p. 95–104.

Kottlowski, F. E., and Stewart, W. J., 1970, The Wolfcampian Joyita uplift in central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 23, 82 p.

Krisle, J. E., 1959, General geology of the Tucumcari Basin of northeastern New Mexico; *in* Thalman, A. L., (ed.), Southern Sangre de Cristo Mountains, New Mexico: Panhandle (Texas) Geological Society, 1959 Field Conference, p. 1–18. [Includes unnumbered plates showing lines of correlated well logs, isopach map of Pennsylvanian–Permian rocks, and structure-contour map of top of Precambrian rocks.]

Landis, E. R., and Dane, C. H., 1967, Geologic map of the Tierra Amarilla quadrangle, Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 19, 16 p., scale 1:62,500.

Lee, W. T., 1909, Stratigraphy of the Manzano Group; *in* Lee, W. T., and Girty, G. H., 1909, The Manzano Group of the Rio Grande Valley, New Mexico: U.S. Geological Survey, Bulletin 389, 141 p.

Lee, W. T., and Knowlton, F. H., 1917, Geology and paleontology of the Raton Mesa and other regions in Colorado and New Mexico: U.S. Geological Survey, Professional Paper 101, p. 9–221.

Lessard, R. H., 1976, First day, roadlog from Las Vegas to Raton via Montezuma, Sapello, La Cueva (and vicinity), Ocate, Wagon Mound, and Springer; *in* Ewing, R. C., and Kues, B. S., (eds.), Vermejo Park, northeastern New Mexico: New Mexico Geological Society, Guidebook 27, p. 1–23.

Lessard, R. H., and Bejnar, W., 1976, Geology of the Las Vegas area; *in* Ewing, R. C., and Kues, B. S., (eds.), Vermejo Park, northeastern New Mexico: New Mexico Geological Society, Guidebook 27, p. 103–108.

Lindgren, W., Graton, L. C., and Gordon, C. H., 1910, The ore deposits of New Mexico: U.S. Geological Survey, Professional Paper 68, 361 p.

Lindsey, D. A., Clark, R. F., and Soulliere, S. J., 1986, Minturn and Sangre de Cristo Formations of southern Colorado—A prograding fan-delta and alluvial-fan sequence shed from the ancestral Rocky Mountains; *in* Peterson, J. A., (ed.), Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists, Memoir 41, p. 541–561.

Lindsey, D. A., Johnson, B. R., and Andriesen, P. A. M., 1983, Laramide and Neogene structure of the northern Sangre de Cristo Range, south-central Colorado; *in* Lowell, J. D., and Gries, R., (eds.), Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists, 1983 conference, p. 219–228.

Lindsey, D. A., and Schafer, R. A., 1984, Principal reference section for the Sangre de Cristo Formation (Pennsylvanian and Permian), northern Sangre de Cristo Range, Saguache County, Colorado: U.S. Geological Survey, Miscellaneous Field Investigations Map MF–1622–A.

Lipman, P. W., and Reed, J. C., Jr., 1984, Second-day road log from Taos to Hondo Canyon, Questa, Red River, Amalia, and back to Taos; *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., (eds.), Rio Grande rift, northern New Mexico: New Mexico Geological Society, Guidebook 35, p. 321–347.

Lisenbee, A. L., Woodward, L. A., and Connolly, J. R., 1979, Tijeras–Cañoncito fault system—A major zone of recurrent movement in north-central New Mexico; *in* Ingersoll, R. V., Woodward, L. A., and James, H. L., (eds.), Santa Fe country: New Mexico Geological Society, Guidebook 30, p. 89–99.

Loleit, A. J., 1963, Cambrian stratigraphic problems of the Four Corners area; *in* Bass, R. O., and Sharps, S. L., (eds.), Shelf carbonates of the Paradox Basin—A symposium: Four Corners Geological Society, 4th Field Conference, p. 21–30.

Long, P. E., 1974, Contrasting types of Precambrian granitic rocks in the Dixon–Peñasco area, northern New Mexico; *in* Siemers, C. T., Woodward, L. A., and Callender, J. F., (eds.), Ghost Ranch, central-northern New Mexico: New Mexico Geological Society, Guidebook 25, p. 101–108.

MacLachlan, M. E., 1967, Oklahoma, Chapter E; *in* Paleotectonic investigations of the Permian System in the United States: U.S. Geological Survey, Professional Paper 515–E, p. 81–92.

MacLachlan, M. E., 1972, Triassic System; *in* Mallory, W. W., (ed.), Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 166–176.

Maher, J. C., and Collins, J. B., 1949, Pre-Pennsylvanian geology of southwestern Kansas, southeastern Colorado, and the Oklahoma Panhandle: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 101, 4 sheets.

Mallory, W. W., 1960, Outline of Pennsylvanian stratigraphy of Colorado; *in* Guide to Geology of Colorado: Rocky Mountain Association of Geologists, p. 23–33.

Mallory, W. W., 1972a, Regional synthesis of the Pennsylvanian system; *in* Mallory, W. W., (ed.), Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 111–127.

Mallory, W. W., 1972b, Pennsylvanian arkose and the ancestral Rocky Mountains; *in* Mallory, W. W., (ed.), Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 131–132.

Mallory, W. W., 1975, Middle and southern Rocky Mountains, northern Colorado Plateau, and eastern Great Basin region; *in* Paleotectonic investigations of the Pennsylvanian System in the United States; Part 1, Introduction and regional analyses of the Pennsylvanian System: U.S. Geological Survey, Professional Paper 853, p. 265–278.

Manley, K., Scott, G. R., and Wobus, R. A., 1978, Preliminary geologic map of the Aztec 1° x 2° quadrangle, northwestern New Mexico: U.S. Geological Survey, Open-File Report 78–466, 7 p., scale 1:250,000.

Mapel, W. J., Johnson, R. B., Bachman, G. O., and Varnes, K. L., 1979, Southern Midcontinent and southern Rocky Mountains region;

in Paleotectonic investigations of the Mississippian System in the United States—Part 1, Introduction and regional analyses of the Mississippian System: U.S. Geological Survey, Professional Paper 1010, p. 161–187.

May, R. T., Strand, J. R., Reid, B. E., and Phillips, W. R., 1977, Preliminary study of favorability for uranium of the Sangre de Cristo Formation in the Las Vegas Basin, northeastern New Mexico: Bendix Field Engineering Corporation report GJBX–82 (77), Grand Junction, Colorado, 46 p. [Issued by U.S. Department of Energy.]

May, S. J., 1984, Miocene stratigraphic relations and problems between the Abiquiu, Los Pinos, and Tesuque Formations near Ojo Caliente, northern Española Basin; *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., (eds.), Rio Grande rift, northern New Mexico: New Mexico Geological Society, Guidebook 35, p. 129–135.

McBryde, J. C., 1979, Pennsylvanian (middle Desmoinesian) coarse-grained fluvial and fluvial-deltaic deposits, Taos trough, north-central New Mexico: Unpublished MS thesis, University of Texas (Austin), 140 p.

McKee, E. D., and Crosby, E. J., coordinators, 1975, Paleotectonic investigations of the Pennsylvanian System in the United States; Part 1, Introduction and regional analyses of the Pennsylvanian System, Chapters A through R: U.S. Geological Survey, Professional Paper 853, 349 p.

McKinlay, P. F., 1956, Geology of Costilla and Latir Peak quadrangles, Taos County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 42, 32 p.

Melton, F. A., 1925a, The ancestral Rocky Mountains of Colorado and New Mexico: Journal of Geology, v. 33, p. 84–89.

Melton, F. A., 1925b, Correlation of Permo–Carboniferous beds of southeast Colorado and northern New Mexico: Journal of Geology, v. 33, p. 807–814.

Miller, J. P., Montgomery, A., and Sutherland, P. K., 1963, Geology of part of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 11, 106 p.

Moench, R. H., and Robertson, J. M., 1980, Geology of the Pecos Wilderness and adjacent areas, Santa Fe, San Miguel, Mora, Rio Arriba, and Taos Counties, New Mexico: U.S. Geological Survey, Open-file Report 80–382, Chapter A, p. 6–41.

Montgomery, A., 1953, Precambrian geology of the Picuris Range, north-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 30, 81 p.

Montgomery, A., 1963, Precambrian rocks; *in* Miller, J. P., Montgomery, Arthur, and Sutherland, P. K., 1963, Geology of part of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 11, p. 7–21.

Muehlburger, W. R., 1967, Geology of Chama quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 89, 114 p.

Myers, D. A., 1960, Stratigraphic distribution of some Pennsylvanian *Fusulinidae* from Brown and Coleman Counties, Texas: U.S. Geological Survey, Professional Paper 315–C, p. C37–C53.

Myers, D. A., 1969, Geologic map of the Escabosa quadrangle, Bernalillo County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ–795, scale 1:24,000.

Myers, D. A., 1973, The upper Paleozoic Madera Group in the Manzano Mountains, New Mexico: U.S. Geological Survey, Bulletin 1372–F, p. F1–F13.

Myers, D. A., 1982, Stratigraphic summary of Pennsylvanian and Lower Permian rocks, Manzano Mountains, New Mexico; *in* Wells, S. G., Grambling, J. A., and Callender, J. F., (eds.), Albuquerque country II: New Mexico Geological Society, Guidebook 33, p. 233–237.

Myers, D. A., 1988a, Stratigraphic distribution of some fusulinids from the Sandia Formation and the Los Moyos Limestone, Manzano Mountains, New Mexico: U.S. Geological Survey, Professional Paper 1446–A, p. 1–21.

Myers, D. A., 1988b, Stratigraphic distribution of some fusulinids from the Wild Cow and Bursum Formations, Manzano Mountains, New Mexico: U.S. Geological Survey, Professional Paper 1446–B, p. 23–65.

Myers, D. A., and McKay, E. J., 1976, Geologic map of the north end of the Manzano Mountains, Tijeras and Sedillo quadrangles, Bernalillo County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I–968, scale 1:24,000.

Myers, D. A., Sharps, J. A., and McKay, E. J., 1986, Geologic map of the Becker SW and Cerro Montoso quadrangles, Socorro County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I–1567, scale 1:24,000.

Needham, C. E., 1937, Some New Mexico *Fusulinidae*: New Mexico Bureau of Mines and Mineral Resources, Bulletin 14, 88 p.

Needham, C. E., and Bates, R. L., 1943, Permian type sections in central New Mexico: Geological Society of America Bulletin, v. 54, p. 1653–1668.

Newberry, J. S., 1876, Geological report; *in* Macomb, J. N., Report of the exploring expedition from Santa Fe, New Mexico, to the junction of the Grand and Green Rivers of the Great Colorado of the West in 1859: Washington, D.C., U.S. Army Engineers Department, p. 9–118.

New Mexico Geological Society, 1982, Deal, E. G., Elston, W. E., Kelley, V. C., Seager, W. R., and Woodward, L. A., compilers, New Mexico highway geologic map: New Mexico Geological Society in cooperation with New Mexico Bureau of Mines and Mineral Resources, scale 1:1,000,000.

Nicholson, J. H., 1960, Geology of Texas Panhandle; *in* Aspects of the geology of Texas, a symposium: University of Texas, Bureau of Economic Geology, Publication 6017, p. 51–64.

Northrop, S. A., Sullwold, H. H., Jr., MacAlpin, A. J., and Rogers, C. P., Jr., 1946, Geologic map of a part of the Las Vegas Basin and of the foothills of the Sangre de Cristo Mountains, San Miguel and Mora Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 54, scales 1:250,000 and 1:42,240.

O'Neill, J. M., 1990, Precambrian rocks of the Mora–Rociada area, southern Sangre de Cristo Mountains, New Mexico, *in* Bauer, P. W., Lucas, S. G., Mawer, C. K., and McIntosh, W. C., (eds.), Tectonic development of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, Guidebook 41, p. 189–199.

O'Neill, J. M., and Mehnert, H. H., 1988, Petrology and physiographic evolution of the Ocate volcanic field, north-central New Mexico: U.S. Geological Survey, Professional Paper 1478–A and B, 49 p.

Parker, J. W., and Roberts, J. W., 1963, Devonian and Mississippian stratigraphy of the central part of the Colorado Plateau; *in* Bass, R. O., and Sharps, S. L., (eds.), Shelf carbonates of the Paradox Basin—A symposium: Four Corners Geological Society, 4th Field Conference, p. 31–60.

Pillmore, C. L., and Laurie, C. O., 1976, Second day, road log from Raton to Underwood Lakes through the Raton coal field via the York Canyon Mine, Vermejo Park, and Gold Creek; *in* Ewing, R. C., and Kues, B. S., (eds.), Vermejo Park, northeastern New Mexico: New Mexico Geological Society, Guidebook 27, p. 25–47.

Plummer, F. B., and Moore, R. C., 1921, Stratigraphy of the Pennsylvanian formations of north-central Texas: Texas University Bulletin 2132, 237 p.

Ray, L. L., and Smith, J. F., Jr., 1941, Geology of the Moreno Valley, New Mexico: Geological Society of America Bulletin, v. 52, p. 177–210.

Read, C. B., and Mamay, S. H., 1964, Upper Paleozoic floral zones and floral provinces of the United States: U.S. Geological Survey, Professional Paper 454–K, 35 p.

Read, C. B., Wilpolt, R. H., Andrews, D. A., Summerson, C. H., and Wood, G. H., Jr., 1944, Geologic map and stratigraphic sections of Permian and Pennsylvanian rocks of parts of San Miguel, Santa Fe, Sandoval, Bernalillo, Torrance, and Valencia Counties, north-central New Mexico: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 21, scale approximately 1:187,700.

Read, C. B., and Wood, G. H., Jr., 1947, Distribution and correlation of Pennsylvanian rocks in late Paleozoic sedimentary basins of northern New Mexico: Journal of Geology, v. 55, p. 220–236.

Reed, J. C., Jr., Lipman, P. W., and Robertson, J. R., 1983, Geologic map of the Latir Peak and Wheeler Peak Wildernesses and Columbine–Hondo Wilderness study area, Taos County, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map MF–1570–B, scale 1:50,000.

Register, M. A., and Brookins, D. G., 1979, Geochronologic and rare-earth study of the Embudo Granite and related rocks; *in* Ingersoll, R. V., Woodward, L. A., and James, H. L., (eds.), Santa Fe country: New Mexico Geological Society, Guidebook 30, p. 155–158.

Roberts, J. W., Barnes, J. J., and Wacker, H. J., 1976, Subsurface Paleozoic stratigraphy of the northeastern New Mexico basin and arch complex; *in* Ewing, R. C., and Kues, B. S., (eds.), Vermejo Park, northeastern New Mexico: New Mexico Geological Society, Guidebook 27, p. 141–152.

Robertson, J. M., and Moench, R. H., 1979, The Pecos greenstone belt; a Proterozoic volcano-sedimentary sequence in the southern Sangre de Cristo Mountains, New Mexico; *in* Ingersoll, R. V., Woodward, L. A., and James, H. L., (eds.), Santa Fe country: New Mexico Geological Society, Guidebook 30, p. 165–173.

Robinson, G. D., Wanek, A. A., Hays, W. H., and McCallum, M. E., 1964, Philmont country; the rocks and landscape of a famous New Mexico ranch: U.S. Geological Survey, Professional Paper 505, 152 p.

Ross, C. A., 1965, Late Pennsylvanian *Fusulinidae* from the Gaptank Formation, west Texas: Journal of Paleontology, v. 39, p. 1151–1176, plates. 141–145.

Ross, C. A., and Sabins, F. F., 1965, Early and Middle Pennsylvanian fusulinids from southeast Arizona: Journal of Paleontology, v. 39, p. 173–209.

Ross, C. A., and Tyrrell, W. W., Jr., 1965, Pennsylvanian and Permian fusulinids from the Whetstone Mountains, southeast Arizona: Journal of Paleontology, v. 39, p. 615–635, plates. 75–78.

Ross, R. J., and Tweto, O., 1980, Lower Paleozoic sediments and tectonics in Colorado; *in* Kent, H. C., and Porter, K. W., (eds.), Colorado Geology: Rocky Mountain Association of Geologists, 1980 Symposium, p. 47–56.

Roth, R. I., and Skinner, J. W., 1930, The fauna of the McCoy Formation, Pennsylvanian, of Colorado: Journal of Paleontology, v. 4, p. 332–352.

Sales, J. K., 1968, Crustal mechanics of Cordilleran foreland deformation, a regional and scale-model approach: American Association of Petroleum Geologists Bulletin, v. 52, p. 2016–2044.

Schowalter, T. T., 1969, Geology of part of the Creston Range, Mora County, New Mexico: Unpublished MS thesis, University of New Mexico, 84 p.

Simms, R. W., 1965, Geology of the Rayado area, Colfax County, New Mexico: Unpublished MS thesis, University of New Mexico, 90 p.

Skinner, J. W., 1946, Correlation of Permian of west Texas and southeast New Mexico: American Association of Petroleum Geologists Bulletin, v. 30, p. 1857–1874.

Skinner, J. W., and Wilde, G. I., 1965, Lower Permian (Wolfcampian) fusulinids from the Big Hatchet Mountains, southwestern New Mexico: Cushman Foundation for Foraminiferal Research, Contributions, v. 16, p. 95–104.

Smith, C. T., Budding, A. J., and Pitrat, C. W., 1961, Geology of the southeastern part of the Chama Basin: New Mexico Bureau of Mines and Mineral Resources, Bulletin 75, 57 p.

Smith, C. T., and Colpitts, R. M., 1980, Geology of Cieneguilla Creek drainage basin in southwest Colfax County, New Mexico: New Mexico Geology, v. 2, p. 1–15.

Smith, C. T., and Muehlburger, W. R., 1960, Geologic map of the Rio Chama country; *in* Beaumont, E. C., and Read, C. B., (eds.), Rio Chama country: New Mexico Geological Society, Guidebook 11, scale 1:250,000.

Smith, H. T. U., 1938, Tertiary geology of the Abiquiu quadrangle, New Mexico: Journal of Geology, v. 46, p. 933–965.

Smith, J. F., Jr., and Ray, L. L., 1943, Geology of the Cimarron Range, New Mexico: Geological Society of America Bulletin, v. 54, p. 891–924.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I 571, scale 1:125,000.

Speer, W. R., 1976, Oil and gas exploration in the Raton Basin; *in* Ewing, R. C., and Kues, B. S., (eds.), Vermejo Park, northeastern New Mexico: New Mexico Geological Society, Guidebook 27, p. 217–226.

Spiegel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey, Water–Supply Paper 1525, 258 p.

Stearns, C. E., 1953, Tertiary geology of the Galisteo–Tonque area, New Mexico: Geological Society of America Bulletin, v. 64, p. 459–508.

Stevenson, J. J., 1881, Report upon geological examinations in southern Colorado and northern New Mexico during the years 1878 and 1879, with an appendix upon the Carboniferous invertebrate fossils of New Mexico by C. A. White: United States Geographical Surveys West of the One Hundredth Meridian (Wheeler Survey), v. III, Supplement, Geology, 420 p., 38 p. appendix.

Stevenson, G. M., and Baars, D. L., 1986, The Paradox, a pull-apart basin of Pennsylvanian age; *in* Peterson, J. A., (ed.), Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists, Memoir 41, p. 513–539.

Stewart, W. J., 1958, Some fusulinids from the upper Strawn, Pennsylvanian, of Texas: Journal of Paleontology, v. 32, p. 1051–1070.

Stewart, W. J., 1970, Fusulinids of the Joyita Hills, Socorro County, central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 23, pt. 2, p. 34–80, plates 1–10.

Stone, D. S., 1977, Tectonic history of the Uncompahgre uplift; *in* Veal, H. K., (ed.), Exploration frontiers of the Central and Southern Rockies: Rocky Mountain Association of Geologists, 1977 Symposium, p. 23–30.

Sutherland, P. K., 1963, Paleozoic rocks; *in* Miller, J. P., Montgomery, A., and Sutherland, P. K., 1963, Geology of part of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 11, p. 22–46.

Sutherland, P. K., 1972, Pennsylvanian stratigraphy, southern Sangre de Cristo Mountains, New Mexico; *in* Mallory, W. W., (ed.), Geologic atlas of the Rocky Mountains: Rocky Mountain Association of Geologists, p. 139–142.

Sutherland, P. K., and Harlow, F. H., 1973, Pennsylvanian brachiopods and biostratigraphy in southern Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 27, 173 p.

Thompson, M. L., 1934, The fusulinids of the Des Moines Series of Iowa: Iowa University Studies in Natural History, v. 16, p. 277–322, plates 20–23.

Thompson, M. L., 1936, Pennsylvanian fusulinids from Ohio: Journal of Paleontology, v. 10, p. 673–683, plates 90, 91.

Thompson, M. L., 1942, Pennsylvanian System in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 17, 90 p.

Thompson, M. L., 1945, Pennsylvanian rocks and fusulinids of east Utah and northwest Colorado correlated with Kansas section: Kansas Geological Survey, Bulletin 60, part 2, p. 17–84.

Thompson, M. L., 1948, Studies of American fusulinids: Kansas University Paleontological Contributions, Article 1, 184 p.

Thompson, M. L., 1954, American Wolfcampian fusulinids: Kansas University Paleontologic Contributions, no. 4, Protozoa, article 5, 226 p.

Thompson, M. L., 1957, Northern midcontinent Missourian fusulinids: Journal of Paleontology, v. 31, p. 289–328.

Thompson, M. L., and Thomas, H. D., 1953, Fusulinids of the Casper Formation of Wyoming, Part II, Systematic paleontology of fusulinids from the Casper Formation: Geological Survey, of Wyoming, Bulletin 46, p. 15–56.

Thompson, M. L., Verville, G. J., and Bissell, H. J., 1950, Pennsylvanian fusulinids of the south-central Wasatch Mountains, Utah: Journal of Paleontology, v. 24, p. 430–465.

Toomey, D. F., 1980, History of a late Carboniferous phylloid algal bank complex in northeastern New Mexico: Lethaia, v. 13, p. 249–267.

Tschanz, C. M., Laub, D. C., and Fuller, G. W., 1958, Copper and uranium deposits of the Coyote district, Mora County, New Mexico: U.S Geological Survey, Bulletin 1030–L, p. 343–398.

Tweto, O., 1975, Laramide (Late Cretaceous–early Tertiary) orogeny in the Southern Rocky Mountains: Geological Society of America, Memoir 144, p. 1-44.

Tweto, O., 1977, Tectonic history of west-central Colorado; *in* Veal, H. K., (ed.), Exploration frontiers of the Central and Southern Rockies: Rocky Mountain Association of Geologists, 1977 Symposium, p. 11–22.

Tweto, O., 1979a, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000.

Tweto, O., 1979b, The Rio Grande rift system in Colorado; *in* Riecker, R. E. , (ed.), Rio Grande rift; tectonics and magmatism: American Geophysical Union, p. 33–56.

Tweto, O., 1980a, Tectonic history of Colorado; *in* Kent, H. C., and Porter, K. W., (eds.), Colorado Geology: Rocky Mountain Association of Geologists, 1980 Symposium, p. 5–9.

Tweto, O., 1980b, Precambrian geology of Colorado; *in* Kent, H. C., and Porter, K. W., (eds.), Colorado Geology: Rocky Mountain Association of Geologists, 1980 Symposium, p. 37-46.

Tweto, O., 1983, Geologic sections across Colorado: U.S. Geological Survey, Miscellaneous Investigations Map I–1416, scale 1:500,000.

Tweto, O., Moench, R. H., and Reed, J. C., Jr., 1978, Geologic map of the Leadville 1° x 2° quadrangle, northwestern Colorado: U.S. Geological Survey, Miscellaneous Investigations Map I–999, scale 1:250,000.

Ulmer, D. S., and Laury, R. L., 1984, Diagenesis of the Mississippian Arroyo Peñasco Group, north-central New Mexico; *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., (eds.), Rio Grande rift, northern New Mexico: New Mexico Geological Society, Guidebook 35, p. 91–100.

Upson, J. E., 1941, The Vallejo formation; new early Tertiary red-beds in southern Colorado: American Journal of Science, v.239, p. 577–589.

Walper, J. L., 1970, Wrench faulting in the mid-continent: Shale Shaker, Oklahoma City Geological Society, v. 21, no. 2, p. 32–40.

Wanek, A. A., 1963, Geology and fuel resources of the southwestern part of the Raton coal field, Colfax County, New Mexico: U.S. Geological Survey, Coal Investigations Map C–45, 2 sheets, scale 1:48,000.

Wanek, A. A., and Read, C. B., 1956, Third day, Taos to Eagle Nest and Elizabethtown, resumé of geology; *in* Rosenzweig, A., (ed.), Southeastern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, Guidebook 7, p. 82–87.

Wanek, A. A., Read, C. B., Robinson, G. D., Hays, W. H., and McCallum, M. E., 1964, Geologic map and sections of the Philmont Ranch region, New Mexico: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I-425, scale 1:24,000.

Wanless, H. R., and Patterson, J., 1951, Cyclic sedimentation in the marine Pennsylvanian of the southwestern United States: Extrait du Compte Rendue, 3rd Congress on Carboniferous Stratigraphy and Geology, Heerlen, p. 655–664.

Warner, L. A., 1983, Comment on plate tectonics of the Ancestral Rocky Mountains: Geology, v. 11, p. 120–121.

White, C. A., 1881, Report on the Carboniferous invertebrate fossils of New Mexico, Appendix; *in* Stevenson, J. J., 1881, Report on geological examinations in southern Colorado and northern New Mexico, during the years 1878 and 1879: U.S. Geographical Surveys West of the One Hundredth Meridian (Wheeler Survey), v. 3 Supplement, Geology.

White, M. A., and Jacobson, M. I., 1983, Structures associated with the southwest margin of the ancestral Uncompahgre uplift; *in* Averett, W. R., (ed.), Northern Paradox Basin–Uncompahgre uplift: Grand Junction Geological Society, 1983 Field trip, p. 33–39.

Wickham, J. S., 1978a, The southern Oklahoma aulacogen; *in* Structural style of the Arbuckle region: Geological Society of America, South-central Section Field Trip no. 3, p. 8-41.

Wickham, J. S., 1978b, Ouachita fold belt, a Paleozoic continental margin; *in* Structural style of the Arbuckle region: Geological Society of America, South-central Section Field Trip no. 3, p. 47–64.

Wobus, R. A., 1984, An overview of the Precambrian geology of the Tusas Range, north-central New Mexico; *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., (eds.), Rio Grande rift, northern New Mexico: New Mexico Geological Society, Guidebook 35, p. 193–198.

Wood, G. H., Jr., and Northrop, S. A., 1946, Geology of the Nacimiento Mountains, San Pedro Mountain, and adjacent plateaus in parts of Sandoval and Rio Arriba Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 57, scale 1:96,000.

Young, J. A., Jr., 1945, Paleontology and stratigraphy of the Pennsylvanian strata near Taos, New Mexico: Cambridge, Mass., Unpublished PhD dissertation, Harvard University, 314 p.

Zeller, H. D., and Baltz, E. H., 1954, Uranium-bearing copper deposits in the Coyote district, Mora County, New Mexico: U.S. Geological Survey, Circular 334, 11 p.

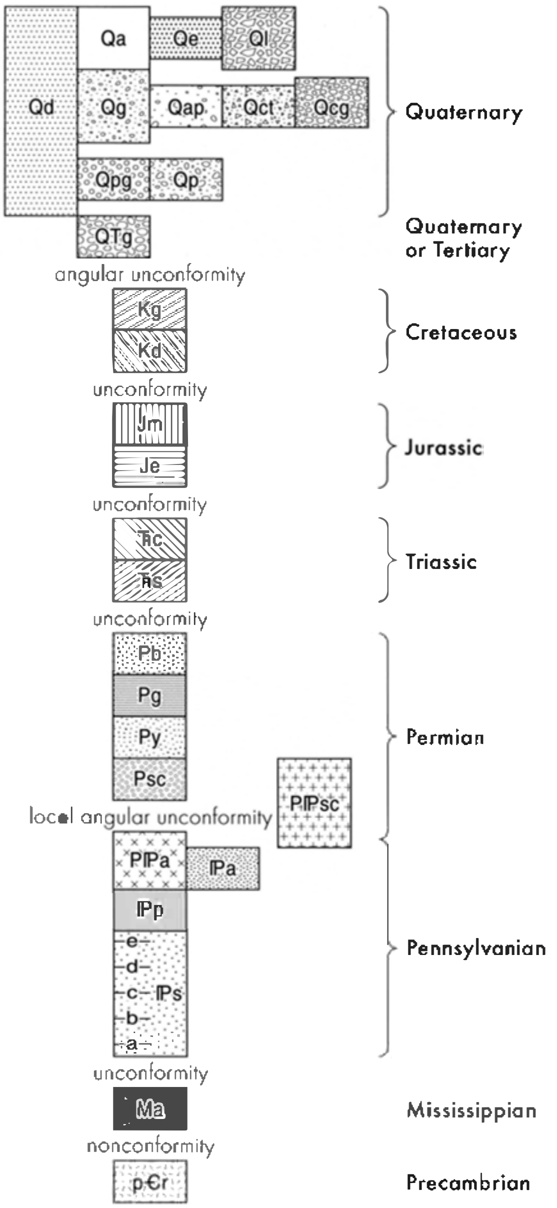
Appendix I

Maps of localities of some stratigraphic sections

Appendix I

Maps of localities of some stratigraphic sections

CORRELATION OF UNITS



DESCRIPTION OF UNITS

- **Qd** — **Alluvial fan and slope-wash deposits**
- **Qa** — **Alluvium in valleys**
- **Qe** — **Eolian deposits**
- **Ql** — **Landslides**—Deposits of chaotically slumped blocks
- **Qg** — **Stream-terrace gravel**
- **Qap** — **Alluvium on low-level pediment**
- **Qct** — **Colluvium and talus on slopes**
- **Qcg** — **Colluvial gravel**—On slopes below and adjacent to older gravel deposits
- **Qpg** — **Pediment gravel**—On remnants of intermediate-level pediments
- **Qp** — **Alluvium on remnant of intermediate-level pediment**
- **QTg** — **Pediment gravel (Quaternary or Tertiary)**—On remnants of high-level pediment
- **Kg** — **Graneros Shale (Upper Cretaceous)**
- **Kd** — **Dakota Sandstone (Lower? and Lower Cretaceous)**
- **Jm** — **Morrison Formation (Upper Jurassic)**
- **Je** — **Entrada Sandstone (Middle Jurassic)**
- **TRc** — **Chinle Formation(Upper Triassic)**
- **TRs** — **Santa Rosa Sandstone (Upper Triassic)**
- **Pb** — **Bernal Formation (Permian)**
- **Pg** — **Glorieta Sandstone (Lower Permian)**
- **Py** — **Yeso Formation (Lower Permian)**
- **Psc** — **Sangre de Cristo Formation (Lower Permian)**—South of Rito Cebolla
- **PIPsc** — **Sangre de Cristo Formation (Lower Permian and Upper Pennsylvanian)**—North of Rito Cebolla
- **PIPa** — **Alamitos Formation (Lower Permian and Pennsylvanian)**—South of vicinity of Gallinas Creek
- **IPa** — **Alamitos Formation (Upper and Middle Pennsylvanian)**—North of vicinity of Gallinas Creek
- **IPp** — **Porvenir Formation (Middle Pennsylvanian)**
- **IPs** — **Sandia Formation (Middle and Lower Pennsylvanian)**—Contacts –a– to –e– are bases of ledge-forming sandstone mapped only north of Mora River
- **Ma** — **Arroyo Peñasco Group (Upper and Lower Mississippian)**—Tererro and Espiritu Santo Formations
- **p€r** — **Precambrian rocks, undivided (Proterozoic)**—Igneous intrusive, metavolcanic, and metasedimentary rocks

FIGURE 80—Explanation for geologic maps (Figs. 81–89) that show localities of some measured sections of Pennsylvanian and Lower Permian rocks, southeastern Sangre de Cristo Mountains.

MAP SYMBOLS

Contacts, faults, anticlines, and synclines are shown by solid lines where accurately located, dashed lines where approximately located, dotted lines where concealed, and question marks where probable

Contact

Normal fault—Bar and ball on downthrown side

(R) **Normal fault inferred to be superposed on older reverse fault**—Bar and ball on downthrown side of normal fault; (R) on upthrown side of reverse fault

Normal fault inferred to be superposed on older strike-slip fault—Strike-slip fault: , relative horizontal movement

High-angle strike-slip fault—Arrows indicate horizontal movement

Reverse fault—Blocks on upthrown side; dip inferred to be steeper than 45° at depth of exposure

Thrust fault—Triangles on overthrust block; dip known or inferred to be less than 45° at depth of exposure

Anticline—Showing crestline and direction of plunge

A **Anticlinal bend**—Showing axis and steepest limb

Syncline—Showing troughline and direction of plunge

Syncline with overturned limb—Showing troughline

S **Synclinal bend**—Showing axis and steepest limb

Strike and dip of beds

⊕	Horizontal
27	Inclined
90	Vertical
68	Overturned
f10137 ×	**Locality of fusulinid collection**—Showing USGS number
27501–PC ×	**Locality of megafossil collection**—Showing USGS number
BM7701 ×	**Locality of megafossil collection**—Showing field number
C	**Line of stratigraphic section**—Letter indicates section described at end of report
6	**Line of stratigraphic section**—Number indicates graphic section only in this report
×××××××××××	**Correlative bed traced between parts of composite stratigraphic section**

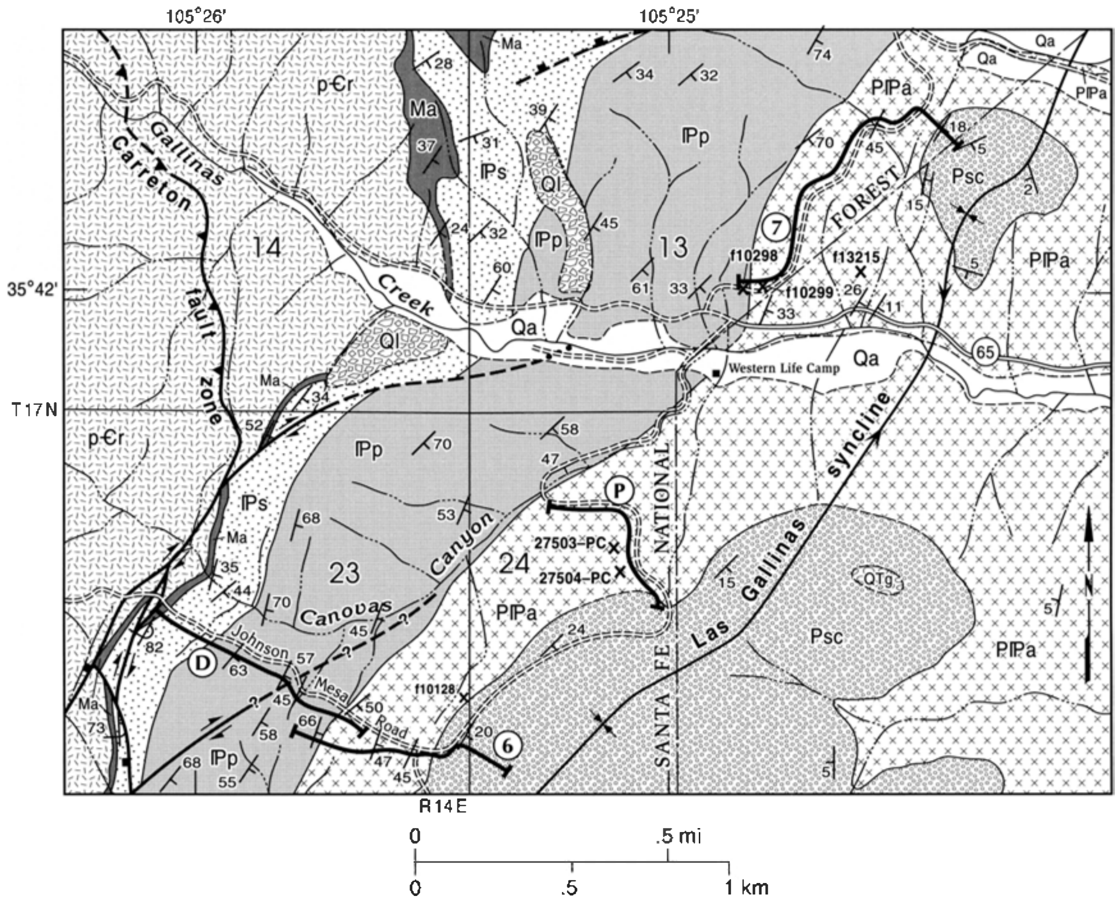


FIGURE 81—Geologic map of upper Gallinas Creek area showing locality of stratigraphic section D of the Sandia and Porvenir Formations and stratigraphic sections P, 6, and 7 of the Alamitos Formation. Symbols are explained in Figure 80. Adapted from Baltz (1972). Regional locations of sections shown in Figures 31 and 55. Locality D is type locality of Porvenir Formation.

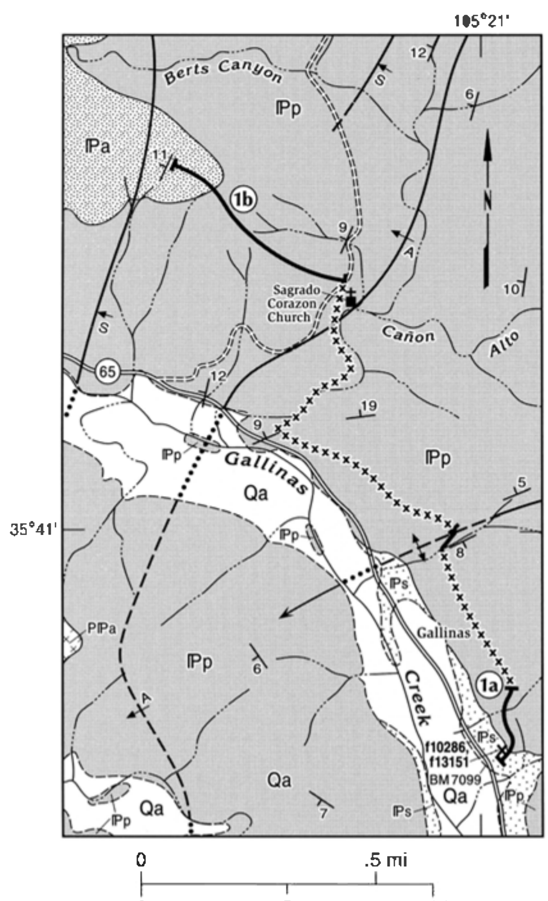


FIGURE 82—Geologic map of Gallinas Creek area northwest of Montezuma showing locality of composite section 1 of the Porvenir Formation. Symbols are explained in Figure 80. Adapted from Baltz (1972). Regional location of section is shown in Figure 31.

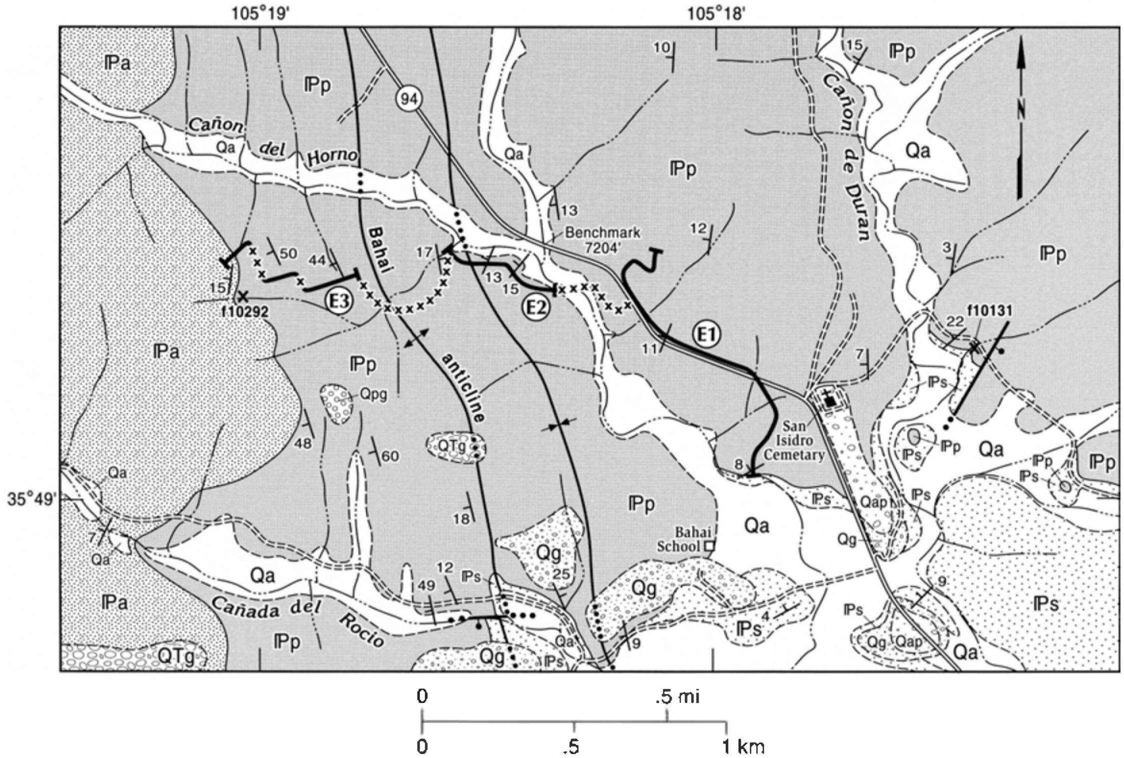


FIGURE 83—Geologic map of Cañon del Horno area northwest of Manuelitas showing localities of composite principal reference section (E1, E2, E3) of Porvenir Formation. Symbols are explained in Figure 80. From Baltz and O'Neill (1986). Regional location of section shown in Figure 31.

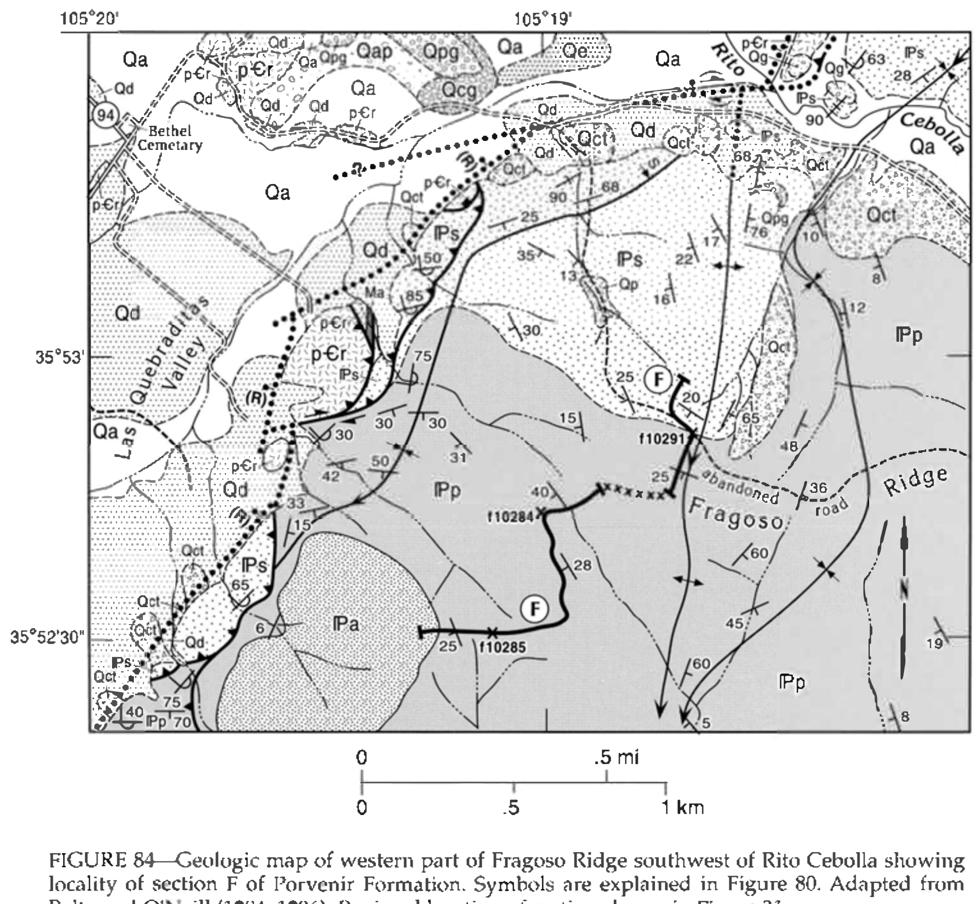


FIGURE 84—Geologic map of western part of Fragoso Ridge southwest of Rito Cebolla showing locality of section F of Porvenir Formation. Symbols are explained in Figure 80. Adapted from Baltz and O'Neill (1984, 1986). Regional location of section shown in Figure 31.

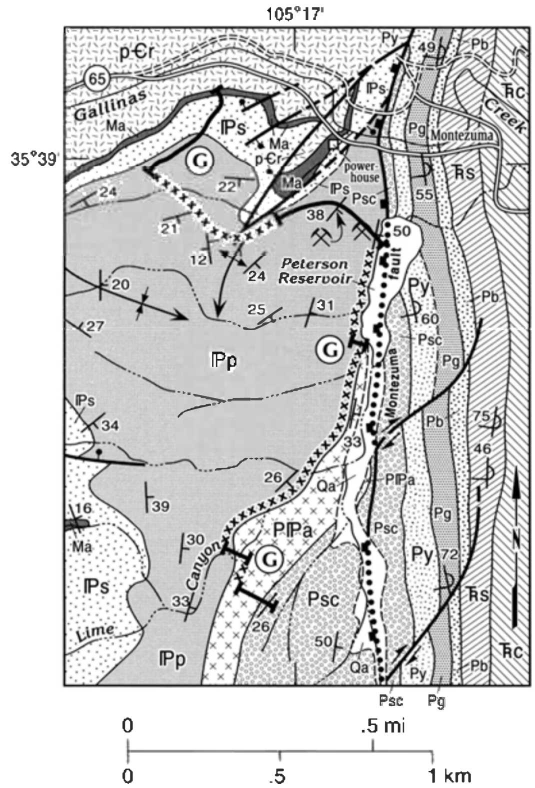


FIGURE 85—Geologic map of Montezuma area showing locality of composite section G of the Sandia, Porvenir, and Alamitos Formations. Symbols are explained in Figure 80. Adapted from Baltz (1972). Regional location of section shown in Figures 31 and 55.

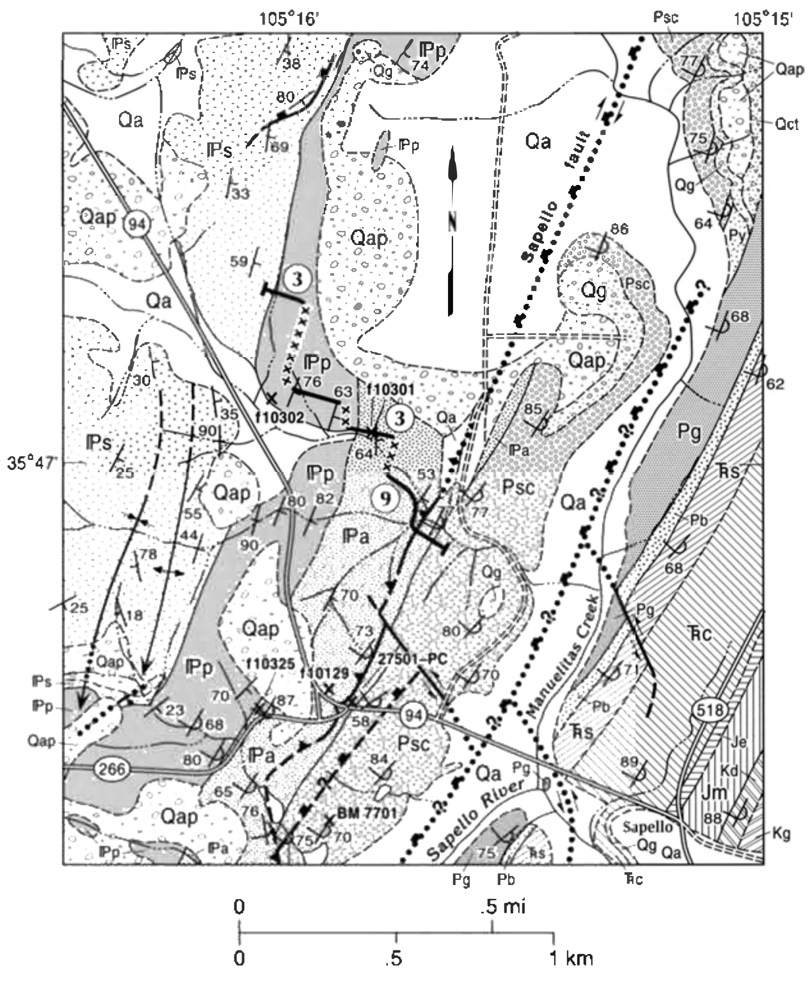


FIGURE 86—Geologic map of area northwest of Sapello showing locality of stratigraphic section 3 of the Porvenir Formation and stratigraphic section 9 of the Alamitos Formation. Symbols are explained in Figure 80. From Baltz and O'Neill (1986). Regional location of sections shown in Figures 31 and 55.

FIGURE 87—Geologic map of Manuelitas Creek southeast of Rociada showing locality of stratigraphic section H of the Sandia, Porvenir, and Alamitos Formations. Symbols are explained in Figure 80. Adapted from Baltz and O'Neill (1986). Regional location of section shown in Figures 17, 31, and 55.

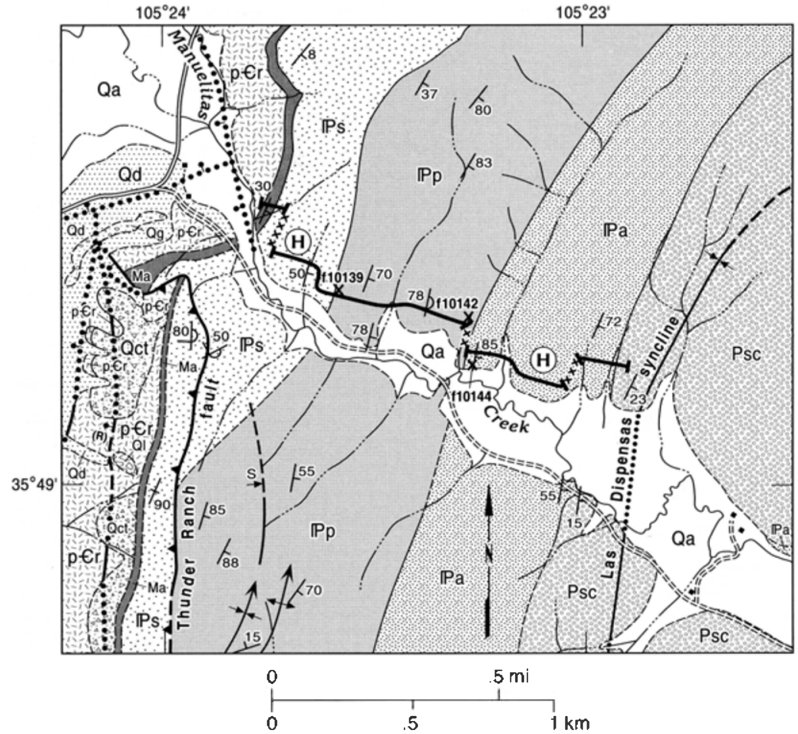


FIGURE 88—Geologic map of eastern Rito Cebolla area and northeast part of Fragoso Ridge showing locality of stratigraphic section C of the Sandia Formation and locality of section I of the Porvenir and Alamitos Formations. Symbols are explained in Figure 80. Adapted from Baltz and O'Neill (1984, 1986). Regional locations of sections shown in Figures 17, 31, and 55.

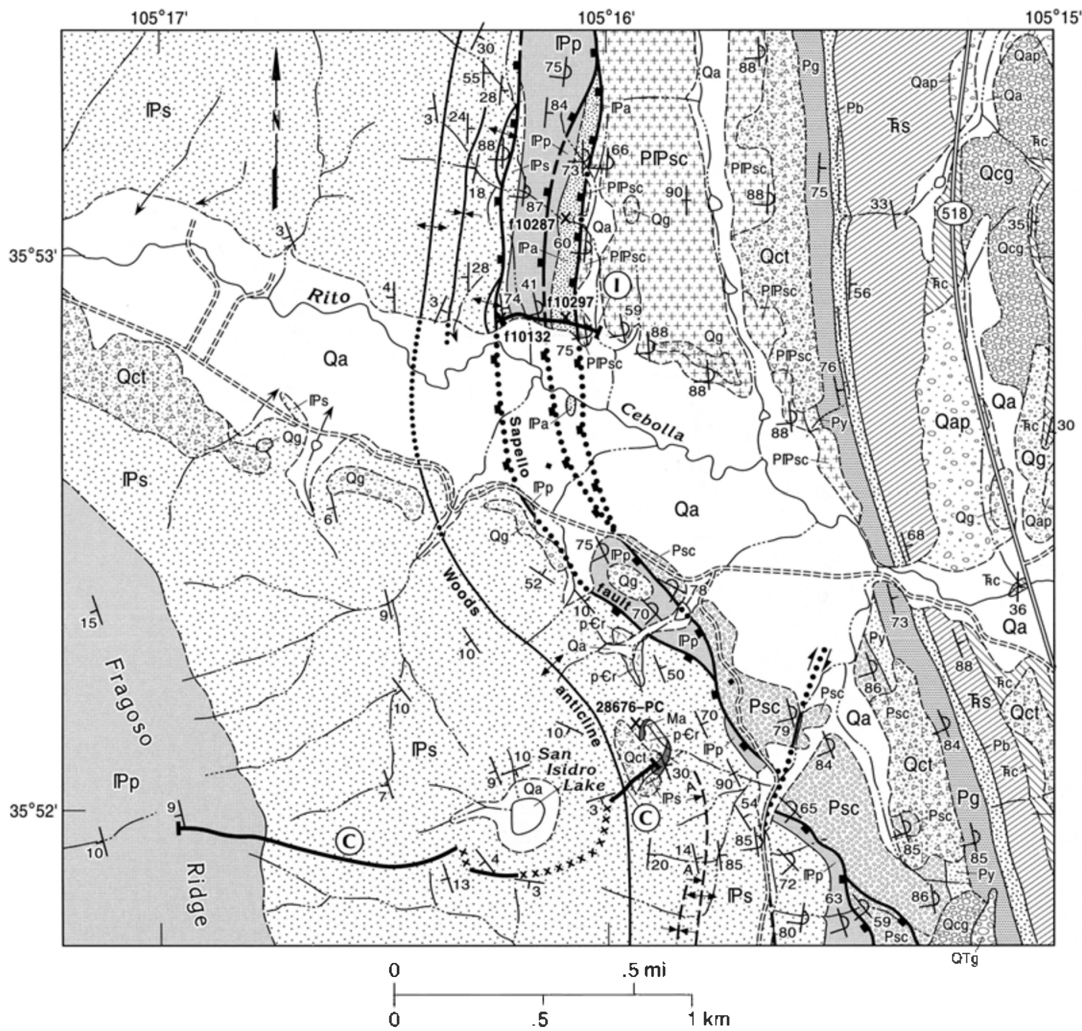


FIGURE 89—Geologic map of Mora River gap southeast of Mora showing locality of composite reference section J1–J7 of the Sandia Formation; locality of reference stratigraphic section K of the Porvenir and Alamitos Formations; and locality of auxiliary section L of the upper part of the Sandia and lower part of the Porvenir Formations. Symbols are explained in Figure 80. Persistent sandstones "a"–"e" in the Sandia Formation were mapped to determine geologic structure and to determine places to measure a relatively completely exposed section of the formation. Adapted from Baltz and O'Neill (1984). Regional locations of sections are shown in Figures 17, 31, and 55. For discussion of structure in this area see Baltz and O'Neill (1990, p. 81–83).

APPENDIX II

DESCRIPTIONS OF STRATIGRAPHIC SECTIONS

Mississippian Tererro and Espiritu Santo Formations of Arroyo Peñasco Group

Localities of sections (except loc. 13) of Tererro and Espiritu Santo Formations are shown in Figure 6. Additional detailed descriptions of these formations are given with descriptions of Pennsylvanian and Lower Permian rocks in stratigraphic sections A–D, G, and J later in this report. All measurements were made in feet and tenths of feet and are converted to meters using the factor 1 ft = 0.305 m. Rounded to nearest centimeter for units less than 3 ft thick; rounded to nearest tenth of a meter for units 3 ft and more thick.

Locality 4

Rociada 7.5-minute quadrangle (1965). North side of gap in hogbacks, Manuelitas Creek, 1.4 mi (2.3 km) east–southeast of Rociada. Base of section is about half way between top and bottom of eastern part of large hill. Modified from Baltz and Read, 1960, p. 1772–1773.

Unit	Lithology	Thickness ft	Thickness m
	Sandia Formation (lower part):		
16.	Sandstone, conglomeratic, light-yellowish-brown. Composed of angular to subangular, medium to very coarse, milky-appearing quartz sand and granules; contains scattered quartzite pebbles. Silica cement. Crossbedded and cross-laminated. Forms blocky jointed ledge.	28	8.5
	Tererro Formation:		
	Cowles Member:		
15.	Siltstone, olive-green; weathers dark brown. Composed of quartz silt and a trace of fine quartz sand; slightly calcareous. Contains fragments of bryozoans. Grades abruptly into underlying unit. Forms irregular upward-retreating slope.	20	6.1
14.	Calcarenite and calcareous quartz siltstone, medium-brownish-gray. Composed mainly of fine to very fine calcite sand; about 40 percent of unit is quartz sand and silt in calcite matrix. Crossbedded and cross-laminated; beds are 1–4 ft (0.3–1.2 m) thick. Grades into underlying unit. Forms prominent, irregularly weathered, slightly rounded ledge.	12	3.7
13.	Siltstone, shaly, yellow. Composed of calcareous, ocherous, quartz silt. Contains small pebbles of limestone and chert. Finely cross-laminated. Erosionally unconformable on underlying unit which locally is tilted and beveled by unconformity. Weathers to conspicuous notch.	3	0.9
	Total thickness of Cowles Member:	35	10.7
	Manuelitas Member (type section of Baltz and Read, 1960):		
12.	Limestone, light-gray, fine to micrograined. Contains scattered round quartz granules and, near the middle, a 1-ft-thick bed of yellow siltstone and limestone-pebble conglomerate. Contains brown-weathering irregular chert bodies and some nodular gray chert. Beds are subparallel and average 2 ft (0.6 m) in thickness. Forms irregularly weathering vertical ledge. Contact with underlying unit is erosional and irregular. This unit and underlying units 11 to 3 were involved in episodic collapses into a large sinkhole in the Macho Member.	7	2.1
11.	Calcarenite, quartz siltstone, and sandy limestone, interbedded; light gray to light yellowish gray. Beds near middle contain brown-weathering chert bodies with pisolitic surfaces. Bedding subparallel; beds are 0.25 inch–1 ft (0.6–30 cm) thick. Forms highly irregular upward-retreating ledgy slope. Irregular erosional contact with underlying unit.	7.5	2.3
10.	Limestone, light-gray, very fine grained. Contains many tiny crinoid columnals and fragments of brachiopods. Irregular bodies of brown weathering chert, 0.25 inch–4 ft (0.6 cm–1.2 m) long, are common, especially near top. Forms irregular vertical ledge. Contact with underlying unit is irregular.	2.4	0.73
9.	Siltstone and interbedded silty, marly shale, yellow-gray. Siltstone beds are 1–2 inches (2.5–5 cm) thick; shale beds are about 0.5 inch (1.3 cm) thick. Locally, unit thickens into sinkhole and contains limestone pebbles and cobbles. Forms low, rounded ledge with notch at base.	1–8	0.3–2.4
8.	Limestone, dark-gray, micrograined, siliceous. Contains hackly weathering irregular bodies of brown-weathering chert. Beds are parallel and 0.5–1 ft (15–30 cm) thick. Forms prominent irregular ledge. Contact with underlying unit is highly irregular.	4	1.2
7.	Siltstone, light-yellowish-gray, marly. Weathers to notch.	0–0.5	0–0.15
6.	Limestone, micrograined, very silty, and calcarenite; light-yellowish-gray. Contains limestone pebbles and cobbles near base. Cross-laminated; laminae are 0.25–0.5 inch (0.6–1.3 cm) thick. Forms rounded ledge. Erosional, irregular contact with underlying unit.	3–8	0.9–2.4

Unit	Lithology	Thickness ft	m
5.	Limestone, medium-gray, fine to micrograined, siliceous. Contains irregular patches of brown weathering, hackly chert. Forms prominent vertical ledge. Slightly irregular contact with underlying unit.	3	0.9
4.	Calcarenite and silty limestone, light-yellowish-brown, fine-grained. About 15 percent of clasts is quartz silt and fine sand. Cross-bedded; beds are 3–8 inches (7–20 cm) thick. Forms irregular ledge with slight notch at base. Slightly irregular contact with underlying unit.	t3	0.9
3.	Conglomerate, medium-gray. Rounded limestone pebbles and small cobbles are in a matrix of fine-grained to granule calcarenite and silty, sandy marl. Bedding is poorly developed. Forms irregular slope. Contact with underlying unit is erosional and highly irregular, having a relief of as much as 6 ft (1.8 m).	6.5	2
	Maximum total thickness of Manuelitas Member:	49.9	15.1
	Macho Member (part):		
2.	Breccia, light-gray; angular blocks of limestone as large as 2 ft (60 cm) across are randomly oriented in marly quartz siltstone and calcarenite. Some breccia fragments have been replaced by gray, granular silica. Forms rounded ledge; base not exposed. Large sinkholes in unit are filled with collapsed part of overlying Manuelitas Member.	4–10+	3.1+
	Maximum thickness of exposed part of Tererro Formation:	94.9+	28.9+
	Espiritu Santo Formation:		
	Not exposed here. May be absent locally. Poor exposures on ridge south of Manuelitas Creek show that the carbonate part is present but thin, and the Del Padre Sandstone Member is present and several feet thick.		
	Precambrian rocks:		
1.	Metaquartzite, pink to grayish-pink, fine-grained, slightly micaceous, slightly chloritic. Contains thin bands of quartz as much as 1 inch (2.5 cm) long that may be deformed pebbles. Slightly cross-laminated. Highly fractured. Dips steeply southeast.	Not measured	

Locality 9

El Porvenir 7.5-minute quadrangle (1961). North of Gallinas Creek, in Santa Fe National Forest north of Gallinas Cabin. Top of ridge in NE¼NE¼ sec. 14 T17N R14E. Measured by E. H. Baltz.

Unit	Lithology	Thickness ft	m
	.Sandia Formation (lower part):		
10.	Sandstone, conglomeratic, tan- to light-brown-weathering, fine- to very coarse grained; clasts are subangular to subround translucent quartz. Contains a large proportion of granules and small pebbles. Thin bedded and slightly crossbedded.	5+	1.5+
	Tererro Formation:		
	Cowles Member:		
9.	Calcarenite, light-gray, fine-grained; contains a large proportion of rounded, fine to medium quartz sand. Medium bedded; beds are cross-laminated.	12.6	3.8
	Manuelitas Member:		
8.	Calcarenite and sandy limestone, yellowish-tan and gray. Contains limestone pebbles and angular chert clasts. Grades into unit below.	4.5	1.4
7.	Limestone, medium-gray, micrograined, partly sandy; contains interbeds of calcarenite. Contains a lens of oolitic limestone. Calcarenite and oolite contain fragments of crinoid columnals. Chert occurs as brown stringers, 1–6 inches (2.5–15 cm) long and 0.5 inch (1.3 cm) thick, and as pink oolitic masses. Units 7 and 6 appear to have collapsed slightly.	3	0.9
6.	Limestone, fine-grained, sandy, and interbedded cross-laminated calcarenite and limestone-pebble conglomerate, yellowish-gray. Calcarenite is cherty. Unit also contains angular chunks of residual chert that are as much as 3 inches (7.6 cm) across. Unit probably is reworked from formerly present breccia of Macho Member.	5	1.5
	Total thickness of Manuelitas Member:	12.5	3.8
	Macho Member:		
	Absent	0	0
	Total thickness of Tererro Formation:	25.1	7.6

Unit	Lithology	Thickness ft	m
	Espiritu Santo Formation:		
5.	Calcarenite, light-gray, sandy, cross-laminated; about 30 percent is coarse quartz sand; basal part is mainly limy sandstone. Unit is recrystallized but cross-lamination is still apparent.	3.4	1
4.	Limestone, light- to medium-gray, dolomitic and sideritic; recrystallized. Contains scattered 0.25 inch (0.6 cm) grains of chert and irregular bodies of black-and-gray banded chert. Beds are subparallel and 6–10 inches (15–25 cm) thick.	9	2.8
3.	Limestone, medium-gray, medium-grained. Contains lenses of angular, medium to coarse quartz sand and some hematite concretions. Beds are about 6 inches (15 cm) thick.	2.2	0.67
	Del Padre Sandstone Member:		
2.	Sandstone, conglomeratic, pinkish-tan to gray, fine- to coarse-grained; contains numerous subangular to subround granules and small pebbles of translucent quartz. Thin bedded and slightly crossbedded. Undulatory contact with underlying rocks causes unit to thin locally to only 3–4 inches (7–10 cm) thick.	3	0.9
	Total thickness of Espiritu Santo Formation:	17.6	5.4
	Precambrian rocks:		
1.	Porphyritic granite, pink, medium- to coarse-grained, slightly foliated.	Not measured	

Locality 10

Montezuma 7.5-minute quadrangle (1961). Measured on north side of canyon of Gallinas Creek in road cuts along New Mexico Highway 65, 5.1 mi (8.2 km) (road distance) west of powerhouse at Montezuma, and about 800 ft (245 m) north–northeast of Trout Springs. Measured by E. H. Baltz.

Unit	Lithology	Thickness ft	m
	Sandia Formation (lower part):		
14.	Sandstone, pinkish-brown-weathering; composed of angular to subangular, very coarse sand and granules of quartz. Contains many fossil twigs, some of which are *Lepidodendron* sp. Base of unit is an erosional unconformity; locally unit thickens, cuts out underlying unit, and lies on Tererro Formation. Forms ledge.	5–14	1.5–4.3
13.	Shale, light-olive-gray-weathering, marly. Contains interbeds of thin, yellowish-brown siltstone and a bed of very coarse grained sand stone. Thickens westward.	10	3
	Tererro Formation:		
	Cowles Member:		
12.	Calcarenite, light-gray, fine-grained; contains much fine quartz sand. Contains small clumps of limonite weathering from pyrite. Beds are 2–3 inches (5–7.5 cm) thick and are finely laminated. Crossbedded and cross-laminated. Chert on bedding and laminae stands in relief on weathered surface. Forms prominent ledge. Unit thickens westward.	4–12	1.2–3.7
11.	Siltstone, light-greenish-gray, calcareous, shaly bedded; weathers to form conspicuous notch. Sharp undulatory erosional surface at base.	2	0.6
	Maximum thickness of Cowles Member:	14	4.3
	Manuelitas Member:		
10.	Calcarenite, light-gray; contains irregular masses of pink, oolitic to massive chert. Forms ledge.	6	1.8
9.	Limestone, medium-gray, micrograined; contains fragments of crinoid columnals. Forms ledge. West of present-day cave in underlying unit, this and overlying unit grade into massive gray limestone.	3	0.9
8.	Limestone, fine-grained, interbedded calcarenite, and thin, marly shale; weathers light-brown. Calcarenite is fine- to very fine grained; as much as 30 percent of insoluble residue is silt to medium quartz sand; contains scattered limestone pebbles and detrital-chert fragments. Calcarenite contains many patches of gray and pink oolitic chert. Calcarenite beds are 1–8 inches (2.5–20 cm) thick; irregular to crossbedded. Unit thickens westward into sinkhole in underlying unit. Basal beds locally are collapsed and slightly brecciated, and are truncated by higher beds at east side of sinkhole. Thickness of unit is irregular, partly because of a well-displayed irregular erosion surface at its base. Weathers to irregular ledges and notches. Present-day cave is in this unit.	3–10	0.9–3
	Maximum thickness of Manuelitas Member:	19	5.7

Unit	Lithology	Thickness ft	Thickness m
	Macho Member:		
7.	Breccia, limestone, medium- to light-gray; clasts are mainly randomly oriented, angular, and range from pebble size to 3 ft (0.9 m) across. Clasts mainly are fine-grained gray limestone, but some are dark-gray, recrystallized and very coarse grained. Contains large, angular blocks and numerous small angular clasts of tan to light-gray banded chert. Contains a few clasts of banded nodular chert. Matrix between blocks is mainly fine-grained, light- to medium-gray calcite that contains highly irregular stringers of marly, sandy shale. Weathers to form a massive ledge. Base is irregular surface on underlying unit.	8–15	2.4–4.6
	Maximum thickness of Tererro Formation:	48	14.6
	Espiritu Santo Formation:		
6.	Shale, light-gray, marly, sandy; very irregular in thickness. Base is irregular and may be an erosion surface.	0–0.75	0–0.23
5.	Limestone, medium-gray, medium- to coarse-grained, recrystallized; contains patches of large, white calcite crystals and a few small concentrically banded chert nodules. Forms ledge.	3.5	1
4.	Limestone, dark-gray, medium-grained, recrystallized. Contains interbedded marly shale. Beds are 0.31–13 inches (2.5–7.6 cm) thick. Weathers to irregular notch.	1–2	0.61
3.	Limestone, dark-gray to black, dolomitic and sideritic, coarse-grained. Contains isolated, ellipsoidal, concentrically banded chert nodules as much as 6 inches (15 cm) long; bands are alternately light and dark gray or tan and brown. Contains solution holes lined or filled by limonite. Bedding is undulatory; beds are 4 inches–1 ft (10–30 cm) thick and at places are finely laminated. Entire unit is recrystallized and fractures on curved cleavage surfaces that cut across lamination and bedding. Forms ledge.	5.5	1.7
	Del Padre Sandstone Member:		
2.	Sandstone, medium-olive-gray to buff, fine- to coarse-grained; matrix is medium quartz sand containing scattered, irregularly shaped, subround to round, coarse to granule-size quartz clasts. Calcareous and slightly argillaceous. Some parts have upward-fining graded bedding. Beds are subparallel and 6 inches–1 ft (15–30 cm) thick and commonly are finely cross-laminated. Base is a relatively smooth but undulatory nonconformity with local relief of several inches.	2.5	0.76
	Total thickness of Espiritu Santo Formation:	14.25	4.3
	Precambrian rocks:		
1.	Granite gneiss, schist, and alaskite pegmatite; layering is mainly nearly vertical. Upper part appears to have been weathered slightly prior to deposition of Espiritu Santo Formation.	Not measured	

Locality 13

Ranchos de Taos 7.5-minute quadrangle (1964). About 25 mi (40 km) northwest of area of report. East of Ponce de Leon Springs and south of Talpa. Locality is about 300 ft (90 m) east of crest of prominent north-trending ridge of Precambrian rocks and is about 2,000 ft (610 m) southeast of Cuchilla del Ojo. Measured by E. H. Baltz.

Unit	Lithology	Thickness ft	Thickness m
	Sandia Formation (lower part):		
15.	Sandstone, brown-weathering; very coarse sand and granules of quartz.	Not measured	
	Tererro Formation:		
	Cowles Member:		
14.	Siltstone, greenish-gray, soft, poorly exposed.	15	4.6
13.	Siltstone, light-yellowish-brown, slightly calcareous, thin-bedded. Contains thin lenses of limestone-pebble conglomerate. Poorly exposed. Forms irregularly rounded slope.	8	2.4
12.	Concealed.	12	3.7
	Total thickness of Cowles Member:	35	10.7
	Manuelitas Member:		
11.	Calcarenite, brownish-gray, containing much quartz silt and fine sand; parts of unit are calcareous siltstone. Contains a few stringers of locally pisolitic gray chert that have parallel internal laminations. Irregular beds, 0.06–0.5 inch (0.16–1.3 cm) thick. Forms an irregular ridge; weathers along bedding to thin slabs. Base is an irregular ero-		

Unit	Lithology	Thickness ft	m
	sion surface.	10	3
10.	Limestone, dark-bluish-gray, micrograined. Contains irregular masses and thin stringers of gray to pink chert that is partly pisolitic. At places, much brown chert occurs at the base of the unit. At places lower part of unit contains limestone pebbles and cobbles. Unit is present at places above erosion surface on underlying unit. At places it has col lapsed slightly into underlying unit.	2.5	0.76
Total thickness of Manuelitas Member:		12.5	3.76
Macho Member:			
9.	Breccia, limestone, light-gray; angular blocks are as large as 2 ft (60 cm) across. Blocks are lithologically similar to underlying unit. Forms resistant irregularly rounded ledge. Thickness varies along outcrop.	12	3.7
Total thickness of Tererro Formation:		59.5	18.2
Espiritu Santo Formation:			
Unit 3:			
8.	Limestone, light-gray, earthy appearing. Fine grained; contains much quartz silt. Beds are subparallel and 0.5–1 ft (15–30 cm) thick. Laminae are undulatory. Moderately exposed; weathers to angular fragments that litter outcrop belt.	18	5.5
Unit 2:			
7.	Limestone, medium- to dark-gray, fine- to medium-grained, recrystallized. Upper part probably is recrystallized calcarenite. Upper part contains lenses of dark-gray chert parallel to bedding; lenses are as much as 4 ft (1.2 m) long and 8 inches (20 cm) thick. Upper part forms small, slabby, irregular ledges; lower part forms a rounded, irregular ledge.	11	3.4
6.	Limestone, dark- to medium-gray, fine- to medium-grained; mainly recrystallized calcarenite.Beds are 3–4 inches (7.6–10 cm) thick. Weathers to small slabby ledges; top half poorly exposed.	3.6	1.1
5.	Limestone, dark-gray, fine- to medium-grained, strongly recrystallized. Laminae are irregular and 0.06–0.25 inch (0.16–0.6 cm) thick. Contact with underlying unit undulatory and probably unconformable. Forms small, hackly weathering ledge.	1.8	0.55
Unit 1:			
4.	Limestone, medium- to dark-gray, fine- to medium-grained, moderately recrystallized. Lower part is as much as 50 percent quartz silt and contains lenses and scattered clasts of rounded quartz granules. Contains a few dark-gray chert nodules that range from 1–8 inches (2.5–20 cm) in longest dimension. Lower beds are 3–6 inches (7.6–15 cm) thick; higher beds are 1–1.5 ft (30–45 cm) thick. Grades into underlying unit. Forms a ledgy slope.	14	4.3
Del Padre Sandstone Member:			
3.	Sandstone, conglomeratic, light-tan to yellowish-gray, medium- to coarse-grained; sand grains are very well rounded; upper part contains small quartzite pebbles, and is highly calcareous. Beds are 3 inches–1 ft (7.6–30 cm) thick; low-angle cross beds. Forms small ledges.	5	1.5
2.	Quartzite, light-yellow to light-brownish-gray; generally medium grained, but contains some coarse quartz sand and granules. Clasts are generally well rounded. Low-angle crossbeds; beds are 2 inches–1 ft (5–30 cm) thick. Weathers to vertical slabby ledges; base not exposed. Unit has a baked and bleached appearance, suggesting it has been altered thermally.	25	7.6
Total thickness of Espiritu Santo Formation:		78.4	24
Precambrian rocks:			
1.	Metaquartzite, grayish-pink, fine-grained, slightly foliated; underlain by greenish-brown weathering granite.	Not measured	

PENNSYLVANIAN AND LOWER PERMIAN ROCKS

Regional locations of all stratigraphic sections of Pennsylvanian and Lower Permian rocks are shown in Figures 17 (Sandia Formation), 31 (Porvenir Formation), and 55 (Alamitos Formation). Localities of measurement of sections C–L and P that are described below are shown also in geologic maps (Figs. 81–89). Localities of several undescribed graphic sections also are shown in these maps. All measurements were made in feet and tents of feet and are converted to meters using the factor 1 ft = 0.305 m. Rounded to nearest centimeter for units less than 3 ft thick; rounded to nearest tenth of a meter for units 3 ft and more thick.

Section A

Villanueva 15-minute quadrangle (1960). Section of Sandia Formation, in Santa Fe National Forest about 5.25 mi (8.5 km) northwest of Bernal. Locality is in southeast-draining canyon near center of sec. 8 T14N R15E. Locality is west of an abandoned mine in coaly shale of the Sandia Formation, and west of livestock-watering troughs and a spring that issues from the Arroyo Peñasco Group in the canyon. Base of section is in good exposures of Arroyo Peñasco Group in narrow part of canyon. Measured southwest through southwest-dipping rocks to base of Porvenir Formation. Measured by E. H. Baltz and D. A. Myers. Locality shown in Figure 17.

Unit	Lithology	Thickness ft	m
	Porvenir Formation (lower part):		
12.	Limestone, gray, bioclastic, sandy. Beds are 0.5–2 ft (15–60 cm) thick. Forms strong ledge. Fusulinids occur about 10 ft (3 m) below the top. Fusulinid collection f10335 contains *Beedeina* aff. *B. arizonensis*.	35	10.7
	Sandia Formation:		
11.	Concealed; slope.	38	1.6
10.	Siltstone, light-yellowish-olive, thin-bedded to shaly. Forms slope; poorly exposed.	40	12.2
9.	Sandstone, yellowish-brown- to gray-weathering, coarse-grained to very coarse grained. Parallel bedded to crossbedded. Forms prominent northwest-trending ledge.	22	6.7
8.	Concealed, slope.	18	5.5
7.	Limestone, gray, micrograined. Forms small ledge.	4	1.2
6.	Concealed, slope.	15	4.6
5.	Limestone, gray, micrograined, slightly fossiliferous. Forms small ledge.	2	0.6
4.	Siltstone and interbedded sandstone; weathers greenish gray to brown. Sandstone is very fine grained; shaly. Forms irregular small ledges.	60	18.3
3.	Sandstone, brown-weathering, coarse-grained to very coarse-grained. Crossbedded. Forms prominent ledge.	21	6.4
	Total thickness of Sandia Formation:	220	67.1
	Tererro Formation:		
	Cowles Member:		
	Absent.	0	0
	Manuelitas Member:		
2.	Limestone, gray, fine- to medium-grained. Contains many small brachiopods. Exposed in canyon bottom and on northeast and southwest walls. Several feet at top and base are concealed.	30±	9.1±
	Macho Member:		
	Absent.	0	0
	Espiritu Santo Formation:		
	Absent.	0	0
	Precambrian rocks:		
1.	Granitic rocks.	Not measured	

Section B

Montezuma 7.5-minute quadrangle (1961). Section of lower part of Porvenir Formation, Sandia Formation, and Arroyo Peñasco Group on ridge northwest of Hot Springs, north side of Gallinas Creek canyon. Base of section is at head of deep canyon about 1 mi (1.6 km) north–northwest of lake at Hot Springs. Top of section is on drainage divide at top of highest ridge at altitude 8,120 ft about 1.5 mi (2.4 km) north–northwest of lake. Measured by E. H. Baltz. Locality shown in Figure 17.

Unit	Lithology	Thickness ft	m
	Porvenir Formation (lower part):		
37.	Limestone, light-gray-weathering, medium-gray, fresh. Micritic to coarse grained; siliceous, hackly weathering; fossiliferous. Forms steep ledge at altitude 8,120 ft. Stratigraphically higher beds of Porvenir occur farther west.	13	4
36.	Shale, gray, calcareous, and interbedded thin gray limestone.	5	1.5
35.	Limestone, gray, fine-grained. Forms ledge.	2	0.61
34.	Limestone, gray, thin, and interbedded gray shale. Forms rounded		

Unit	Lithology	Thickness ft	m
	slope; poorly exposed.	11	3.4
33.	Limestone, gray, fine- to coarse-grained. Contains irregular bands and patches of yellow-brown, hackly weathering chert. Highly fossiliferous locally; contains clumps of *Chaetetes* sp. Bedding subparallel and slightly undulatory; beds 2–4 ft (60–120 cm) thick. Forms steep ledge.	16.5	5
32.	Sandstone, tan-weathering, coarse-grained, well-cemented. Forms blocky ledge; basal third poorly exposed.	16.5	5
31.	Shale, gray, contains gray limestone nodules. Forms slope; poorly exposed.	8	2.4
30.	Sandstone, conglomeratic, light-brown-weathering. Matrix is subangular to subround, fine to coarse quartz sand; contains quartz granules and small pebbles. Poorly exposed; upper half may contain some shale beds.	6	1.8

[Unit 29 was traced about 300 ft (90 m) west, and section above continues west up ridge crest.]

Unit	Lithology	Thickness ft	m
29.	Limestone, light-gray, fine- to medium-grained, partly recrystallized. Beds are 6 inches to 2 ft (15–60 cm) thick. Caps ridge at about altitude 8,040 ft.	25	7.6
28.	Concealed; probably shale and thin nodular limestone.	12	3.7
27.	Limestone, medium-gray, weathers light gray. Fine- to coarse-grained; partly recrystallized. Siliceous networks cause hackly weathering. Contains abundant clumps of *Chaetetes*. Bedding is subparallel; beds are 1–4 ft (30–120 cm) thick. Forms massive ledge. Fusulinid collection f24353 contains *Fusulinella* sp. and *Beedeina* sp., identified by R. C. Douglass, 1971. Megafossil collection USGS 24494–PC listed on Plate 5.	27	8.2
	Thickness of measured lower part of Porvenir Formation:	142	43.2

Sandia Formation:

Unit	Lithology	Thickness ft	m
26.	Mainly concealed; slope. Upper third is poorly exposed dark-gray calcareous shale containing some thin nodular limestone.	55	16.8
25.	Limestone, medium-gray, fine-grained. Clumps of *Chaetetes* are abundant. Contains irregular patches and fracture fillings of yellowish-brown-weathering silica. Bedding is subparallel; beds are 2–3 ft (60–90 cm) thick. Forms slightly slumped ledge; base and top not exposed. Megafossil collection USGS 24493–PC listed in text discussion of Sandia.	11	3.4
24.	Shale, gray to light-greenish-gray, silty. About 20 percent of unit is thin beds of gray limestone. Forms slope; poorly exposed. Megafossil collection USGS 24492–PC obtained from a thin limestone near the middle of the unit.	22	6.7
23.	Concealed; slope; probably shale and interbedded thin limestone.	28	8.5
22.	Sandstone, fine-grained, similar to unit 21; poorly exposed.	6	1.8
21.	Sandstone, light-olive-brown, fine- to medium-grained, thin bedded to shaly. Forms irregular slope; poorly exposed.	13	4
20.	Sandstone, conglomeratic, buff. Composed of subround, medium to coarse quartz sand that contains scattered granules and tiny pebbles of quartz. Middle third is brown-weathering, limy, coarse-grained, highly crossbedded sand stone. Forms small ledge.	23	7
19.	Siltstone, shaly, dark-gray, carbonaceous; contains interbedded shaly, carbonaceous limestone. Forms slope; poorly exposed.	12	3.7
18.	Sandstone, similar to unit 16; composed of coarse sand and granules. Contains limonite-replaced wood fossils. Forms prominent ledge.	22	6.7
17.	Mainly concealed; slope. Scattered poor exposures indicate unit is mostly dark gray shale containing some thin limestone bed.	82	25
16.	Sandstone, conglomeratic, light-brown-weathering. Composed of subangular to subround, medium to coarse quartz sand and granules; contains small quartz pebbles; contains a trace of weathered, yellowish-gray feldspar. Crossbedded and cross-laminated; beds are 2–6 ft (60–180 cm) thick. Laminae are inclined mainly southwest. Forms prominent rounded ledge.	20	6
15.	Shale, dark-gray to black; weathers yellow-buff. Composed of shaly siltstone and interbedded silty, shaly limestone. Carbonaceous, contains plant fossils and brachiopods. Grades upward into shaly, fine-grained sandstone. Forms slope; poorly exposed. Megafossil collection USGS 24491–PC from near the top; listed in text discussion of Sandia.	22	6.7
14.	Limestone, light-gray, fine-grained. Forms small ledge. Megafossil collection USGS 24490–PC listed in text discussion of Sandia.	2	0.6
13.	Concealed; slope.	10	3
12.	Limestone, medium-gray, fine- to medium-grained, highly fossiliferous. Forms ledges; poorly exposed.		

Unit	Lithology	Thickness ft	m
	Megafossil collection USGS 24489 listed in text discussion of Sandia	0.7	0.2
11.	Claystone, silty, light-gray to buff. Contains some small gray-limestone nodules. Contains some white fine-grained sandstone in beds as much as 4 ft (120 cm) thick.	13	4
	Total thickness of Sandia Formation:	341.7	104.1
	Tererro Formation:		
	Cowles Member:		
10.	Limestone, silty, light-brownish-gray, and siltstone, olive-gray. Lower half is fine-grained, very silty, crossbedded and cross-laminated limestone; basal part contains small limestone pebbles and angular chert fragments. Upper half is shaly siltstone that is slightly nodular and calcareous. Top concealed. Base probably is erosional unconformity.	18	5.5
	Manuelitas Member:		
9.	Limestone, gray, silty, earthy-appearing. Contains brachiopods and crinoid columnals. Forms small ledges. Thickness highly irregular, probably because of unconformity at top.	10	3
8.	Conglomerate, light-brown-weathering. Composed mainly of rounded limestone pebbles. Grades upward into medium-grained, marly calcarenite which forms upper third of unit. Contains small, irregularly shaped, bodies of pink chert. Poorly bedded. Forms small rounded ledge.	9.5	2.9
	Macho Member:		
7.	Limestone breccia, light-gray-weathering. Contains angular clasts ranging from an inch (several centimeters) to 1 ft (30 cm) across; contains, rusty weathering, pebble-size, angular clasts of gray chert. Forms rounded ledge.	15	4.6
	Total thickness of Tererro Formation:	52.5	16
	Espiritu Santo Formation:		
6.	Concealed.	1.5	0.46
5.	Limestone, medium-gray, silty, fine-grained. Contains small, ellipsoidal, chert nodules. Forms ledge.	4.5	1.4
4.	Sandstone, light-buff, very fine to coarse-grained; contains quartz granules. Forms notch; poorly exposed.	2	0.6
3.	Limestone, medium-gray-weathering, fine-grained, dolomitic, slightly sandy, partly recrystallized. Contains lenses of quartz granules. Bedding slightly undulatory; beds are 1–2 ft (30–60 cm) thick. Forms ledge.	6	1.8
2.	Concealed.	5	1.5
	Total thickness of Espiritu Santo Formation:	19	5.8
	Precambrian rocks:		
1.	Granite gneiss, pink, alaskitic, well foliated.	not measured	

Section C

Sapello 7.5-minute quadrangle (1965). Composite section of lower part of Porvenir Formation, Sandia Formation, and Espiritu Santo Formation, northeast slopes of Fragoso Ridge and lower hills south of Rito Cebolla. Base of section is at outcrops of Precambrian rocks in small southeast-draining canyon about 4,500 ft (1.37 km) west–southwest of New Mexico Highway 518 bridge across Rito Cebolla. Section was measured southwestward through poor exposures, around the south side of San Isidro Lake, thence generally westward to the top of Fragoso Ridge. Measured by E. H. Baltz. Locality shown in Figures 17 and 88.

Unit	Lithology	Thickness ft	m
	Porvenir Formation (lower part):		
60.	Sandstone, conglomeratic, light-yellowish-gray; weathers light yellowish orange to light brown. Lower two-thirds is composed of subangular, coarse quartz sand and granules and a trace of weathered feldspar. Cement is clay and silica. Upper third is coarser and contains many scattered, quartzite and weathered feldspar pebbles as large as 0.75 inch (1.9 cm) diameter. Bedding is subparallel to slightly inclined; beds are 2 inches–3 ft (5–90 cm) thick. Forms a steep, irregular cliff. Forms caprock of Fragoso Ridge at this point; top eroded. Units 60–52 are parts of the informally designated sandstones of Fragoso Ridge of the Porvenir.	33	10
59.	Concealed; slope.	38	11.6
58.	Sandstone, conglomeratic, light-yellowish-gray, feldspathic. Matrix is medium to coarse quartz sand containing scattered angular quartz and feldspar granules and pebbles as large as 0.25 inch (0.6 cm) diameter. Unit is cross-laminated. Forms small ledge.	5.5	1.7
57.	Sandstone, light-grayish-yellow,		

Unit	Lithology	Thickness ft	m
	medium-grained, well-sorted, micaceous. Bedding is subparallel; beds are 0.1–3 inches (0.3–7.6 cm) thick. Forms small slabby ledge.	3	0.9
56.	Concealed; slope.	36	11
55.	Shale, clay, olive-gray; forms slope; poorly exposed.	5.5	1.7
54.	Sandstone, conglomeratic, light-yellowish-gray, feldspathic. Matrix composed of angular to subangular, very coarse sand and granules; lower two-thirds contains many yellow feldspar pebbles and angular quartz pebbles as large as 1 inch (2.5 cm) diameter. Basal 3 ft (0.9 m) contains many limestone pebbles as much as 2 inches (5 cm) diameter; smaller limestone pebbles are present scattered through higher part of unit. Upper third is cross-laminated; lower two-thirds is obscurely bedded. Forms small resistant ledge.	17	5.2
53.	Concealed; slope.	27.5	8.4
52.	Sandstone, conglomeratic, light-tan; weathers light grayish tan. composed of subangular, coarse quartz sand and granules; contains a few scattered quartz pebbles as large as 0.5 inch (1.3 cm) diameter; contains a trace of muscovite. Bedding and laminae are subparallel, locally slightly inclined, and locally cross-bedded; beds are 1–6 ft (30–180 cm) thick. Forms prominent ridge. Base not exposed. Basal part of sand stones of Fragoso Ridge.	25	7.6
51.	Concealed; slope; float includes shale and some gray limestone.	66	20
50.	Shale, clay, light-olive-gray. Flaky weathering; forms slope.	7	2.1
49.	Concealed; gentle slope; float includes some slabby, thin, gray lime stone.	60	18.3
48.	Shale, clay, calcareous, olive-gray; poorly exposed; forms slope.	11	3.4
47.	Limestone, medium-gray, light-yellowish-gray-weathering. Dense-appearing micrite containing a few fossil fragments. Beds are as much as 8 inches (20 cm) thick. Forms poorly exposed, slabby, small ledge.	11	3.4
46.	Shale, gray, calcareous; may contain some thin, beds of light-gray, fine-grained limestone. Forms slope; poorly exposed.	16.5	5
45.	Limestone, medium-gray, light-gray- to yellowish-gray-weathering. Part of unit is fine-banded stromatolite; remainder is recrystallized to sugary texture. Forms slumped ledge; poorly exposed.	5.5	1.7
44.	Sandstone, light-yellowish-gray. Composed of fine to medium quartz sand and contains coarse sand and granules. Contains small limestone pebbles apparently derived from the underlying unit. Forms a small slabby ledge.	5.5	1.7
43.	Limestone, light-gray, light-gray-weathering; partly recrystallized. Lumpy appearance because of low, stromatolitic mounds; part of unit is small fragments of brecciated algal-mat surrounded by streaks of angular, medium to coarse quartz sand and granules. Forms small ledge; poorly exposed; occurs at about altitude 7,750 ft.	1±	0.3±
	Thickness of measured lower part of Porvenir Formation:	374	114
	Sandia Formation:		
42.	Shale, clay, silty, light-olive-gray. Forms slope; poorly exposed.	16	4.9
41.	Shale, yellowish-gray-weathering; interbedded with platy, fine-grained, micaceous sandstone. Sandstone is ripple-marked; beds are 0.06–1 inch (0.16–2.5 cm) thick. Upper half contains some yellow, coarse-grained, pebbly sandstone. Forms slope; poorly exposed.	25	7.6
40.	Sandstone, conglomeratic, light-grayish-yellow-weathering, feldspathic. Composed of fine to very coarse sand and granules; as much as 15 percent of some beds is yellow, weathered feldspar; slightly micaceous. Contains scattered angular pebbles of quartz and yellow feldspar 0.25–0.5 inch (0.6–1.27 cm) diameter. Bedding is subparallel; beds are 1–6 inches (2.5–15 cm) thick. Forms slabby slope.	12	3.6
39.	Shale and sandy shale, gray, poorly exposed. Forms slope.	11	3.4
38.	Limestone, dark-gray, light-gray-weathering. Micrite containing a few scattered, small gastropods and brachiopod fragments. Forms small ledge.	2	0.61
37.	Sandstone, conglomeratic, similar to unit 35. Forms small ledge.	15	4.6
36.	Concealed; gentle slope.	16	4.9
35.	Sandstone, conglomeratic, light-yellowish-gray-weathering. Composed of coarse to very coarse sand and granules; contains a trace of weathered yellow feldspar; contains some angular quartz pebbles as much as 0.5 inch (1.27 cm) diameter. Forms small ledge; poorly exposed.	10	3
34.	Concealed; gentle slope; probably shale.	38	11.6
33.	Sandstone, conglomeratic, light-yellow-gray, weathers light yellowish orange. Composed of angular to subangular, very coarse quartz sand and granules; contains scattered quartz pebbles as large as 1 inch (2.5 cm) diameter. Contains a trace		

Unit	Lithology	Thickness ft	m
	of weathered, yellow feldspar. Cement is silica and clay. Irregular bedded to crossbedded; contains scour-and-fill structures. Beds are 1 inch–1 ft (2.5–30 cm) thick. Upper part forms a prominent ledge that is a persistent narrow bench at toe of the long slope up Fragoso Ridge; middle part is soft and poorly exposed; lower part forms a blocky ledge.	74	22.6
32.	Mainly concealed. A few small, poor exposures reveal gray shale and a few interbeds of slabby sand stone similar to unit 31.	115	35
31.	Sandstone, yellowish-gray, medium-grained, well-sorted, well-cemented, and hard. Beds are 1–8 inches (2.5–20 cm) thick. Forms small bench; slabby weathering.	7.5	2.3
30.	Concealed; slope; probably shale.	66	20
29.	Sandstone, conglomeratic, similar to unit 27. Forms small, slumped bench.	3	0.9
28.	Concealed; slope; probably shale.	11	3.3
27.	Granule conglomerate, pinkish-gray; clasts are angular to subangular quartz granules. Well cemented by silica and clay. Forms small bench.	12	3.7
26.	Concealed.	10	3
25.	Sandstone, pinkish-gray; matrix is medium to coarse grained and contains scattered granules. Bedding is irregular. Forms small ledge.	7	2.1
24.	Concealed; slope covered by blocks from overlying unit.	78	23.8
23.	Limestone, light-gray, micritic to coarse-grained and recrystallized. Contains some crinoid columnals. Part of unit is mounded and contains traces of undulatory bedding and stromatolitic banding. Contains angular fragments of limestone. Forms prominent ledge.	13	4
22.	Concealed; slope; probably shale.	12	3.7
21.	Limestone, light-gray, micritic; contains nodular, recrystallized patches; contains a few brachiopods. Beds are 0.5–1 ft (15–30 cm) thick; contains a few thin shale interbeds. Forms slope; poorly exposed.	5	1.5
20.	Concealed; slope; float suggests unit is shale and some interbedded noduar limestone.	27	8.2
19.	Limestone, similar to unit 17; forms small ledge.	2.5	0.76
18.	Concealed; slope; probably mainly shale.	36	11
17.	Limestone, light-gray, yellowish-gray-weathering. Matrix is micrite containing much bioclastic debris and a few small brachiopods and corals. Forms small ledge.	2.5	0.76
16.	Concealed.	16	4.9

[Unit 15 was traced about 270 ft (80 m) north along ranch road. Section above continues westward up topographic spur east of Fragoso Ridge.]

Unit	Lithology	Thickness ft	m
15.	Sandstone, conglomeratic, similar to unit 11. Forms prominent ledge capping a small bluff at south end of ranch road. Water well is on this ledge.	21	6.4
14.	Concealed; slope.	64	19.5
13.	Sandstone, conglomeratic, similar to unit 11; contains some fine- to medium-grained interbeds. Forms small ledge.	29	8.9
12.	Concealed; slope; probably shale.	17	5.2

[Section above continues west on topographic spur north of deep, east-draining canyon southwest of San Isidro Lake.]

Unit	Lithology	Thickness ft	m
11.	Sandstone, conglomeratic, pinkish-gray, pinkish-brown-weathering. Matrix is subangular to subround, coarse to very coarse sand; about 20 percent is angular to subangular granules. About 5 percent of clasts is yellow, weathered feldspar. Becomes coarser upward and higher part is composed mainly of granules and pebbles as much as 0.25 inch (0.6 cm) diameter. Clay and silica cementation is fair to good. Bedding is subparallel to moderately inclined; beds are 4 inches–3 ft (10–90 cm) thick. Forms a blocky weathering prominent ledge that encircles San Isidro Lake. Lower 40 ft (12 m) was measured east of lake. The top, approximately, of this interval was traced around the south side of the lake. An additional 30 ft (9 m), approximately, was measured from a ranch road southwest of the lake to top of a ledge on a spur west of the road.	70	21.3
10.	Concealed; slope.	44	13.4
9.	Limestone, medium-gray, light-gray-weathering. Bioclastic; consists of fine-grained fragments of crinoids and other fossils. Bedding undulatory; beds are 1–3 inches (2.5–7.6 cm) thick. Outcrop is slightly slumped.	5	1.5
8.	Mainly concealed by talus; scanty exposures in middle are olive-gray silty shale containing some thin beds of gray, fossiliferous, limestone nodules.	50	15.3
7.	Sandstone, yellowish-gray, medium-grained, argillaceous, obscurely bedded. Forms slope in gulch.	21	6.4
6.	Sandstone, conglomeratic, light-gray, yellowish-gray-weathering. Matrix is fine to very coarse quartz sand; about 15 percent of unit is angular granules and vein-quartz pebbles as much as 0.25 inch (0.6 cm)		

Unit	Lithology	Thickness ft	m
	diameter. Slightly calcareous. Forms blocky ledge.	5.4	1.7
5.	Sandstone, yellowish-gray, fine- to medium-grained, argillaceous. Forms small ledge in gully.	5	1.5
4.	Shale, gray, and interbedded thin, fine-grained to coarse-grained brown sandstone; poorly exposed in gully. Float indicates a 1-ft (30-cm) thick coquina of brachiopods, large crinoid columnals, and echinoids about 20 ft (6 m) above base. Base concealed.	30	9.2

[Better exposures about 600 ft (180 m) to the north, at the head of the main southeast-draining canyon, show that the lower part of the Sandia is mainly yellowish-gray-weathering marly shale that contains interbeds of thin, irregular-bedded fossiliferous limestone and thin calcareous sandstone and sandy limestone similar to units 4–9 above. Megafossil collection USGS 28676–PC was made at the northern locality from the interval 100–150 ft (30–45 m) above the base of the Sandia. Collection described in text discussion of Sandia.]

Total thickness of Sandia Formation:		1,003.9	306
Tererro Formation:			
	Absent because of unconformity at base of Sandia Formation.	0	0

Unit	Lithology	Thickness ft	m
Espiritu Santo Formation:			
3.	Limestone, light-gray, fine-grained, partly recrystallized. Contains lenses of fine to coarse quartz sand and angular granules and pebbles as much as 0.25 inch (0.6 cm) across, of white vein quartz. Bedding parallel; beds 6–8 inches (15–20 cm) thick. Base and top not exposed in gulch.	10+	3+
Del Padre Sandstone Member:			
2.	Sandstone, conglomeratic, brown-weathering, very coarse-grained, silica-cemented; contains angular pebbles as large as 2.5 inches (6.3 cm) of white vein quartz. Unit exposed on east wall of main canyon where it wedges out locally.	2.5+	0.76+
Total thickness of Espiritu Santo Formation:		12.5+	3.8+

[Basal part of section, from unit 2 upward, is in east-draining gulch west of large outcrop of white Precambrian pegmatite. Units 2–10 were measured westward up the gulch to the large sandstone bench east of San Isidro Lake.]

Precambrian rocks:			
1.	Amphibolite schist, quartz-muscovite schist, and white, coarse-grained pegmatite.	Not measured	

Section D

El Porvenir 7.5-minute quadrangle (1961). Section of Porvenir, Sandia, Tererro, and Espiritu Santo Formations measured across east-tilted beds of hogback exposed in roadcuts on U.S. Forest Service Johnson Mesa road on ridge south of Canovas Canyon. Type section of Porvenir Formation of Madera Group. Locality is near center of sec 23 T17N R14E. Measured by E. H. Baltz and D. A. Myers. Locality shown in Figures 17, 31, and 81.

Unit	Lithology	Thickness ft	m
Alamitos Formation (lower part):			
135.	Claystone and siltstone, shaly, red; contains some thin beds of gray limestone; poorly exposed. Higher beds are poorly exposed in gully at the east.	50+	15.3+
134.	Sandstone, conglomeratic, buff, arkosic; composed of angular very coarse sand, granules, and small pebbles of quartz and pink feldspar. Forms ridge.	9.9	3
133.	Siltstone and claystone, shaly, yellowish-gray, poorly exposed. Forms slope.	13.2	4
132.	Sandstone, conglomeratic, light-grayish-orange, feldspathic. Composed of angular to subangular, very coarse quartz sand. Contains angular granules and small pebbles of pink feldspar and quartz. Forms small ridge.	2.6	0.8
131.	Limestone, medium-gray, very coarse grained, bioclastic. Contains medium to very coarse quartz sand and some pink feldspar clasts near top. Beds are 6 inches–1 ft (15–30 cm) thick. Forms slight ridge.	7.3	2.2
130.	Sandstone, orange-gray, medium-grained, micaceous.	0.6	0.2
129.	Limestone, light-gray, bioclastic, crinoidal. Forms ridge.	4.6	1.4
128.	Siltstone, olive-brown, shaly. Lower third contains interbedded nodular gray limestone in beds that are about 6 inches (15 cm) thick.	18.4	5.6
127.	Limestone, light-gray, fine-grained, bioclastic; contains many brachiopod fragments. Forms ledge. Fusulinid collection f10124 from this bed contains *Beedeina sulphurensis*.	2.3	0.7
126.	Shale, silty, and interbedded mica-		

Unit	Lithology	Thickness ft	Thickness m
	ceous sandstone; purple-red weathering. Forms slope.	17	5.2
125.	Sandstone, orange-brown, very coarse grained, arkosic. Contains stratigraphically lowest fresh-appearing, pink, angular feldspar clasts. Forms small ridge.	6.5	2
	Thickness of measured lower part of Alamitos Formation:	132.4+	40.4+
	Porvenir Formation (type section):		
124.	Claystone, shaly, purple; weathers to dark-red soil.	5	1.5
123.	Limestone, light-gray, bioclastic, slightly shaly; bedding is irregular to nodular.	3	0.9
122.	Sandstone, light-yellowish-brown, very coarse grained; contains small amount of weathered yellowish-gray feldspar. Forms lens.	2	0.6
121.	Siltstone and very fine grained sandstone, light-yellowish-gray, slightly shaly; contains scattered nodules of light-gray limestone.	17.6	5.4
120.	Limestone, medium-gray, fine-grained; forms small ridge. Fusulinid collection f10123 from this bed contains *Beedeina* aff. *B. sulphurensis* and *Bradyina* sp.	1	0.3
119.	Claystone and siltstone, light-olive-yellow, calcareous; middle third contains limestone pebbles in claystone matrix. Upper 6 inches (15 cm) weathers purple.	15.9	4.9
118.	Conglomerate, limestone-pebble; pebbles are rounded and are as large as 2 inches (5 cm) diameter. Matrix is limestone.	2	0.6
117.	Siltstone, light-yellowish-gray, dense to shaly; contains limestone nodules.	10	3
116.	Limestone, medium-gray, bioclastic, thin bedded to shaly; contains crinoid debris and brachiopods. Forms small ridges.	5	1.5
115.	Shale, dark-gray, calcareous, and interbedded limestone. Upper 2 ft (60 cm) is a coquina of brachiopods and crinoid columnals in calcareous shale matrix. Lower part contains several 1.5–6-inch (3–15-cm) thick lenses of bioclastic limestone.	7	2.1
114.	Limestone, light-brownish-gray, coarsely bioclastic; contains fragments of brachiopods, crinoids, and other fossil debris. Irregularly bedded. Forms strong ledge.	4.9	1.5
113.	Limestone, gray, medium- to fine-grained, bioclastic, silty. Grades downward into yellowish-gray fine-grained limestone containing calcareous siltstone interbeds; about 50 percent of the lower half is interbeds of calcareous siltstone and silty shaly limestone. Unit forms ledge.	24.4	7.4
112.	Shale, clay, dark-gray; contains several 0.75–5-inch (2–13-cm) thick lenses of gray limestone.	11.6	3.5
111.	Limestone, light-gray, very fine grained. Beds are undulatory and 6–16 inches (15–40 cm) thick; yellowish-gray chert stringers are on bedding planes. Forms ridge. Fusulinid collection f10122 from this bed includes *Beedeina* sp. and *Millerella* sp.	5	1.5
110.	Claystone, light-olive-gray, shaly, calcareous.	9.4	2.9
109.	Limestone, gray, nodular; nodules are as large as 2 inches (5 cm) diameter and are nearly spherical.	3	0.9
108.	Limestone, gray, coarse-grained, bioclastic; consists mostly of crinoid debris. Contains some fine-grained quartz sand. Crossbedded and cross-laminated. Forms strong ridge. About 200 ft (60 m) to the south the unit contains medium to coarse angular quartz sand and interbeds of limy sandstone. Unit is the "marker" zone in upper part of Porvenir Formation.	21.5	6.6
107.	Limestone, light-gray, and interbedded shaly siltstone. Limestone is coarse-grained bioclastic calcarenite. Beds are 0.5–2 ft (15–60 cm) thick. Upper 4 ft (1.2 m) is siltstone.	23	7
106.	Siltstone, gray, shaly.	7	2.1
105.	Concealed; small valley. Concealed strike fault of small displacement probably occurs in this interval.	104	31.7
104.	Sandstone, light-yellowish-gray, fine-grained; contains interbedded siltstone and shaly siltstone; about half of unit is sandstone. Beds are 1–2 ft (30–60 cm) thick.	61	18.6
103.	Sandstone, light-yellowish-gray, fine-grained. Contains interbeds of silty sandstone and siltstone. Forms slope.	14	4.3
102.	Siltstone and claystone, interbedded; light-gray, weathers light yellowish brown. Forms broad slope in roadcut; outcrops at east end are slumped.	65	19.8
101.	Limestone, light-gray, very fine grained; forms ridge.	2.5	0.76
100.	Claystone, light-gray, shaly, calcareous, carbonaceous; weathers to notch.	4	1.22
99.	Limestone, light-gray, very fine grained; forms ridge.	5	1.5
98.	Shale, light-olive-brown, poorly exposed.	51	15.6
97.	Limestone, light-gray; lower 12 ft (3.7 m) is recrystallized, and internally partly structureless. Probably biohermal. Upper part is nodular, thin-bedded limestone.	16	4.9
96.	Shale, clay, light-gray, calcareous.	5	1.5
95.	Limestone, light-gray, recrystal-		

Unit	Lithology	Thickness ft	Thickness m
	lized; mainly structureless, internally. Probably biohermal. Contains brachiopods and algal filaments. Forms strong ridge.	14	4.3
94.	Limestone, medium-gray, very fine grained. Beds are 1 inch–2 ft (2.5–60 cm) thick; thin calcareous shale partings occur between beds.	21.5	6.5
93.	Shale, clay, gray, calcareous; weathers to notch.	3.5	1
92.	Limestone, light-gray, medium- to coarse-grained, bioclastic calcarenite. Forms massive ledge; bedding apparent only in lower part.	25	7.6
91.	Sandstone, medium- to coarse-grained, quartz.	0.5	0.15
90.	Claystone, yellowish-gray to dark-gray; upper part is highly carbonaceous to coaly and sulphurous.	7.5	2.3
89.	Limestone, medium-gray, fine-grained, bioclastic; contains brachiopods, crinoid fragments, bryozoans, and a few fusulinids. Beds are 1–8 inches (2.5–20 cm) thick and undulatory. Calcareous-shale partings as much as 1 ft (30 cm) thick form about 25 percent of unit. Forms ridges; upper 6 ft (1.8 m) is massive.	29	8.9
88.	Sandstone, conglomeratic, light-brown, medium- to coarse-grained, calcareous; contains small rounded quartz pebbles and some weathered yellowish feldspar.	2	0.61
87.	Siltstone and claystone, light-gray to yellowish-brown; upper 3 ft (0.9 m) is highly carbonaceous.	13.5	4.1
86.	Sandstone, light-yellowish-gray, medium- to coarse-grained; contains scattered quartz granules and a trace of weathered feldspar. Forms moderate ridge.	19	5.8
85.	Claystone, light-gray and light-olive-brown, calcareous; contains a few thin beds of nodular gray limestone in lower half. Carbonaceous shale, 6 inches (15 cm) thick, occurs at top.	31	9.5
84.	Limestone, light-gray, fine-grained, bioclastic, slightly nodular. Forms ridge.	4.5	1.4
83.	Siltstone, gray, calcareous.	4	1.2
82.	Sandstone, medium-gray; contains crinoid and bryozoan debris. Silty near top.	3.5	1
81.	Claystone, light-gray, calcareous; lower 4 ft (1.2 m) is mostly gray limestone nodules.	18	5.5
80.	Limestone, light-gray; mostly finely bioclastic, but contains some coarse-grained crinoidal bioclastic limestone. Mainly consists of irregular limestone masses in light-yellowish-gray, silty, cherty matrix. Beds are 2–3 ft (60–90 cm) thick. Forms massive ridge.	45	13.7
79.	Claystone, gray, calcareous, shaly.	8	2.4
78.	Concealed.	30	9.2
77.	Limestone, light-gray, micritic; contains streaks of bioclastic limestone and many brachiopods; thin bedded. Forms small ridge.	8	2.4
76.	Shale, clay, gray, calcareous; poorly exposed.	5	1.5
75.	Concealed.	13	4
74.	Limestone, gray, bioclastic; contains yellow, earthy chert and claystone partings on bedding planes. Beds are 1–2 inches (2.5–5 cm) thick.	8	2.4
73.	Concealed.	17	5.2
72.	Sandstone, light-yellowish-tan, fine- to medium-grained.	5	1.5
71.	Limestone, light-gray, very coarse grained, bioclastic, crinoidal. Brachiopods and horn corals are abundant.	6	1.8
70.	Limestone, medium-gray, bioclastic; contains many large productid brachiopods. Beds are slightly undulatory. Forms a double ridge.	5	1.5
69.	Sandstone, light-yellowish-tan, coarse- to very coarse grained; contains some yellowish-gray weathered feldspar. Contains shaly beds near top.	5.9	1.8
68.	Sandstone, light-yellowish-brown, fine- to medium-grained, micaceous; shaly to irregular bedded.	2	0.6
67.	Limestone, dark-gray, and interbedded calcareous gray shale. Limestone beds are undulatory to nodular and are 1–8 inches (2.5–20 cm) thick. Horn corals, brachiopods, and crinoid debris are common. Fusulinid collection f10127 was obtained 6 ft (1.8 m) below top and contains *Beedeina* aff. *B. Rockymontana.*	16.5	5
66.	Limestone, light-gray, coarse-grained, bioclastic, crinoidal; contains many brachiopods. Beds are 0.5–2 ft (15–60 cm) thick; unit weathers massive.	34	10.4
65.	Limestone, medium-gray, coarse-grained; contains dark-gray, fine-grained, thin-bedded to shaly, fetid limestone.	10.5	3.2
64.	Claystone and siltstone, light-olive-brown, calcareous.	26	7.9
63.	Shale, silty clay, gray, and interbedded gray limestone and shaly siltstone that contains small limestone concretions. Unit is mostly shale except near base and top.	19	5.8
62.	Limestone, medium-gray, fine-grained. Bedding is undulatory; beds are 1–2 inches (2.5–5 cm) thick. Fusulinid collection f10126 from 9 ft (2.74 m) above base contains *Beedeina* aff. *B. apachensis.*	18	5.5
61.	Shale, clay, gray, carbonaceous; contains brachiopods.	0.9	0.27
60.	Limestone, medium-gray, medium-		

Unit	Lithology	Thickness ft	m
	grained.	0.9	0.27
59.	Sandstone, yellowish-brown to light-gray, fine-grained, silty, micaceous, calcareous; contains brachiopods. Weathers to notch.	2.3	0.7
58.	Claystone and siltstone, calcareous, siliceous; silica stands in relief along bedding. Contains many brachiopods.	18.9	5.8
57.	Siltstone and claystone, shaly, dark-gray, carbonaceous.	0.4	0.12
56.	Sandstone, grayish-orange, fine-grained, calcareous, cross-laminated.	2.7	0.82
55.	Claystone, shaly, olive-gray; contains numerous gray limestone nodules and brachiopods.	3	0.9
54.	Limestone, gray, fine-grained, bioclastic; contains lenticular secondary chert and thin clay interbeds in upper third. Bedding is undulatory.	11.5	3.5
53.	Siltstone, shaly, grayish-brown-weathering.	1.9	0.58
52.	Limestone, gray; contains fine-grained bioclastic beds. Bedding is nodular to undulatory; beds are 1–8 inches (2.5–20 cm) thick. Contains thin calcareous clay interbeds. Fusulinid collection f10125 obtained from near the top contains *Beedeina* cf. *B. insolita.*	12.5	3.8
51.	Limestone, light-gray, coarse-grained, bioclastic, massive.	6	1.8
50.	Limestone, light-gray, nodular; contains gray clay partings. Thickens upslope as underlying unit thins.	2	0.6
49.	Limestone, medium-gray, fine-grained, dense-appearing; contains scattered brachiopods and fine-grained bioclastic debris. Forms ridge. Probably biohermal; thins upslope.	9.5	2.9
48.	Limestone, medium-gray, fine-grained; contains fossil fragments and unbroken brachiopods; contains calcareous clay partings. Beds are 3–10 inches (7–25 cm) thick. Forms ridge.	8.2	2.5
Total thickness of Porvenir Formation:		1,064.9	324.3
Sandia Formation:			
47.	Claystone, medium-gray, calcareous; lower third contains thin interbeds of nodular limestone. Forms irregular slope.	14.5	4.4
46.	Limestone, medium-gray, bioclastic; contains interbeds of calcareous claystone.	4.3	1.3
45.	Siltstone, shaly, light-olive-gray; contains a bed of fossiliferous limy concretions.	7.2	2.2
44.	Limestone, gray, fine-grained, calcarenite; thin-bedded; contains rusty yellow chert.	3.5	1
43.	Concealed.	14	4.3
42.	Limestone, light-gray, fine-grained, dense-appearing; contains a few brachiopods and crinoid columnals. Bedding is undulatory; beds are 1–1.5 ft (30–45 cm) thick. Hackly yellow chert occurs on bedding planes.	5.5	1.7
41.	Concealed.	16	4.9
40.	Limestone, light-olive-gray, slightly nodular; contains brachiopods. Forms small ridge.	1.5	0.46
39.	Concealed. Float indicates unit contains siltstone, claystone, and some fine-grained sandstone.	86	26
38.	Sandstone, olive-brown, silty to medium-grained; contains scattered quartz granules.	5	1.5
37.	Claystone and siltstone, gray to olive.	17	5.2
36.	Sandstone, light-yellowish-gray, medium- to coarse-grained; contains lenses of quartz granules and trace of yellowish-gray, weathered feldspar. Cross-laminated. Forms ridge.	10	3
35.	Claystone, gray.	0.5	0.15
34.	Sandstone, brown-weathering; composed mainly of fine to medium quartz sand; contains quartz granules that have secondary crystal faces.	1	0.31
33.	Claystone, gray to olive.	8	2.4
32.	Claystone, dark-gray, carbonaceous to coaly.	7	2.1
31.	Claystone and siltstone, olive-brown; contains fine-grained sandstone, 2 ft (60 cm) thick, near middle of unit.	24	7.3
30.	Sandstone, olive-gray, fine-grained to very fine grained, silty.	15	4.6
29.	Sandstone, light-yellowish-gray, medium- to coarse-grained; contains lenses of quartz granules and a trace of weathered, yellowish-gray feldspar. Unit is cross-laminated but is essentially one bed.	12.5	3.8
28.	Siltstone and claystone, olive-green. This unit and unit 29 are folded and faulted into a nearly horizontal position.	25.5	7.8
27.	Claystone and siltstone, gray to yellowish-orange.	4	1.2
26.	Coal.	0.2	0.06
25.	Siltstone and claystone, olive-gray.	15	4.6
[Units 22–24 are repeated by a low-angle fault above point of measurement.]			
24.	Sandstone, fine-grained, ledge-forming.	8	2.4
23.	Siltstone and claystone, gray to olive-gray.	4.5	1.4
22.	Sandstone, fine-grained; forms ridge.	4.5	1.4
21.	Claystone, gray, shaly.	2	0.6
20.	Sandstone, dusky-yellow to olive-gray, fine- to very fine grained.		

Unit	Lithology	Thickness ft	m
	Basal bed is 8–10 ft (2.4–3 m) thick; beds in upper part are 0.5–3 ft (15–90 cm) thick.	31	9.5
19.	Claystone, gray; weathers ocherous yellow. Contains two thin beds of brachiopod- and pelecypod-bearing limestone nodules; collection USGS 27487–PC, listed in text discussion of Sandia, was obtained from shale beneath the lower bed.	7.5	2.3
18.	Shale, clay, light-gray, carbonaceous. Near the middle, unit contains several 1–2 inches (2.5–5 cm) thick coal beds.	11	3.4
17.	Sandstone, light-yellowish-gray, fine- to medium-grained; contains a few small pebbles of vein quartz. Lower third is very fine grained and contains thin shale lenses. Contains limonite-filled impressions of fossil wood. Forms small ledge.	10	3
16.	Claystone and siltstone, olive-brown.	2.5	0.76
15.	Shale, clay, yellow, silty.	4	1.2
14.	Shale, clay, medium- to dark-gray, carbonaceous.	4	1.2
13.	Claystone and siltstone, medium-olive-brown; contains a few beds of dark-gray claystone 1–8 inches (2.5–20 cm) thick. Slightly micaceous and carbonaceous. Upper part contorted.	26	7.9
12.	Mainly concealed; slope. Lower 10 ft (3 m), approximately, is claystone; olive-brown, hard. Float suggests that tan, coarse-grained sandstone, olive-brown claystone, and yellow siltstone occur in the concealed interval.	85	25.9
	Total thickness of Sandia Formation:	497.2	151.2
	Tererro Formation:		
	Cowles Member:		
11.	Calcarenite, light-bluish-gray, fine-grained. Contains minute patches and laminae of medium- to coarse-grained quartz sand. Forms ridge.	15.3	4.7
	Manuelitas Member:		
10.	Concealed.	4.8	1.5
9.	Limestone, grayish-orange, sandy, and interbedded siltstone. Beds are 1–18 inches (2.5–45 cm) thick.	1.7	0.52
8.	Limestone, gray; contains irregular masses of pink chert. Basal contact irregular.	3	0.9
	Macho Member:		
7.	Limestone breccia, light-gray; limestone fragments are angular to rounded and range in size from 1 inch–1 ft (2.5–30 cm). Forms ledge.	29.5	9.0
	Total thickness of Tererro Formation:	54.3	16.6
	Espiritu Santo Formation:		
6.	Concealed.	3.5	1.1
5.	Limestone, medium- to dark-gray, sideritic, mostly recrystallized. Contains pods of light-gray limestone near base; upper 1.5 ft (46 cm) contains thin, black-and-white banded chert parallel to bedding. Top foot (30 cm) is gray, coarsely recrystallized limestone with white patches. Beds are 0.5–3 ft (15–90 cm) thick.	8	2.4
4.	Siltstone, shaly, light-olive-brown; forms slight notch.	1	0.3
3.	Limestone, medium-gray, weathers light olive brown; slightly sandy. Beds are 2 inch–2.5 ft (5–75 cm) thick and parallel but slightly undulatory. Silty sandstone partings between beds are 1 inch (2.5 cm) and less thick.	5.7	1.7
	Del Padre Sandstone Member:		
2.	Sandstone, conglomeratic, light-gray, coarse-grained, silica cement; contains vein-quartz pebbles as much as 1 inch (2.5 cm) diameter. Beds are parallel and undulatory.	2	0.61
	Total thickness of Espiritu Santo Formation:	20.2	6.1
	Precambrian rocks:		
1.	Granite gneiss, amphibolite schist, and granite pegmatite; complexly interlayered. Sharp angular unconformity with overlying Espiritu Santo Formation. Just to the west the lower part of the Arroyo Peñasco Group is repeated by a fault that is down-thrown to the west.	Not measured	

Section E

Sapello 7.5-minute quadrangle (1965). Composite section of Porvenir Formation near Cañon del Horno, 1.6–2.5 mi (2.6–4 km) northwest of Manuelitas, at localities E1, E2, and E3. Reference section for northern sandstone-shale-limestone facies of Porvenir Formation. Locality E1 begins in the arroyo in the lower part of Cañon del Horno, about 1,200 ft (365 m) southwest of San Isidro Cemetery, and extends northwestward to exposures along New Mexico Highway 94. Locality E2 is on west side of Cañon del Horno about 800 ft (245 m) southeast of bridge (bench mark 7204 on Highway 94). Locality E3 is on west flank of Bahai anticline on ridges south of Cañon del Horno 2,000–3,500 ft (610–1070 m) west of bridge on Highway 94. Measured by E. H. Baltz. Localities shown in Figures 31 and 83.

Locality E3

Unit	Lithology	Thickness ft	Thickness m
	Alamitos Formation (lower part):		
38.	Conglomerate, light-orange-yellow, weathers brown. Clasts are mainly angular to subangular granules and small pebbles of quartz; about 10 percent of unit is granules and small pebbles, some as much as 0.75 inch (1.9 cm) across, of yellowish-pink and pink potassium feldspar. Contains quartzite pebbles that are angular shaped but have rounded edges and are as much as 1.5 inch (3.8 cm) across. Beds are subparallel and 8 inch–3 ft (0.2–0.9 m) thick; cross-laminated. Forms resistant ledge capping highest part of ridge south of Cañon del Horno. About 200 ft (60 m) to the west the unit contains interbedded red clay shale. Base of unit concealed.	37+	11.3+
	Porvenir Formation:		
37.	Concealed; slope covered by slumped blocks of above unit.	21	6.4
36.	Shale, silty, olive-gray, and interbedded shaly sandstone and thin beds of nodular gray limestone; limestone contains brachiopods and crinoid columnals. Entire unit is poorly exposed and forms a slope.	64	19.5
35.	Sandstone, conglomeratic, light-olive-yellow, feldspathic. Upper third is composed of angular to subrounded, coarse sand, granules, and pebbles as large as 0.5 inch (1.3 cm) of quartz; many pebbles are yellowish-pink, weathered feldspar. Lower part is medium to coarse grained, and about 10 percent is pinkish-gray feldspar; contains a trace of muscovite. Bedding is subparallel to irregular; beds are 0.25 inch–1 ft (0.6–30 cm) thick. Unit forms a moderate ledge.	24	7.3
34.	Concealed; slope.	15	4.6
33.	Limestone, medium-gray, weathers light yellowish gray, micritic. Upper part contains small brachiopods and fusulinids. Unit is nodular weathering and poorly exposed. Fusulinid collection f10292, collected from this unit about 400 ft south of section, contains *Beedeina sulphurensis*.	10	3
32.	Concealed; slope. Float indicates unit is mainly shale.	23	7
31.	Calcarenite, light-tan, weathers light gray. Composed of whole and broken brachiopods in a coarse-grained matrix of brachiopod and crinoid fragments; contains much angular, medium to very coarse sand and granules of quartz and a trace of pink feldspar. Upper 5 ft (1.52 m) is silty, fine-grained calcarenite. Some beds grade laterally into highly calcareous quartz sandstone. Bedding is subparallel to crossbedded; beds are 0.5–2 ft (15–61 cm) thick; generally cross-laminated. Forms resistant ledge. This is the "marker" zone of the upper part of the Porvenir Formation.	25	7.6
30.	Shale, clay, and siltstone and shaly sandstone; weathers olive gray. Lower part is shaly, calcareous, fine-grained sandstone and siltstone. Contains a few 6 inch thick (15 cm) beds of sandy, silty, limestone. Calcareous sandstone beds contain many large brachiopods and a few small zaphrentid corals. Forms slope on west side of gully.	66	20.1
	[Locality offset about 500 ft (150 m) north from ridge crest by tracing unit 29 northward to gully. Section above continues westward.]		
29.	Limestone, medium-gray, weathers brown; slightly sandy and micaceous; about 50 percent of rock is small brachiopods. Forms small rounded ledge.	1	0.3
28.	Shale, clay, and silt, olive-brown-weathering. Forms small outcrop on slope.	5	1.5
27.	Concealed; slope. Poor outcrops nearby indicate unit is interbedded shale and shaly calcareous sand stone.	52	15.9
26.	Sandstone, olive-brown, fine- to medium-grained, argillaceous, slightly micaceous. Beds are 0.5 inch (1.27 cm) and less thick. Forms slight ledge.	5.5	1.7
25.	Concealed; gentle slope.	40	12.2

Unit	Lithology	Thickness ft	Thickness m
24.	Sandstone, orange-brown-weathering, medium- to coarse-grained, slightly micaceous. Forms small ledge.	4	1.2
23.	Concealed; slope.	18	5.5
22.	Sandstone, conglomeratic, light-yellowish-gray, weathers pinkish-brown. Mainly angular, very coarse sand, granules, and pebbles as large as 0.25 inch (0.64 cm) of quartz. About 10 percent is yellow, weathered feldspar. Forms small ledge.	13	4
21.	Concealed; gentle slope. Poor exposures nearby indicate unit is interbedded shale and thin sandstone.	35	10.7
20.	Limestone, light-tan, weathers light gray. Oolitic, bioclastic, sandy; contains much crinoid-columnal debris. Angular, medium quartz sand is common as scattered grains and in irregular stringers 0.06–0.25 inch (0.16–0.64 cm) thick. Beds are 2–6 inches (5–15 cm) thick. Poorly exposed; forms ledge.	9	2.8
19.	Concealed; gentle slope. Float suggests unit is mainly shale.	20	6.1
18.	Sandstone, conglomeratic, light-yellowish-gray, weathers light-pinkish-brown. Coarse- to very coarse grained; contains lenses of granules and pebbles of quartz as much as 0.25 inch (0.6 cm) diameter. About 5 percent is yellow and yellowish-pink feldspar in all size ranges. Forms ridge; top is poorly exposed.	18	5.5
17.	Concealed; slope.	41	12.5
16.	Siltstone, shaly, light-olive-gray. Forms slope.	33	10
15.	Limestone, light-brownish-gray, fossiliferous; forms small ledge.	1	0.3
14.	Concealed; slope.	25	7.6
13.	Sandstone, conglomeratic, weathers light yellowish brown, feldspathic. Composed of fine to coarse sand and granules; upper third contains pebbles as large as 1 inch (2.5 cm) diameter. About 10 percent of all clast sizes is yellow, weathered feldspar. Lower part is soft; upper part forms a weak ledge.	35	10.7
12.	Shale, clay, silty, light-olive-gray. About 20 percent of unit is limestone beds 1–3 inches (2.5–7.6 cm) thick. Forms slope; exposed in gully.	30	9.2

[Locality offset about 150 ft (45 m) north by tracing unit 11 north from ridge crest to gully. Section above continues westward.]

Unit	Lithology	Thickness ft	Thickness m
11.	Limestone, light-gray, silty, micritic, slightly siliceous. Algal filaments are common in some beds. Bedding is undulatory; beds are 1 inch–1 ft (2.5–30 cm) thick. Forms small ledge.	10	3
10.	Sandstone, conglomeratic, light-orangish-tan. Clasts are angular to subangular, coarse sand and granules of quartz; about 5 percent of clasts is yellow, weathered feldspar. Upper 11 ft (3.4 m) contains quartzite pebbles as much as 1 inch (2.5 cm) diameter. Forms moderate ledge.	44	13.4
9.	Limestone, gray, nodular, sandy. Irregularly shaped nodules, 1–2 inches (2.5–5 cm) across, are surrounded by brown-weathering sandy limestone matrix. Forms poorly exposed, ledgy slope; probably contains thin interbeds of shale.	10	3
8.	Limestone, medium-gray, weathers light gray, silty, micritic. Contains a few brachiopods and crinoid columnals and many algal filaments and bands. Bedding is undulatory; beds are 2–6 inches (5–15 cm) thick. Forms small ledge.	19	5.8
7.	Concealed; gentle slope.	48	14.6
6.	Sandstone, brown, medium-grained, slightly micaceous. Beds are 1–2 inches (2.5–5 cm) thick. Forms slabby ledge.	8	2.4
5.	Siltstone and limestone, brownish-gray-weathering. Lower half is calcareous siltstone, thin bedded to shaly; grades upward into silty, fossiliferous, thin-bedded limestone. Unit forms small ledge.	10	3
4.	Mainly concealed; gentle slope. A few small outcrops are olive-gray, silty clay shale.	66	20.1
3.	Limestone, gray, silty, micritic; contains some fine-grained fossil debris. Forms small ledge.	9	2.8
2.	Siltstone, greenish-gray, calcareous, shaly. Contains some interbeds of thin limestone. Forms slight ledge.	23	7
1.	Sandstone, feldspathic; forms poorly exposed ledge just east of wire fence just south of crest of ridge between Cañon del Horno and first canyon to the south. Base of locality E3; overlying units were measured westward along the crest of the ridge.	Not measured	

Locality E2

[Units 11–13 below, were traced southwestward from locality E2 along south wall of small canyon south of Cañon del Horno, across the axis of the Bahai anticline, and northward to the crest of the ridge between canyons. Unit 9, below, correlates approximately with unit 1 of locality E3. Therefore, the thicknesses of units 10–16 below are not included in the total thickness of the composite section.].

Unit	Lithology	Thickness ft	Thickness m
	Porvenir Formation-Continued		
16.	Shale, dark-gray, carbonaceous, flaky, and olive-gray silty mudstone. Unit is poorly exposed below grassy slope in axial part of syncline, just south of tributary canyon south of Cañon del Horno. Top of locality E2. Thickness is 5 ft (1.5 m).	(See note above)	
15.	Sandstone, light-orangish-gray-weathering. Composed of subangular to subround, medium to coarse sand and granules of quartz; slightly micaceous. Slightly inclined bedding; beds are 2 inch–1 ft (5–30 cm) thick. Forms slabby ledges in bottom of arroyo. Thickness is 9 ft (2.8 m).	—	—
14.	Shale, clay, dark-gray, carbonaceous. Poorly exposed; forms slope. Thickness is about 6 ft (1.8 m).	—	—
13.	Limestone, light-olive-gray, silty; contains many brachiopods. Forms small ledge. Thickness is about 2 ft (0.6 m).	—	—
12.	Shale, clay, gray; poorly exposed on slope. Thickness is 2 ft (0.6 m).	—	—
11.	Limestone, brownish-gray, silty; contains corals and brachiopods. Forms small ledge. Thickness is 2.5 ft (0.76 m).	—	—
10.	Siltstone, dark-gray, weathers brownish gray; calcareous and highly carbonaceous. Thin bedded to shaly. Forms slight ledge and blocky outcrop on south bank of arroyo. Thickness is 17 ft (5.2 m).	—	—

[Thicknesses of units 10–16 are not used in composite thickness of Porvenir Formation and therefore, are not shown in columns at the right.]

Unit	Lithology	Thickness ft	Thickness m
9.	Sandstone, conglomeratic, similar to unit 6. Forms small benchy ledge. Upper part of sandstones of Fragoso Ridge.	5	1.5
8.	Concealed.	5.5	1.7
7.	Sandstone, shaly, and interbedded sandy shale. Forms poorly exposed slope.	11	3.4
6.	Sandstone, conglomeratic, light-orange-gray. Composed of angular to subround, coarse sand, granules, and pebbles as large as 0.75 inch (1.9 cm) diameter. About 5 percent is yellow to gray, weathered feldspar. Crossbedded; beds are 1–3 ft (0.3–0.9 m) thick. Forms ledge; base concealed, upper half poorly exposed.	30	9
5.	Concealed; slope. Probably shaly sandstone.	3	0.9
4.	Sandstone, light-olive-tan, fine- to medium-grained, micaceous. Thin to shaly bedded. Grades into under lying unit. Forms slope.	5.5	1.7
3.	Sandstone, conglomeratic, yellowish-gray-weathering. Composed of angular to subround, coarse sand, granules and quartzite pebbles as large as 0.75 inch (1.9 cm). Contains a trace of yellow, weathered feldspar. Moderately crossbedded; beds are 2–6 ft (0.6–1.8 m) thick. Grades abruptly into underlying unit. Forms ledge.	11	3.4
2.	Sandstone, orangish-gray-weathering. Composed of subround, fine to medium quartz sand; slightly micaceous and argillaceous. Beds are less than 1 inch (2.54 cm) thick. Base not exposed. This unit is the basal part of the sandstones of Fragoso Ridge.	6	1.8
1.	Limestone, gray, very fine grained. Contains unbroken brachiopods and zaphrentid corals scattered through matrix. Contains fine-grained bioclastic layers. Bedding is highly undulatory; beds in upper part swell to form local mounds; beds are 1 inch–1 ft (2.5–30 cm) thick. Forms massive ledge at west side of alluvial valley in Cañon del Horno. Unit is contorted into a small anticline. West end of outcrop is slickensided, probably along a small fault that may be a concentric shear in the fold. Displacement probably is small because the succession is approximately the same as at outcrops east of valley. Base of locality E2.	17.5	5.3

Locality E1

[Unit 20 below was traced southwestward from locality E1 along the ledge at the east side of the valley of Cañon del Horno. Taking into account a small syncline and anticline in the valley, unit 20 of locality E1 probably correlates with the massive limestone of unit 1 (above) of locality E2, which crops out on the west side of the valley. Units 21–28 of locality E1 apparently correlate with units 2–9 of locality E2, although the interval is thinner and a little more shaly at locality E2. Therefore, the thickness of units 20–35 of locality E1, below, are not included in the total thickness of the composite section. Section at locality E2, above, was measured westward into the lower part of a small canyon that is tributary to Cañon del Horno just west of bridge (bench mark 7204) on New Mexico Highway 94.]

Unit	Lithology	Thickness ft	Thickness m
35.	Sandstone, orangish-brown. Composed of subangular to subround, fine to coarse quartz sand; contains a trace of muscovite and yellow, weathered feldspar. Bedding is parallel; beds are 4 inch–1 ft (10–30 cm) thick. Forms a blocky ledge at top of hill. Thickness is 12 ft (3.7 m).	(See note above)	
34.	Sandstone, medium-gray, weathers grayish brown. Fine grained, highly calcareous; thin bedded. Poorly exposed on slope; float indicates some thin interbeds of gray, fossiliferous limestone. Thickness is 11 ft (3.4 m).	—	—
33.	Mainly concealed; slope. Exposure near middle is shaly sandstone about 3 ft (0.9 m) thick. Unit is 40 ft (12.2 m) thick.	—	—

[Unit 32 was traced eastward about 250 ft (76 m) along the hillside and section then continues up the hill.]

Unit	Lithology	Thickness ft	Thickness m
32.	Limestone, light-gray, very fine grained. Contains rare gastropods and brachiopods. Contains irregular, brown-weathering siliceous patches. Bedding is 3–8 inches (7.6–20 cm) thick. Forms blocky ledge. Thickness is 6 ft (1.8 m).	—	—
31.	Concealed; bench on slope. Thickness is 12 ft (3.7 m).	—	—
30.	Sandstone, feldspathic, granule-grained, micaceous. Forms small ledge. Thickness is 4 ft (1.2 m).	—	—
29.	Concealed; slope on bench. Float indicates unit is probably sandy shale and shaly sandstone. Thickness is 22 ft (6.7 m).	—	—
28.	Sandstone, feldspathic; similar to unit 25. Forms small bench. Thickness is 11 ft (3.4 m). Upper part of sandstones of Fragoso Ridge.	—	—
27.	Concealed; slope on bench. Thickness is 6 ft (1.8 m).	—	—
26.	Sandstone, arkosic; similar to unit 25 and continuous with it. Thickness is 8 ft (2.4 m).	—	—

[At crest of hill on Highway 94 locality of measurement turns north. Units above were measured northward up the hill west of a house.]

Unit	Lithology	Thickness ft	Thickness m
25.	Sandstone, conglomeratic, light-olive-buff, weathers light yellowish orange, feldspathic. Composed mainly of angular to subangular, irregularly shaped, very coarse sand, granules, and pebbles as large as 0.5 inch (1.27 cm) of quartz. About 20 percent of clasts in all grain sizes is yellow, weathered feldspar. Contains a trace of muscovite. Large-scale trough crossbedding, mainly inclined southwest; beds are 1 inch–1 ft (2.5–30 cm) thick. Lower and upper parts of unit form blocky ledges in roadcut; middle part less well exposed in gully north of road. Thickness is 71.5 ft (21.8 m). Unit is basal part of sandstones of Fragoso Ridge.	—	—
24.	Shale, light-orange-yellow-weathering. Unit is interbedded clay shale, shaly siltstone, and sandy, micaceous shale. Forms slope in road cut. Thickness is 6.5 ft (2 m).	—	—
23.	Sandstone, conglomeratic, light-yellowish brown. Composed of angular to subangular, fine to very coarse quartz sand; contains quartz pebbles as large as 0.5 inch (1.3 cm) across. Contains a trace of white and yellow weathered feldspar and muscovite. Forms ledge in road cut. Thickness is 2 ft (0.6 m).	—	—
22.	Shale, clay, light-yellowish-gray-weathering. About 20 percent of unit is irregularly bedded to nodular limestone in beds 1–6 inches (2.5–15 cm) thick. Limestone contains a few tiny brachiopods. Shale in upper half is highly carbonaceous. Unit forms slope in road cut. Thickness is 8 ft (2.4 m).	—	—
21.	Sandstone, light-yellowish-gray, weathers light orangish gray. Clasts are mainly subangular, fine to coarse quartz sand; contains a trace of weathered, yellowish feldspar. Some bedding planes are covered with muscovite plates. Bedding is subparallel; beds are 1–6 inches (2.5–15 cm) thick. Forms blocky ledge in road cut. Thickness is 5.5 ft (1.7 m).	—	—
20.	Limestone, light-gray, weathers light yellowish gray. Matrix is very fine grained, but contains many small brachiopods and fossil debris. Contains thin shaly partings that are partly silicified and weather in relief. Bedding is irregular and un-		

Unit	Lithology	Thickness ft	Thickness m
	dulatory; beds are 0.5–2 ft (15–60 cm) thick. Forms irregular, hackly weathering ledge in road cut. Top and base not exposed. Thickness is 6 ft (1.8 m). Unit was traced south of Highway 94 where it forms a bench on which a house and windmill are situated. Unit thickens southward and forms a strong ledge east of the alluvial valley of Cañon del Horno. Unit is correlated with ledge-forming limestone at west side of valley which is unit 1 of locality E2. Thicknesses of units 20–35 of locality E1, above, are not included in the composite thickness of the Porvenir and, therefore, are not shown in the columns at the right. Section above unit 20 at locality E1 continues westward in road cuts along Highway 94.	—	—
19.	Shale, clay, gray, silty, slightly calcareous, slightly fossiliferous. Forms slope in road cut.	34	10.4
18.	Limestone, light-gray, fine-grained, dense-appearing; partly brecciated and recrystallized; sparsely fossiliferous. Forms small ledge in road cut; base and top not exposed.	3	0.9
17.	Shale, yellowish-gray to light-yellowish-brown; contains interbedded calcareous siltstone and claystone. Upper 3 ft (0.9 m) is shaly, very fine grained sandstone. Unit contains brachiopods. Forms slope in road cut.	11	3.4
16.	Shale, clay, medium-gray. Forms slope in road cut.	11	3.4
15.	Limestone, light-gray, weathers yellowish gray, very fine grained. Contains brachiopods, crinoid columnals, bryozoans, and fusulinids scattered through the matrix; some thin layers are bioclastic. Bedding parallel but undulatory; beds are 2 inch–1.5 ft (5–45 cm) thick, and are generally thinner in lower half than in upper half. Upper half contains a few shale beds less than 1 inch (2.5 cm) thick; about 20 percent of lower half is shaly limestone and limy shale interbedded with thin limestone. Forms ledge in eastern part of road cut on Highway 94.	18	5.5
14.	Mainly concealed; slope on west side of hill and small valley south of Highway 94 and west-southwest of San Isidro Cemetery. Uppermost 5 ft (1.5 m) of unit in easternmost part of road cut on Highway 94 is gray, calcareous shale that grades into overlying unit. Exposures in Cañon del Horno to the southwest indicate unit is mostly shale. Thickness approximate.	54	16.5
13.	Limestone, light-gray, and interbedded light-grayish-brown shale. Limestone is fine grained and contains sparse brachiopods and other fossil fragments. Bedding is undulatory; beds are 1–6 inches (2.5–15 cm) thick. Shale beds are generally less than 2 inches (5 cm) thick. Forms low ledge and cuesta on grassy hill southwest of Highway 94.	11	3.4
12.	Shale, clay, gray, calcareous; contains thin irregular interbeds of gray limestone. Poorly exposed on slope.	11	3.4
11.	Limestone, light-yellowish-gray-weathering, partly recrystallized. Contains banded algal structures and limestone breccia in dense matrix. Bedding not apparent. Unit may be a low, complex bioherm composed of small algal mounds and algal-mat breccia. Grades into underlying unit. Forms rounded weathering ledge.	8	2.4
10.	Limestone, medium-gray, very fine grained. Contains lenses, about 1 inch (2.5 cm) thick, of angular limestone fragments and a few lenses containing brachiopods and gastropods. Bedding is wavy; beds are 1–6 inches (2.5–15 cm) thick. Forms ledge. Large "biscuit-shaped" bioherm standing in field southeast of San Isidro Cemetery is in about same stratigraphic position as this unit. Fusulinid collection f10131 from limestone in approximately the same stratigraphic position about 1,600 ft (490 m) east–northeast of San Isidro Cemetery contains *Fusulinella* aff. *F. oakensis*.	3	0.9
9.	Concealed; slope.	5.5	1.7
8.	Limestone, light-gray, weathers light yellowish gray; fine-grained; locally bioclastic. Locally slightly brecciated and recrystallized. Bedding is highly undulatory; beds are 4 inches–2 ft (10–60 cm) thick. Beds form small low mounds. Brachiopods are common in some beds. Forms ledge.	6	1.8
7.	Concealed; slope.	3	0.9
6.	Limestone, light-gray, weathers light yellowish gray. Matrix is dense and contains scattered small brachiopods, crinoid columnals, and echinoid spines; upper part is finely bioclastic. Forms small ledge. Units 6–11 form a low grassy ridge rising above the north bank of the arroyo in Cañon del Horno and were measured northward along the ridge.	2.5	0.76
Total	composite thickness of Porvenir Formation (units 6–19 of loc. E1, units 1–9 of loc. E2, and units 2–37 of loc. E3):	1,156	352.4

Unit	Lithology	ft	m
	Sandia Formation (upper part):		
5.	Concealed; interval measured up slope on north side of arroyo to out crop of unit 6.	27	8.2
4.	Shale, clay, gray, calcareous. Near middle, unit contains two limestone beds, each 6 inches (15 cm) thick, that are similar to unit 3.	13	4
3.	Limestone, dark-gray, micritic; contains scattered small gastropods, ostracodes(?), and tiny fragments of fossils. Beds are 1–6 inches (2.5–15 cm) thick.	1.5	0.46
2.	Concealed; alluvium in arroyo.	16	4.9
1.	Shale, clay, medium-gray, weathers light yellowish gray, calcareous. Scanty exposures to the east are similar. Base of locality E1.	10	3

[Base of locality E1 is in the arroyo in the lower part of Cañon del Horno northeast of the Bahai school and about 1,200 ft (365 m) southwest of San Isidro Cemetery (in Fig. 83). Units 1–5 were measured in the arroyo and on its north bank.]

Section F

Mora 7.5-minute quadrangle (1965). Composite section of Porvenir Formation, northwest side of Fragoso Ridge. South of west end of water gap of Rito Cebolla, about 3.6 mi (5.8 km) west–northwest of bridge across Rito Cebolla on New Mexico Highway 518 (shown as Highway 3 on Sapello 7.5-minute quadrangle, 1965). Base of section is on north-trending spur north of Fragoso Ridge near axis of anticline at about altitude 7,620. Lower part of section was measured eastward on abandoned road to about axis of anticline, then southward up Fragoso Ridge to its crest. Section was then offset west and continued southward along the drainage divide south of Fragoso Ridge to another high ridge about 1.3 mi (2 km) southwest of Rito Cebolla. Measured by E. H. Baltz. Locality shown in Figures 31 and 84.

Unit	Lithology	Thickness ft	Thickness m
	Alamitos Formation (lower part):		
74.	Sandstone, conglomeratic, pinkish-gray, weathers purplish brown, feldspathic. Composed of angular to subangular, coarse sand, granules, and small pebbles; about 15 percent of clasts is pink feldspar in all grain sizes up to 0.25 inch (0.6 cm) pebbles. Forms ledge capping hill. Exposures about 150 ft (45 m) south show that maroon shale is interbedded. Top eroded; forms south-sloping cuesta.	38+	11.6+
73.	Concealed; slope.	15	4.6
72.	Shale, silty, gray; contains several 6-inch (15-cm) thick beds of gray nodular limestone. Poorly exposed on slope.	20	6.1
71.	Limestone, light-gray, weathers light yellowish gray. Bioclastic, silty, sandy; mainly coarse-grained fragments of brachiopods. Slightly nodular-weathering. Poorly exposed on slope.	2.5	0.76
70.	Concealed; slope.	19	5.8
69.	Sandstone, conglomeratic, weathers light yellowish gray, feldspathic; mainly very coarse grained. Contains weathered, yellowish-gray, cleavage fragments of feldspar as large as 0.25 inch (0.6 cm). Forms slight ledge.	2	0.6
68.	Mainly concealed; slope. Scanty exposures suggest unit is mainly soft sandstone.	26	7.9
67.	Sandstone, pinkish-gray, feldspathic. Clasts are coarse sand and granules. Some feldspar clasts are unweathered and pink to pinkish red. Forms slight ledge.	20	6.1
66.	Shale, maroon-weathering, poorly exposed. May contain some thin interbeds of olive-green hard sand stone.	4	1.2
	Thickness of measured lower part of Alamitos Formation:	146.5+	44.7+
	Porvenir Formation:		
65.	Limestone, light-gray, weathers light gray; bioclastic, sandy. Coarse-grained matrix is mainly brachiopod fragments; contains scattered, angular, quartz granules. Bedding is slightly undulatory but mainly is parallel; beds are 1 inch–1 ft (2.5–30 cm) thick. Forms prominent ledge.	12	3.7
64.	Shale, silty, olive-gray. Poorly exposed on slope.	42	12.8
63.	Limestone, light-gray; mainly a coquina of brachiopods and bryozoans; contains some angular, quartz-granule sand. Bedding is irregular; beds are 1–6 inches (2.5–15 cm) thick. Forms small ledge.	6	1.8
62.	Shale, clay, olive-gray, silty. Poorly exposed on slope.	13	4
61.	Limestone, light-gray, sandy, bioclastic. Mainly very coarse grained fragments of crinoid columnals and bryozoans; contains some brachiopods. Contains much angular quartz sand. Contains angular pebbles of dense, gray limestone. Forms a moderately exposed low ledge.	8.5	2.6
60.	Sandstone, calcareous, similar to unit 58.	2	0.6
59.	Shale, poorly exposed; similar to unit 55.	21	6.4
58.	Sandstone, light-gray, weathers yellow gray; fine- to medium-grained. Some beds are highly calcareous. Bedding is parallel; beds are		

Unit	Lithology	Thickness ft	m
	1–6 inches (2.5–15 cm) thick. Forms slabby-weathering, low ledge.	21	6.4
57.	Shaly siltstone, similar to unit 56, but forms slope.	21.6	6.6
56.	Siltstone, medium-gray, weathers olive gray, calcareous, shaly. Forms low ridge.	3	0.9
55.	Shale, olive-gray-weathering, sandy, poorly exposed. Contains 6-inches (15-cm) thick bed of gray limestone coquina near base. Forms slope.	15	4.6
54.	Sandstone, conglomeratic, yellowish-gray, feldspathic; similar to unit 50. Upper half forms low ridge; lower part forms slope.	31	9.5
53.	Shale, olive-yellow, calcareous; poorly exposed; forms slope.	2.5	0.76
52.	Limestone, medium-gray, weathers light gray; fine grained and even textured; contains scattered ostracodes. Upper half is silty. Beds are parallel and 0.5–2 inches (1.3–5 cm) thick. Forms slabby outcrop.	5	1.5
51.	Shale, olive-gray, calcareous; poorly exposed; forms slope.	2	0.6
50.	Sandstone, conglomeratic, yellow-gray-weathering, feldspathic. Mainly medium to coarse grained; contains angular, yellowish-gray feldspar granules and pebbles as much as 0.25 inch (0.6 cm) diameter. Upper part contains feldspar pebbles as large as 0.75 inch (1.9 cm) diameter. Upper part forms small ridge; lower part is soft and forms slight ledge.	25	7.6
49.	Shale, clay, olive-gray; poorly exposed.	3	0.9
48.	Limestone, light-olive-gray, weathers brown, bioclastic. Matrix is coarse grained, composed mainly of fragments of brachiopods, bryozoans, and echinoid spines; contains some large brachiopods and scattered fusulinids. Forms slight ledge. Fusulinid collection f10285 contains *Fusulinella* sp., *Beedeina* sp., and ?*Plectofusulina* sp. The fusulinids are abraded and apparently reworked.	0.5	0.15
47.	Shale, clay, olive-gray; poorly exposed.	5	1.5
46.	Sandstone, light-grayish-orange-weathering, feldspathic. Clasts are angular to subangular, coarse to very coarse sand and granules; becomes fine- to medium-grained near top. 20 percent of clasts is pink feldspar. Forms small ridge.	5	1.5
45.	Shale, clay, olive-gray. Poorly exposed; forms slope.	10.5	3.2
44.	Sandstone, conglomeratic, light-yellowish-orange-weathering, arkosic. Clasts are angular to subround, fine to very coarse sand, granules, and pebbles as much as 0.5 inch (1.3 cm) diameter. Matrix is micaceous and argillaceous. Weathered feldspar clasts are orange-pink granules and small pebbles. Lower two thirds is soft and weathers to slope; upper third is hard, medium-grained, micaceous, feldspathic sandstone that forms a small ridge.	21	6.4
43.	Concealed; gentle slope.	15	4.6
42.	Shale, clay, olive-gray; contains botryoidal limestone concretions 0.1–1.25 inch (0.3–3.2 cm) in length. Poorly exposed on gentle slope.	10.5	3.2
41.	Concealed; slope.	3	0.9
40.	Sandstone, conglomeratic, light-yellowish-brown-weathering, arkosic, very coarse grained; contains pebbles as much as 0.5 inch (1.3 cm) in diameter of weathered yellowish feldspar. Forms low ridge.	13	4
39.	Concealed.	7	2.1
38.	Limestone, sandy, and interbedded calcareous sandstone, light-gray. Unit is mostly angular, coarse quartz sand and granules in calcite cement. Contains a trace of bioclastic material and a trace of mica. Forms low poorly exposed ledge.	10.5	3.2

[Unit 37 was traced about 150 ft (45 m) east to place where wood-haulers road crosses the ridge. Unit 37 was measured at that point. Top of unit was then traced back to west and section continues southwest along drainage divide, mainly along the wood-haulers road.]

Unit	Lithology	Thickness ft	m
37.	Sandstone, conglomeratic, light-yellowish-gray, weathers light yellowish brown, feldspathic. Composed of angular to subangular, very coarse sand, granules, and scattered subround pebbles 0.25–0.5 inch (0.6–1.3 cm) diameter; 15 percent is pinkish-gray to yellowish-gray, weathered feldspar in all grain sizes including small pebbles. Cross-bedded; beds are 0.5–2.5 ft (15–76 cm) thick. Forms rounded ledge.	43	13.1
36.	Concealed; low, flat saddle along wood-haulers road.	50	15.3
35.	Sandstone, yellowish-gray, weathers yellowish orange, feldspathic. Composed of angular to subangular, coarse sand; about 10 percent is weathered yellow feldspar. Bedding is irregular; beds are 4 inch–2 ft (10–60 cm) thick. Upper and lower parts form slabby low ridges; middle part poorly exposed.	52.8	16.1
34.	Limestone, light-gray, sandy, bioclastic, oolitic. Matrix is mainly fine to coarse fossil fragments; contains brachiopods, a trace of crinoid columnals, algal filaments, oolitic lenses, fusulinids, and fine to medium quartz sand. Forms prominent		

Unit	Lithology	Thickness ft	m
	high ridge but is poorly exposed. Unit was traced about 200 ft (60 m) southeast to better exposures where it was measured. There, the unit is massive to crossbedded, and contains lenses of angular quartz granules; the upper 5 ft (1.52 m) contains a lens of gray, granule arkose. Fusulinid collection f10284 contains *Bradyina* sp., *Tetrataxis* sp., *Wedekindellina* sp., *Beedeina* sp., and *Fusulinella* sp. The association suggests early Desmoinesian age, but the fusulinids are abraded and probably are reworked.	24.6	7.5
33.	Sandstone, shaly, very fine grained; contains several sandy limestone beds that are 1–6 inches (2.5–15 cm) thick. Forms slope; poorly exposed.	10.3	3.1
32.	Concealed; slope; probably shale.	31	9.5
31.	Sandstone, light-yellowish-orange, medium- to coarse-grained, feldspathic; contains yellow and orange, weathered feldspar. Platy weathering; forms small, rounded ledge.	17.4	5.3
30.	Mainly concealed; slope; lower half has poor exposures of gray, calcareous shale.	52	15.9
29.	Limestone, light-gray. Matrix is mainly micrite that contains algal filaments and small brachiopods. Forms small, resistant ledge.	2.5	0.76
28.	Sandstone, light-yellowish-gray, medium-grained to very coarse grained; contains some granules. About 5 percent is yellow to pink, weathered feldspar. Forms poorly exposed rounded ledge.	24	7.3
27.	Shale, similar to unit 23; poorly exposed on slope.	19	5.8
26.	Limestone, light-yellowish-gray; contains silt and fine sand. Platy weathering. Forms slight ledge.	2.5	0.76
25.	Shale, clay, light-gray-weathering, silty, calcareous. Poorly exposed on slope.	23.4	7.1

[Units 25–33 above were measured along wood-haulers road up the slope from the saddle southward toward a prominent southeast-trending ridge.]

Unit	Lithology	Thickness ft	m
24.	Limestone, medium-gray, argillaceous; beds are 0.25–2 inches (0.6–5 cm) thick. Forms platy-weathering small ledge.	3	0.9
23.	Shale, clay, medium-gray, weathers light gray; calcareous and silty. Contains some brachiopods. Forms valley east of topographic saddle.	6.4	2
22.	Concealed.	24	7.3
21.	Sandstone, conglomeratic, feldspathic, similar to unit 14. Forms small ledge. Uppermost unit of sandstones of Fragoso Ridge.	9.6	2.9
20.	Sandstone, similar to unit 18. Poorly exposed.	20.6	6.3
19.	Sandstone, conglomeratic, feldspathic, coarse-grained to pebbly; similar to unit 14. Forms small ridge	16.4	5
18.	Sandstone, fine-grained, micaceous, shaly; platy weathering. Poorly exposed.	6	1.8
17.	Sandstone, light-orange-brown, fine- to medium-grained, thinly laminated, partly shaly; coarse-grained near top. Poorly exposed on south-facing slope.	6	1.8

[Unit 16 was traced westward about 750 ft (230 m) along Fragoso Ridge to a point about 250 ft (75 m) east of a major topographic saddle between southeast- and northwest-draining canyons. Correlation of unit 16 to this point, just north of a wood-haulers road, is approximate because of poor exposures. Units 17–24 were measured southward down the slope of Fragoso Ridge to the southeast-draining valley.]

Unit	Lithology	Thickness ft	m
16.	Sandstone, conglomeratic, feldspathic; similar to unit 14. Caps Fragoso Ridge.	38.5	11.7
15.	Sandstone, yellowish-orange-weathering, medium- to coarse-grained; slightly feldspathic, slightly micaceous. Poorly exposed; may contain some thin shale interbeds.	47	14.3
14.	Sandstone, conglomeratic, light-yellowish-gray, weathers light yellowish brown, feldspathic. Composed of angular to subround, very coarse sand and granules of quartzite; contains scattered quartzite pebbles as large as 0.25 inch (0.6 cm) diameter; about 15 percent of clasts is yellow, deeply weathered feldspar; muscovite flakes are common. Kaolin and silica cement is fair to good. Bedding is subparallel to slightly inclined; beds are 4 inch–2 ft (10–60 cm) thick. Forms massive basal ledge of the sandstones of Fragoso Ridge. Base concealed.	65	19.8
13.	Concealed by talus from above; steep, north-facing slope. Probably mostly shale; float in lower 100 ft (30 m) contains a trace of limestone.	176	54

[Section above continues southward up the north slope of Fragoso Ridge.]

Unit	Lithology	Thickness ft	m
12.	Limestone, light-gray. Upper part is coarsely recrystallized and is mainly interbedded oolite and fine- to medium-grained bioclastic limestone; contains some angular limestone pebbles as much as 0.5 inch (1.3 cm) across. Lower part is fine-banded stromatolitic limestone that has been largely replaced by white-and-gray banded chert. Forms poorly exposed ledge on abandoned road near axis of anticline.		

Unit	Lithology	Thickness ft	m
	Fusulinid collection f10291 from the unit contains *Beedeina* cf. *B. arizonensis* and *Wedekindellina* aff. *W. cabezasensis*.	21	6.4
	Total thickness of Porvenir Formation:	1,127	343.7
	Sandia Formation (upper part):		
11.	Concealed.	10	3
10.	Shale, clay, light-yellowish-gray-weathering, silty, calcareous. Contains several 6-inch (15-cm) thick beds of dark-gray, very fine grained, silty limestone. Contains a few brachiopods. Forms slope.	10	3
9.	Concealed.	74.5	22.7
8.	Shale, dark-gray; composed mainly of silty, very fine-grained shaly sandstone and sandy shale. About 10 percent of unit is 1–6-inch (2.5–15-cm) thick beds of fine-grained sandstone. Some thin, dark-gray, silty limestone beds occur near top.	16	4.9
7.	Concealed.	37	11.3
6.	Shale, dark-gray, sandy, silty, poorly exposed.	5.3	1.6
5.	Siltstone, dark-gray, and interbedded dark-gray silty, fine-grained limestone. Contains a few brachiopod fragments; carbonaceous. Beds are 1–6 inches (2.5–15 cm) thick.	5	1.5
4.	Shale, gray, sandy; poorly exposed.	21	6.4
3.	Sandstone, light-yellowish-gray, medium- to coarse-grained, feldspathic, micaceous. Bedding is parallel to irregular; beds are 0.06–1 inch (0.16–2.5 cm) thick. Forms slope.	5.3	1.6

[Units 3–12 above were measured eastward along abandoned wood-haulers road at north base of Fragoso Ridge.]

Unit	Lithology	Thickness ft	m
2.	Sandstone, conglomeratic, light-yellowish-gray, weathers yellowish brown, feldspathic. Composed of angular to subround very coarse quartz sand, granules, and pebbles as much as 0.25 inch (0.6 cm) across. About 20 percent is yellowish-gray to pink, weathered feldspar in all grain sizes. Contains scattered, 0.5–2 inch (1.3–5 cm) diameter subangular to subround pebbles of vein quartz; also contains distinct lenses of pebbles. Near base, unit contains limestone-pebble conglomerate. Bedding is irregular to crossbedded. Forms ledges holding up north-projecting topographic spur. Base not exposed.	120+	36+
1.	Concealed.	Not measured	
	Thickness of measured upper part of Sandia Formation:	304+	92+

[Unit 2 was measured beginning near south end of north-trending topographic spur north of Fragoso Ridge near axis of anticline at about altitude 7,620 ft. Top of unit is at abandoned wood-haulers road at south end of spur.]

Section G

Montezuma 7.5-minute quadrangle (1961). Composite section of Alamitos, Porvenir, Sandia, Tererro, and Espiritu Santo Formations measured west and southwest of Montezuma. Base of section is on hill south of Gallinas Creek along abandoned ditch of Public Service Company about 0.3 mi (0.5 km) west of Montezuma powerhouse. Sandia Formation was measured through poor exposures up the hill to ledge-forming basal limestone of Porvenir Formation that forms a sloping bench on the hillside. Lower part of Porvenir was measured up the hill to a limestone that caps another higher east-sloping bench. The stratigraphic position of this limestone was traced southeastward around the head of the small north-draining valley that debouches at the Montezuma powerhouse.

Section of Porvenir resumes at abandoned wood-haulers road on west side of ridge southwest of the large limestone quarry, continues eastward through the quarry and down the hill toward the Public Service Co. Peterson Reservoir to the spillway in the ditch at the west side of the lake. Rocks exposed here were traced south to mouth of small canyon west of the earth dam at south end of lake. Upper part of Porvenir and poorly exposed lower part of Alamitos Formation were measured eastward from west side of canyon up the ridge on the east side of canyon.

Base of Alamitos was traced southwestward about 0.5 mi (0.8 km) to sharp meander kink in Lime Canyon. Detailed section of lower part of Alamitos was measured from west edge of Lime Canyon eastward partly up ridge east of Lime Canyon. Section was then offset southward about 300 ft (90 m) along the ridge and continued east across the ridge to a small northeast-draining valley in the Sangre de Cristo Formation. Measured by E. H. Baltz. Localities shown in Figures 31 and 85.

Unit	Lithology	Thickness ft	m
	Sangre de Cristo Formation:		
108.	East-dipping, poorly exposed red shale and interbedded feldspathic and arkosic sandstones in valley and slopes to southeast. Search did not disclose any marine fossils at exposures in gullies. Blocks of fossiliferous gray limestone occur in Quaternary terrace gravel on hill at southeast, but are not from the Sangre de Cristo. Unit 108 and underlying unit 107 are Sangre de Cristo Formation as mapped by Northrop and others (1946) and		

Unit	Lithology	Thickness ft	m
	Baltz (1972). Overlain by Yeso Formation in hogbacks at the east. Estimated thickness.	830±	253±
107.	Conglomerate, pinkish-brown-weathering; matrix is angular to subangular, coarse sand and granules of quartz. About 10 percent is yellowish-pink, angular, potassium feldspar in all grain sizes up to pebbles 0.25 inch (0.6 cm) across. Contains lenses and scattered pebbles, as much as 2 inches (5 cm) across, of vein quartz. Slightly inclined crossbeds. Forms small ridge; base not exposed.	20±	6±
Total thickness of Sangre de Cristo Formation (estimated):		850±	260±
Alamitos Formation:			
106.	Concealed.	40	12.2
105.	Shale, clay, purplish-red-weathering; contains some small limestone nodules; forms small valley.	3	0.9
104.	Limestone, purplish-red, bioclastic, silty. Contains bryozoans, brachiopods, and large broken crinoid columnals. Beds are undulatory and 2–6 inches (5–15 cm) thick. About 10 percent of unit is red shale partings. Forms slight ledge.	2	0.6
103.	Concealed. Float suggests unit is fossiliferous nodular limestone and shale.	15.3	4.7

[Locality of measurement of overlying units is about 300 ft (90 m) south on ridge. Locality of measurement was offset south to avoid a small, northeast-trending fault. Units 99 and 102 were recognized south of the fault where unit 102 has thickened to 17.5 ft (5.3 m) and forms a ridge.]

Unit	Lithology	Thickness ft	m
102.	Limestone, sandy, and interbedded limy sandstone, light-gray. Quartz clasts are angular, very coarse sand and granules. Unit contains a trace of pink potassium feldspar. Slightly inclined crossbedding; beds are 2–8 inches (5–20 cm) thick. Foreset laminae dip north. Forms blocky ledge. Unit is 7 ft (2.1 m) thick at this locality, but it is thicker where measured farther south. Slightly unconformable with underlying unit.	17.5	5.3
101.	Shale, yellow-weathering, siliceous, and interbedded gray, nodular limestone; about two thirds of unit is shale. A coquina of fusulinid tests about 1 inch (2.5 cm) thick occurs 1.5 ft (46 cm) above base; some higher beds also contain fusulinids. Collection f10157 contains *Beedeina* cf. *B. sulphurensis*. Forms notchy weathering vertical cliff at east side of Lime Canyon.	7	2.1
100.	Concealed interval in bottom of Lime Canyon. Exposures to south indicate this interval is partly red shale.	13.9	4.2
99.	Conglomerate, light-yellowish-gray, weathers pinkish brown. Matrix is mostly angular to subangular coarse sand and granules of quartz; about 10 percent of clasts is pink angular potassium feldspar ranging from coarse sand to pebbles 0.25 inch (0.6 cm) diameter. Contains lenses and scattered pebbles of vein quartz and some quartzite; pebbles are as large as 2 inches (5 cm) diameter. Slightly inclined crossbedding; beds are 2–6 inches (5–15 cm) thick. Forms blocky, slumped ledge on west side of the bottom of Lime Canyon; base and top concealed.	8.9	2.7
98.	Concealed by talus from Quaternary terrace.	19.6	6
97.	Limestone, gray, very sandy, bioclastic; contains coarse, angular quartz sand and a trace of feldspar. Forms small ledge.	1.5	0.46
96.	Concealed by talus from Quaternary terrace.	16	4.9
95.	Limestone, light-brown-gray; upper part is sandy crinoidal coquina containing some angular, pink feldspar sand. About 20 percent of unit is thin shale interbeds. Forms small ledge.	8.9	2.7
94.	Shale, clay, light-grayish-tan, marly. Weathers to form gully.	4.9	1.5
93.	Limestone, light-brownish-gray-weathering, silty. Contains crinoid columnals scattered through a dense, recrystallized bioclastic matrix. Forms small ridge.	2.5	0.76
92.	Concealed.	6.2	1.9
91.	Sandstone, conglomeratic, light-yellowish-gray-weathering, feldspathic, coarse-grained to very coarse grained. About 20 percent of clasts is angular, pink potassium feldspar ranging from coarse sand to pebbles 0.75 inch (1.9 cm) in diameter. Forms ledge on north wall of Lime Canyon. On ridge south of Lime Canyon unit contains a lens of red shale.	12	3.7
Total thickness of Alamitos Formation:		179.2	54.6

[Locality of measurement of above units begins on north wall of Lime Canyon along east-trending segment south of sharp meander "kink" about 0.5 mi (0.8 km) southwest of Peterson Reservoir.

The lower part of the Alamitos Formation on the low ridges at the south end of the reservoir, and immediately east of the locality described below (unit 90), consists of a basal arkose about 8 ft (2.4 m) thick, overlain by poorly exposed limestone and shale about 25 ft (7.6 m) thick, in turn overlain by poorly exposed ledge-forming arkose about 25 ft (7.6 m) thick. These rocks probably are faulted against the Sangre de Cristo Formation, but the contact is concealed by alluvium in the valley to the east (Fig. 85). Traced southward

Unit	Lithology	Thickness ft	Thickness m

from the reservoir, the lower part of the Alamitos becomes a zone of intergrading limy arkosic sandstone and sandy limestone that correlates with units 91–99 of the Alamitos in the above section.

The contact of the Alamitos and Porvenir Formations is a low-angle unconformity and, southward from the reservoir, unit 91 of the Alamitos bevels gently downward across the Porvenir. As shown by section 7 of Northrop and others (1946), the Porvenir is only about 300 ft (90 m) thick at Lime Canyon 0.7 (1.1 km) southwest of Peterson Reservoir. This contrasts with the thickness of 548 ft (167 m) of the Porvenir measured at the localities described below.]

Porvenir Formation:

Unit	Lithology	ft	m
90.	Shale, clay, light-brown-gray; contains tiny limestone nodules. Poorly exposed.	5.4	1.7
89.	Limestone, light-gray, bioclastic, silty, sandy; contains scattered small crinoid columnals and brachiopods; beds are about 1 ft (30 cm) thick. Forms irregular ridge.	9	2.8
88.	Shale, clay, light-brownish-gray; contains tiny limestone nodules. Forms slope on ridge; poorly exposed.	9.5	2.9
87.	Limestone, light-gray, very silty and sandy. Beds are 1–3 ft (30–90 cm) thick. Forms prominent ledge.	9.5	2.9
86.	Concealed by alluvium in bottom of small canyon.	14	4.3
85.	Limestone, light-gray, massive. Micrite containing scattered crinoid columnals and a few small brachiopods. Thin reticulating siliceous stringers are pervasive. Unit is probably the core of a small bioherm. Forms strong ledge.	9.5	2.9

[Locality of measurement of above units begins on west side of small canyon west of an earth dam just southwest of Peterson Reservoir. Underlying unit 84 was traced south to this locality which is a little less than 0.2 mi (0.3 km) south of the spillway from the intake ditch on the west side of the reservoir.]

Unit	Lithology	ft	m
84.	Siltstone, light-yellowish-gray, shaly, calcareous. About 5 percent of unit consists of light-gray, dense limestone nodules that are 1–2 inches (2.5–5 cm) long. Forms slope at west edge of intake ditch west of Peterson Reservoir. Overlying beds are concealed at this place.	3	0.9
83.	Limestone, yellowish-gray, and interbedded thin, silicified calcareous shale; shale is about 15 percent of unit. Limestone is partly replaced by yellow silica. Beds average 8 inches (20 cm) thick. Forms irregular, small ridges.	4.3	1.3
82.	Limestone, light-gray, medium-grained; contains many brachiopods and thin interbeds of bioclastic, fusulinid-bearing limestone. Bedding is undulatory; beds are 0.5–1.5 ft (15–45 cm) thick. Forms ridge on west side of intake ditch. Fusulinid collection f10156 contains *Beedeina* sp. and *Wedekindellina* sp.	5	1.5
81.	Shale, gray, marly, silty, slightly carbonaceous. Upper third contains thin undulatory limestone beds and some discoid (algal?) limestone. Unit is poorly exposed.	4	1.2
80.	Limestone, light-gray, matrix is fine-grained; contains many brachiopods, some bryozoans, and some fusulinids. Beds are undulatory and 1–3 inches (2.5–7.6 cm) thick. Forms small ledge on east side of intake ditch at spillway.	3	0.9
79.	Limestone, light-gray, fine-grained; contains abundant brachiopods. Forms ledge near wooden spillway of intake ditch for Peterson Reservoir.	14	4.3
78.	Concealed.	3	0.9
77.	Limestone, light-gray, fine-grained, bioclastic; 15 percent is fine to medium quartz sand. Limestone has a nodular appearance because of replacement of 30 percent of unit by silica. Beds average 7 inches (18 cm) thick. Upper half forms moderate ridge; lower half poorly exposed.	23.5	7.2
76.	Limestone, light-gray, micritic; about 10 percent is brachiopod shells. Upper part contains lenses of bioclastic limestone that contains large fusulinid tests. Beds are about 1 ft (30 cm) thick. Poorly exposed.	11	3.4
75.	Sandstone, light-gray, fine-grained to very coarse grained. Clasts are mainly subround to rounded quartz; contains a few quartz granules and small limestone pebbles. Moderately cemented by silica and calcite. Forms small ledge.	5	1.5
74.	Limestone, light-gray, fine-grained; contains many scattered crinoid columnals. Contains lenses of bioclastic crinoidal limestone that are replaced partly by yellowish-gray silica and give a nodular appearance to the unit. Beds are 1–1.5 ft (30–46 cm) thick. Forms moderate ledge.	18	5.5
73.	Shale, silty, marly; contains limestone nodules 1–2 inches (2.5–5 cm) across. Lower part is dark-gray carbonaceous calcareous shale containing thin undulatory beds of limestone. Poorly exposed in a gully on a slope.	8.7	2.7
72.	Concealed; slope.	9.5	2.9
71.	Limestone, light-gray, fine-grained. Contains many brachiopods and crinoid columnals. Zaphrentid corals occur in upper part. Contains lenses of bioclastic limestone that have large brachiopod fragments		

Unit	Lithology	Thickness ft	m
	and many large fusulinids. Some parts of the bioclastic lenses are silicified to hackly weathering brown and gray chert. Some parts of unit are recrystallized. Beds are undulatory and generally 4–8 inches (10–20 cm) thick; some beds are 2–3 ft (60–90 cm) thick. Forms ridge. Fusulinid collection f10155 contains *Beedeina* aff. *B. rockymontana* and *Wedekindellina* cf. *W. minuta*.	21	6.4
70.	Limestone, gray, sandy, bioclastic, and interbedded limy sandstone. Quartz clasts are subangular to subround very coarse sand and granules. Poorly exposed.	4.5	1.4
69.	Concealed; slope.	8.5	2.6
68.	Limestone, light-gray, fine- to medium-grained, bioclastic. As much as 20 percent is subangular coarse sand and granules of quartz. Poorly exposed ledge.	2.4	0.73
67.	Concealed; slope.	2	0.6
66.	Limestone, light-gray, fine-grained; about 10 percent is quartz silt and very fine sand. Contains a few tiny fossil fragments. Beds are 4–5 inches (10–13 cm) thick. Forms poorly exposed small ledge; base and top concealed.	4	1.2
65.	Limestone, sandy, and interbedded limy sandstone, light-brownish-gray; proportion of limestone and sandstone is about equal. Limestone matrix is fine grained and contains a few brachiopods and some crinoid columnals; contains scattered subangular coarse quartz sand clasts and irregular lenses of limy sandstone. Forms small ridge; top and base concealed.	2.5	0.76
64.	Concealed.	14	4.3
63.	Limestone, light- to medium-gray, fine-grained to micritic; as much as 40 percent is articulated brachiopod shells. Contains a few small crinoid columnals, some bryozoans, and some worm tubes. Patches are recrystallized to coarse-grained texture. Beds are undulatory and about 8 inches (20 cm) thick. Forms moderate ledge on slope east of eastern quarry.	4.5	1.4
62.	Concealed by tailings from quarry.	6.6	2
61.	Shale, light-gray to light-olive-gray, slightly marly, plastic.	5	1.5
60.	Limestone, light-gray, fine-grained, partly recrystallized. Forms ledge.	2.9	0.88
59.	Limestone, light-gray, nodular. Nodules are 0.25–1 inch (0.6–2.5 cm) diameter; matrix is limestone and marly shale. Weathers to slight notch. Base is slightly eroded surface.	0.6	0.18
58.	Limestone, light-gray, massive, largely recrystallized. Traces of highly undulatory bedding are apparent. Unit is a bioherm that thins rapidly northward to about half the thickness at locality of measurement. Forms cliff on east side of eastern quarry.	15.5	4.7
57.	Limestone, gray, nodular; nodules are 0.5–4 inches (1.3–10 cm) in length; many nodules are brachiopods with limy (algal?) coatings. Contains a few fusulinids. Part of the matrix is clay. Forms slope on west side of eastern quarry.	5	1.5
56.	Limestone, light-gray, fine-grained matrix. Contains many brachiopods. Forms small ledge at top of west side of eastern quarry.	8	2.4
55.	Limestone, light-tan-gray, fine-grained, bioclastic; about 15 percent is quartz silt and fine sand. Much of unit is replaced by yellowish-gray silica. Forms slope; poorly exposed.	12.3	3.8
54.	Limestone, light-gray, fine-grained; about 10 percent is unbroken brachiopod shells. Bedding is slightly undulatory; beds are 3–4 inches (7.6–10 cm) thick. Uppermost part contains yellow silica stringers along bedding. Forms poorly exposed ledgy slope.	7.5	2.3
53.	Concealed.	5.7	1.7
52.	Shale, clay, marly. Forms slope at east top of western quarry.	6±	1.8±
51.	Limestone, nodular, and limestone-pebble conglomerate in marly shale matrix.	2.5	0.76
50.	Limestone, gray, very coarse grained; mainly a coquina of crinoid columnals; fusulinids are abundant. Forms prominent ledge on east face of western quarry. Fusulinid collection f10154 contains *Beedeina* cf. *B. rockymontana* and *Wedekindellina* sp.	5.2	1.6
49.	Limestone, gray, and interbedded shale. Bedding is undulatory; limestone beds are 3–8 inches (7.6–20 cm) thick; shale beds are about 0.25 inch (0.6 cm) thick. Forms ledge.	4	1.2
48.	Shale, clay, marly.	4.7	1.4
47.	Limestone, light-gray, fine-grained; locally recrystallized to coarse, sparry calcite. Contains scattered but numerous brachiopods, crinoid columnals, bryozoans, echinoid spines, zaphrentid corals, fusulinids, and stringers of bioclastic material. Unit is mainly massive, but traces of bedding indicate local mound-like growth centers. Unit is the core of a bioherm that thins rapidly northward as overlying units 48 and 49 thicken. Forms south and east walls of western quarry. Fusulinid collection f10153 from middle of unit contains		

Unit	Lithology	Thickness ft	Thickness m
	Beedeina aff. *B. rockymontana*, *Bradyina* sp., *Wedekindellina* sp., and climacamminid foraminifers.	36	11
46.	Limestone, light-gray; mainly a mass of brachiopods cemented by calcite. Thins eastward in quarry and forms a local mound in south west corner.	0–3	0–0.9
45.	Limestone, light-gray; mostly a mass of broken and unbroken brachiopod shells and some large crinoid columnals. Contains much phylloid algal material. Bedding is highly undulatory; beds are about 1 ft (30 cm) thick. Exposed on sloping western floor of quarry.	5	1.5
44.	Limestone, light-gray, fine- to coarse-grained, bioclastic. Mostly crinoid-columnal fragments, some as much as 0.5 inch (1.27 cm) diameter. Contains many large (up to 2 inch) unbroken brachiopod shells, some zaphrentid corals, and some large fusulinids. Becomes finer grained near top. Bedding is undulatory; beds average 6 inches (15 cm) thick. Upper part has nodular appearance because of partial replacement by yellowish-gray silica. Forms ledgy slope west of western quarry.	6.6	2
43.	Siltstone, yellowish-gray-weathering, and interbedded thin, concretionary limestone. Siltstone is micaceous and slightly carbonaceous. Beds are 3–6 inches (7.6–15 cm) thick. Poorly exposed.	2.2	0.67
42.	Sandstone, medium-gray, weathers light yellowish gray. Mostly fine quartz sand, but contains angular to well-rounded coarse quartz sand and small pebbles of quartzite. Contains limestone pebbles as much as 2 inches (5 cm) diameter. Upper 2 ft (60 cm) is sandy limestone containing irregular lenses of fine to coarse quartz sand in bioclastic limestone and calcarenite. Beds are 0.5–1 ft (15–30 cm) thick. Forms small irregularly weathering ridge.	7.4	2.3
41.	Limestone, gray, nodular; nodules are 1–3 inches (2.5–7.6 cm) thick and are in a matrix of dense, yellowish-gray silica. Probably contains some interbedded shale. Poorly exposed; forms notch along road.	7.4	2.3
40.	Limestone, light-gray, micritic; contains thin, irregular lenses of tiny fragments of brachiopods and crinoid columnals. Contains a few zaphrentid corals, gastropods, and fusulinids. Bedding is undulatory; beds are 4–8 inches (10–20 cm) thick. Some beds contain stringers of yellowish-gray silica parallel to bedding. Forms moderate ledge; top and base concealed.	8	2.4
39.	Concealed; slope.	8	2.4
38.	Limestone, light-brownish-gray, medium-grained; recrystallization has obscured most of primary structures. Contains large complete brachiopods, numerous crinoid columnals, and zaphrentid corals, all partly recrystallized. Upper part contains fusulinids and has nodular appearance due to patchy replacement of part of limestone by yellowish-gray silica. Forms small, poorly exposed ledge.	5.6	1.7
37.	Limestone, light- to medium-gray, micritic. Contains many complete brachiopods, some bryozoans, and some crinoid columnals. Bedding is highly undulatory; beds are 2–6 inches (5–15 cm) thick. Replacement by stringers of yellowish-gray silica is common along bedding planes. Forms moderate ledge. May correlate with unit 33, as explained. below.	16	4.9
36.	Sandstone, conglomeratic, light-pinkish-brown, weathers light gray; clasts are mostly fine to very coarse, angular to well rounded quartz sand. Contains scattered well-rounded quartzite pebbles as much as 0.25 inch (0.6 cm) in diameter. Basal part contains limestone pebbles and cobbles as much as 6 inches (15 cm) long. Cemented by silica and calcite. Thins and grades southward into sandy limestone. Forms poorly exposed rubbly ledge; top and base concealed.	10	3
35.	Shale, clay, light-yellowish-brown, slightly ferruginous. Lower 1.5 ft (46 cm) contains nodules of dense, gray limestone. Moderately fissile. Poorly exposed in small gully in old road. May correlate with part of unit 32, as explained below. Thickness is 10.4 ft (3.2 m). (See explanation below)		
34.	Limestone, light-gray; matrix is fine-grained and contains brachiopods and numerous crinoid columnals. Much of unit is replaced by yellowish-olive, dense silica. Poorly exposed on west side of abandoned wood-haulers road; probably some interbedded shale. Base not exposed. Exposed thickness is 10 ft (3 m). (See explanation below)		

[Locality of measurement of above units begins on ridge southwest of western limestone quarry in exposures in abandoned wood-haulers road, east side of small valley that debouches at Montezuma powerhouse. Unit 33 below seems to correlate with unit 37 above. This was determined by tracing unit 33 from the locality of measurement of lower part of section eastward around the head of the small valley past the Public Service Company water well to the wood-haulers road. For this reason, the thicknesses of units 33, 34, and 35 are not included in the composite thickness of the Porvenir Formation.]

Unit	Lithology	Thickness ft	m
33.	Limestone, medium-brownish-gray, weathers light gray; fine- to coarse-grained; recrystallized. Contains many brachiopods and some gastropods and zaphrentid corals. Some gray chert occurs along bedding and laminae. Bedding is undulatory; beds are 1–3 ft (30–90 cm) thick. Uppermost bed is light gray, micritic limestone containing a few fossil fragments, a few fusulinids, and locally numerous small mounds of *Chaetetes* sp. Middle part weathers to a notch, causing the entire unit to weather to a double ledge with the upper part set back from the lower part. Unit forms a narrow dip slope around the south end of the small valley east of locality of measurement. Thickness is 13 ft (4 m).	(See explanation above)	
32.	Mainly concealed; slope. A few scattered exposures are gray calcareous shale interbedded with undulatory-bedded gray limestone.	27	8.2
31.	Limestone, gray, very fine grained, containing lenses of fine-grained bioclastic limestone. Weathering character of the outcrop suggests interbeds of shale, but none were observed. Poorly exposed; weathers to a slope with minor ledges.	13	4

[Unit 30 was traced about 250 ft (75 m) west to locality of measurement of above units.]

Unit	Lithology	Thickness ft	m
30.	Limestone, light- to medium-gray, fine-grained. Contains fine-grained bioclastic material cemented by dense calcite. Contains a few clumps of syringoporid tubular corals and a few fusulinids. Bedding is undulatory. Forms a prominent ledge that holds up a dip slope at top of topographic spur.	3.5	1
29.	Sandstone, light-yellowish-brown-weathering; clasts are mainly subangular to subround, medium quartz sand. Contains scattered grains and small lenses of coarse sand and granules. Contains a trace of coarse muscovite flakes. Uppermost bed contains patches, 1–6 inches (2.5–15 cm) diameter, of limestone that may be algal. Forms small slabby ledges; base not exposed.	9.5	2.9
28.	Shale, silt, light-olive-gray; lower 2 ft (0.6 m) is carbonaceous and dark gray. Upper part contains a few crinoid columnals and bryozoans. Weathers to poorly exposed slope.	7	2.1

[Unit 27 was traced about 250 ft (75 m) west to locality of measurement of above units.]

Unit	Lithology	Thickness ft	m
27.	Limestone, light-gray, fine-grained to micritic, partly bioclastic, mildly recrystallized. Contains many brachiopods and brachiopod fragments, some syringoporid corals, a few zaphrentid corals, and fairly abundant mounds of *Chaetetes* sp. A fine-grained bioclastic lens near the top contains abundant unbroken fusulinids. Part of unit has been slightly silicified to yellowish-gray-weathering chert. Bedding is undulatory. Forms thin, upward-retreating ledges and intervening poorly exposed intervals; unit set back topographically from underlying unit. Fusulinid collection f10152 contains *Beedeina insolita*, *Fusulinella* sp., and *Bradyina* sp.	14	4.3
26.	Limestone, similar to unit 25, but bedding is more distinct. Contains *Chaetetes* sp. Beds average 2.5 ft (0.76 m) thick. Weathers to rounded ledge; notches are weathered along bedding.	5	1.5
25.	Limestone, light-gray; matrix is fine grained to micritic. Brachiopods are abundant. Bedding is highly undulatory and locally indistinct. Forms prominent vertical cliff with a notch weathered at the top.	11	3.4
24.	Concealed; exposures nearby suggest this is limestone similar to unit 23.	16.5	5
23.	Limestone, light-gray; matrix is fine grained to micritic. About 30 percent of rock is brachiopod shells; about 20 percent is small fossil fragments. Bedding is undulatory and indistinct; beds are about 3 inches (7.6 cm) thick. Forms strong ledge; base not exposed.	3	0.9
	Total thickness of Porvenir Formation:	548.5	167.2

Sandia Formation:

Unit	Lithology	Thickness ft	m
22.	Concealed; steep slope; probably mostly gray shale.	35	10.7
21.	Concealed; benchy slope.	26	7.9
20.	Limestone, similar to unit 18; contains clumps of *Chaetetes* sp. Poorly exposed; forms upward-retreating benchy slope.	11	3.4
19.	Limestone, similar to unit 18, but contains much scattered, coarse, well-rounded quartz sand. Contains brachiopods. Bedding is irregular and undulatory; beds are 1–3 inches (2.5–7.6 cm) thick. Forms small ledge.	4	1.2
18.	Limestone, medium-brownish-		

Unit	Lithology	Thickness ft	m
	gray; slightly carbonaceous; contains much quartz silt and fine sand. Brachiopods are abundant. Beds are 1–3 inches (2.5–7.6 cm) thick. Forms a slabby slope.	5	1.5
17.	Concealed; slope.	37	11.3
16.	Sandstone, conglomeratic, light-pinkish-gray, weathers brownish gray. Matrix is fine to coarse quartz sand with a trace of greatly weathered, yellowish-gray feldspar. About 20 percent is subangular to subround quartz granules and pebbles as much as 0.5 inch (1.3 cm) diameter. Upper half is mainly fine to coarse sand with granules dispersed throughout. Calcareous. Contains numerous flattened, limonite-replaced fossil logs. Cross-bedded; beds are 2–4 ft (60–120 cm) thick. cross-laminated; foreset laminae dip mainly east. Lower half forms strong rounded ledge; upper half forms slabby ledges. Base is undulatory and probably unconformable with underlying unit. About 2,000 ft (600 m) to the west unit 16 is not far above the base of the Sandia where the formation is only about 90 ft (27 m) in total thickness, indicating a local intraformational angular unconformity.	32	9.8
15.	Siltstone, dark-gray, shaly, carbonaceous, slightly micaceous. Poorly exposed; forms slope.	5	1.5
14.	Limestone, light-gray; matrix is fine grained; contains a large proportion of small fossil fragments. Contains much yellowish-gray silica that replaces parts of unit and gives it a nodular appearance. Forms ledge; base not exposed.	2	0.6
13.	Poorly exposed; forms slope. Float and a few exposures indicate unit may be mostly carbonaceous silty shale containing some thin sandstone.	52	15.9
12.	Limestone, light-gray, recrystallized. Mainly a coquina of brachiopod and crinoid fragments. Forms small, slumped ledge.	1	0.3
11.	Poorly exposed; forms slope above ditch. Float and a few exposures indicate unit is mainly yellowish-gray ferruginous, argillaceous, shaly siltstone. Upper third contains some carbonaceous shale.	43	13.1
10.	Sandstone, conglomeratic, light-brown, medium- to coarse-grained. Contains subrounded quartz granules and small chert pebbles. Forms small, irregular ledge; poorly exposed along abandoned ditch of Public Service Company.	2.5	0.76
9.	Shale, clay, light-gray; carbonaceous; contains irregular yellow ocherous bands. Poorly exposed along abandoned ditch of Public Service Company.	21	6.4
8.	Sandstone, conglomeratic, light-yellowish-gray, weathers brown, fine- to coarse-grained. Contains pebbles and cobbles of limestone. Poorly exposed along abandoned ditch of Public Service Company. Unconformable with underlying unit; thickens eastward and forms ledge below ditch.	3±	0.9+
	Total thickness of Sandia Formation:	279.5	85.3
	Arroyo Peñasco Group:		
	Tererro Formation:		
	Cowles Member:		
	Absent because of unconformity.	0	0
	Manuelitas Member:		
7.	Conglomerate, light-gray, yellow-stained. Subangular to subround pebbles and cobbles of light- to dark-gray limestone, 2–6 inches (5–15 cm) diameter, in calcarenite matrix. Matrix contains quartz sand, fragmental chert, crinoid columnals and brachiopod fragments. Forms poorly exposed slight ledge along abandoned ditch of Public Service Company. Lower contact is irregular. Megafossil collection USGS 16688–PC was obtained on ridge about 300 ft (90 m) west of this locality from beds of the Manuelitas that are present at places above this unit.	3.5	1
6.	Shale, yellowish-gray, silty, marly; forms local notch; thickness irregular. Basal contact is an unconformity; unit 6 cuts out underlying unit 5 a few feet to the east.	0–0.8	0–0.24
	Macho Member:		
	Absent because of unconformity. About 300 ft (90 m) to the west breccia of this member is present below unit 6.	0	0
	Maximum total thickness of Tererro Formation:	4.3	1.24
	Espiritu Santo Formation:		
5.	Limestone, medium- to dark-gray, coarse-grained. Recrystallized; brownish-gray calcite granules average about 0.06 inch (0.16 cm) diameter; contains a few large brown and white calcite crystals. Probably a recrystallized calcarenite. Contains small, irregular patches of limonite weathered from pyrite and very thin stringers of gray chert. Bedding is irregular and wavy; beds are 0.5–1 ft (15–30 cm) thick. Forms local ledge; unit cut out by unit 6 at		

Unit	Lithology	Thickness ft	m
	east end of exposure. Lower contact irregular.	2.3±	.7±
4.	Quartz sandstone, calcarenite, and limestone-pebble conglomerate, interbedded; light-tan, medium-gray, and light-olive-gray. Contains interbeds of light-yellowish-gray marly shale 0.25–1 inch (0.64–2.5 cm) thick. Bedding is highly irregular; includes distinct channel fills. Forms slight notches and ledges. Base of unit is sharp and erosional; relief is as much as 2 ft (0.6 m).	1–2.5	0.3–0.76
3.	Limestone, dark-gray to black, sideritic, recrystallized; fractures along curved cleavage faces. Contains a few white calcite crystals as large as 2 inches (5 cm) across. Contains a few concentrically banded gray and black ellipsoidal chert nodules 1–2 inches (2.5–5 cm) long. Beds are wavy, parallel, and 6 inch–1 ft (15–30 cm) thick; forms ledge.	3.3	1
	Del Padre Sandstone Member:		
2.	Sandstone, light-gray to buff, silica-cemented. Subangular to subround, medium to coarse quartz sand and granules. Slightly cross-laminated. Forms ledge along abandoned ditch of Public Service Company.	1.3	0.4
	Maximum total thickness of Espiritu Santo Formation:	9.4	2.9
	Precambrian rocks:		
1.	Granitic gneiss, strongly foliated. Deeply weathered; altered to greenish sandy clay. Weathering extends about 4 ft (1.2 m) downward into the gneiss.	Not measured	

Section H

Rociada 7.5-minute quadrangle (1965). Section of Alamitos, Porvenir, and Sandia Formations measured in beds that dip steeply east in lower part of hogback ridges north of Manuelitas Creek. Reference section for shaly facies of Porvenir Formation. Base of section is near western end of the narrow water gap about 1.4 mi (2.25 km) east-southeast of Rociada. Measured by E. H. Baltz and D. A. Myers. Locality shown in Figures 17, 31, and 87.

Unit	Lithology	Thickness ft	m
	Sangre de Cristo Formation (lower part):		
176.	Sandstone, conglomeratic, arkosic; forms massive, major ridge.	Not measured	
175.	Concealed; slope.	38	11.6
174.	Shale, red-weathering; contains abundant limestone concretions; forms slope.	18	5.5
173.	Sandstone, brown-weathering, coarse-grained to very coarse grained, feldspathic; forms slight ledge.	13	4
172.	Sandstone, conglomeratic. Composed mainly of angular to subangular, very coarse quartz sand and granules; contains many small limestone pebbles in basal 6 inches (15 cm). Forms small ledge.	3	0.9
	Alamitos Formation:		
171.	Concealed; slope. Float is red shale.	38	11.6
170.	Concealed; slope on west side of side canyon.	28	8.5
169.	Shale, light-olive-gray, silty, sandy, micaceous. Contains trace of nodular limestone.	12	3.7
168.	Shale, red-weathering, poorly exposed. Upper 6 ft (1.8 m) contains thin beds of arkosic sandstone.	43	13
167.	Sandstone, light-reddish-brown, coarse-grained to very coarse grained, feldspathic. Forms ledge.	9	2.8
166.	Shale, red-weathering, poorly exposed. Contains limestone concretions and thin sandy limestone beds that contain fragments of plecypods, brachiopods, and bryozoans.	43	13.1
165.	Sandstone, similar to unit 161. Forms ridge.	9	2.8
164.	Shale, red-weathering, poorly exposed.	18	5.5
163.	Sandstone, similar to unit 161. Forms ridge at west side of the deep part of a north-trending strike canyon.	6	1.8
162.	Shale, red-weathering, poorly exposed. To the north, better exposures show yellowish-olive siltstone with a medial lens, about 3 ft (1 m) thick, of tan sandy limestone and limy sandstone that contains fragments of crinoid columnals, plecypods, and brachiopods.	20	6.1
161.	Sandstone, light-reddish-brown, coarse-grained to very coarse grained, arkosic. Forms ridge.	16	4.9
160.	Concealed; slope.	43	13.1
159.	Sandstone, conglomeratic, light-reddish-brown, feldspathic. Composed of angular to subangular, very coarse sand and granules;		

Unit	Lithology	Thickness ft	m
	about 20 percent is angular fresh-appearing pink feldspar. Contains scattered pebbles about 1 inch (2.5 cm) diameter. Basal 2–2.5 ft (60–80 cm) is limestone-pebble conglomerate; gray limestone pebbles are as much as 2 inches (5 cm) diameter and are in a sparse matrix of angular quartz and feldspar granules. This basal part is exposed only at the north edge of a small Quaternary alluvial fan in the strike valley.	8	2.4
158.	Shale, olive-gray to light-red, poorly exposed. Contains layers of concretionary gray-limestone nodules. Fossiliferous, gray, sandy limestone beds occur at several positions in the unit nearly to the top; fossils include brachiopods, bryozoans, and crinoid debris. Unit forms a strike valley.	91	27.8
157.	Concealed; slope.	25	7.6
156.	Sandstone, light-greenish-gray, tan-weathering, feldspathic. Composed of angular to subangular, very coarse sand; about 15 percent is pink feldspar. Forms small ledge.	19	5.8
155.	Shale, gray, calcareous; lower part weathers red. Contains many layers of light-purple and light-gray limestone nodules 0.1–2 inch (0.3–7.5 cm) in diameter. Unit forms slope.	24	7.3

[Unit 154 traced about 300 ft (91 m) north. Units 155 and above measured to northeast and east.]

Unit	Lithology	Thickness ft	m
154.	Sandstone, conglomeratic, light-reddish-brown, feldspathic. Composed of angular to subangular coarse sand and some granules; 10 percent is pink and yellowish-pink weathered feldspar. Contains 2–6-inch (5–15-cm) thick layers of pebbles that are mainly quartz; some pebbles are feldspar; some pebbles are as large as 2 inches (5 cm). Forms low ridge west of small valley.	14	4.3
153.	Shale, light-olive-gray, silty, micaceous.	16	4.9
152.	Sandstone, dark-gray to reddish-gray, fine- to medium-grained, silica-cemented. Thin bedded and finely laminated.	2.5	0.76
151.	Shale and shaly sandstone. Upper third is light-gray to light-purplish-gray calcareous to marly shale containing unfossiliferous limestone nodules. Middle third is dark-purplish-red shaly sandstone. Lower part is red-weathering shale containing light-gray unfossiliferous limestone nodules. Unit poorly exposed on a slope.	65	19.8
150.	Sandstone, conglomeratic, reddish-brown, arkosic. Composed of subangular, coarse sand that contains irregularly shaped to subrounded, quartz pebbles, some as much as 1.5 inches (3.7 cm) long; contains pink feldspar pebbles. Forms ridge.	55	16.8
149.	Mainly concealed; slope. Red shale exposed at places.	42	12.8
148.	Sandstone, conglomeratic, grayish-orange to light-brown, feldspathic. Composed of subangular, coarse sand. Contains quartz and feldspar pebbles as much as 0.75 inch (1.9 cm) long; pebbles are sub rounded. Forms strong ridge.	13	4
147.	Concealed; slope.	91	27.8
146.	Sandstone, feldspathic, poorly exposed.	10	3
145.	Concealed; slope. Float indicates interval is partly red shale and some thin sandstone.	179	54.6
144.	Sandstone, conglomeratic, light-gray to yellowish-orange, feldspathic; coarse-grained to very coarse grained; contains scattered granules and small (less than 2.5 cm) pebbles. Forms three strong ridges with intervening concealed thin intervals that probably are shaly.	117	35.7
143.	Shale, light-olive-green; mainly silt and very fine grained sand. Contains scattered gray limestone nodules. Upper part weathers red. Forms slope.	28	8.5
142.	Sandstone, yellowish-olive, fine-grained to very fine grained, shaly. Upper 2 ft (60 cm) forms ridge.	8	2.4
141.	Limestone, sandy, and limy sandstone; brown, coarse grained; forms slight ridge.	1	0.3
140.	Shale, light-olive-gray, silty. Upper 4 ft (1.2 m) is shaly, fine-grained sandstone; basal 6 ft (1.8 m) contains gray limestone nodules and weathers red. Unit forms slope.	39	11.9
139.	Sandstone, conglomeratic, feldspathic, similar to unit 125. Forms strong ridge.	7	2.1
138.	Shale, light-greenish-gray, silty, sandy, slightly micaceous. Upper 5 ft (1.5 m) contains light-gray limestone nodules. Middle part of unit contains a 1-ft (30-cm) thick bed of sandstone and a 1-ft (30-cm) thick bed of brown sandy limestone. Unit forms slope.	36	11
137.	Sandstone, conglomeratic, feldspathic, similar to unit 125. Forms small ridge.	16	4.9
136.	Concealed; slope. Float indicates interval probably is red and greenish-gray silty shale.	28	8.5
135.	Sandstone, conglomeratic, feldspathic, similar to unit 125. Forms ridge.	9	2.8

Unit	Lithology	Thickness ft	m
134.	Shale, greenish-gray, silty, sandy. About 10 percent of unit is nodular, silty, bioclastic limestone and some concretionary limestone in beds 1 inch–1 ft (2.5–30 cm) thick. Limestones contain brachiopods, bryozoans, and crinoid columnals. Unit forms slope.	99	30.2
133.	Shale, reddish- to greenish-gray, silty, sandy, micaceous. Poorly exposed slope.	20	6.1
132.	Mainly concealed. Upper 3 ft (90 cm) is silty limestone nodules in greenish-gray silicified matrix.	41	12.5
131.	Limestone, gray, coarsely bioclastic, partly nodular. Nodules are in greenish-gray, silicified fine-grained matrix. Beds are 6–8 inches (15–20 cm) thick. Unit forms small ridge.	7	2.1
130.	Sandstone, conglomeratic, feldspathic, similar to unit 125. Forms strong ridge.	24	7.3
129.	Limestone, light-gray to light-purplish-red, sandy. Mainly a mixture of brachiopod and crinoid fragments in matrix of comminuted fossil debris. Forms small ridge.	8	2.4
128.	Shale, olive-gray, silty Contains some nodular gray limestone. Poorly exposed.	50	15.3
127.	Sandstone, conglomeratic, feldspathic, similar to unit 125. Forms ridge.	20	6.1
126.	Shale, red, poorly exposed.	9	2.8
125.	Sandstone, conglomeratic, light-yellowish-orange, feldspathic. Composed of angular to subangular, coarse to very coarse quartz sand. Contains angular pink feldspar sand and granules. Contains scattered granules and pebbles as much as 1 inch (2.5 cm) diameter. Forms strong double ridge; middle third is poorly exposed on a slope probably underlain mainly by shale.	55	16.8
124.	Limestone, gray, silty, sandy; fine to medium grained; thin bedded.	3	0.9
123.	Concealed interval in valley.	70	21.4
122.	Sandstone, light-greenish-gray, feldspathic. Lower half is medium grained, slightly micaceous, and contains scattered angular granules of pink feldspar. Crossbedded and cross-laminated; beds are 8–10 ft (2.4–3 m) thick. Upper half is very coarse grained; red shale and red shaly sandstone interbeds occur near the middle of the upper half. Forms strong ridge.	74	22.6
121.	Shale, gray, silty, sandy; lower part poorly exposed, but contains a thin, gray, fossiliferous limestone near the base. Upper part contains interbeds of shaly, slightly calcareous sandstone. Forms slope.	41	12.5
120.	Limestone, light-gray, fine-grained. Contains brachiopods and fusulinids. Fusulinid collection f10144 contains *Beedeina sulphurensis.*	1	0.3
119.	Sandstone, conglomeratic, light-grayish-orange, weathers light grayish red to pale yellowish brown, feldspathic. Composed of subangular, very coarse sand and granules; 15–20 percent is weathered yellowish-pink feldspar; fresh-appearing, angular, pink feldspar occurs in upper 20 ft (6 m). Contains many subrounded pebbles of quartzite and some feldspar; pebbles range up to 1 inch (2.5 cm) diameter. Crossbedded; beds are 1–6 ft (0.3–1.8 m) thick. Forms strong ridge.	77	23.5
	Total thickness of Alamitos Formation:	1,828	557.5

[Top of unit 118 was traced south about 300 ft (91 m) nearly to alluvium of Manuelitas Creek. Units 119 and above were measured east along southern margins of hogbacks.]

Porvenir Formation (reference section for shaly facies):

Unit	Lithology	Thickness ft	m
118.	Mainly concealed; slope on hillside above valley. Probably mostly gray shale. Near Manuelitas Creek gray limestone 3 ft (0.9 m) thick occurs about 14 ft (4.3 m) below top of unit. Fusulinid collection f10143 from the limestone contains *Beedeina* cf. *B. sulphurensis.*	43	13.1
117.	Shale, clay, dark-gray, weathers medium gray to yellow gray; silty, calcareous. Forms slopes in gully.	46	14
116.	Limestone, gray, fine-grained, bioclastic; beds are 6 inch–1 ft (15–30 cm) thick; contains minor amount of interbedded thin gray shale. Forms irregular slope. Fusulinid collection f10142 from top of unit contains *Beedeina* aff. *B. sulphurensis.*	10	3
115.	Limestone, light-gray, medium-grained; contains much bioclastic debris, mainly crinoidal, but also fragments of brachiopods and corals. Beds are 0.5–2.5 ft (15–75 cm) thick. Forms ledge continuous with underlying unit.	5	1.5
114.	Limestone, sandy, and sandstone, calcareous, brownish-gray, weathers medium-brown. Limestone and sandstone are interbedded and intergrade laterally. Limestone is bioclastic, consisting mainly of fine- to coarse-grained crinoid and brachiopod debris that contains many unbroken brachiopods; contains angular, medium to coarse, quartz sand. Beds of sandstone are medium to coarse grained and contain varied amounts of bioclastic debris. Beds		

Unit	Lithology	Thickness ft	m
	are 1 inch–1 ft (2.5–30 cm) thick; cross-laminated and crossbedded. Part of the unit is silty, very fine grained sandstone containing limestone nodules 6 inches (15 cm) diameter. Unit forms prominent ridge and grades abruptly into overlying unit. "Marker" zone in upper part of Porvenir Formation.	56	17
113.	Shale, clay, dark-gray, silty; contains a few beds, 1–3 inches (2.5–7.5 cm) thick, of silty limestone. Exposed in gully.	17	5.2
112.	Sandstone, pale-orangish-brown, fine-grained, slightly micaceous, calcareous. Bedding is very thin to shaly. Forms small ridge.	21	6.4
111.	Shale, gray, silty, slightly calcareous. Trace of silty nodular limestone interbedded. Basal 1 ft (30 cm) is brown, sandy limestone.	20	6
110.	Sandstone and interbedded siltstone, medium-gray, weathers medium orange brown. Sandstone is very fine grained. Unit contains some interbedded silty clay shale and is very thinly bedded to shaly throughout. Forms slight ridge.	64	19.5
109.	Shale, clay, gray, silty, slightly micaceous. Near middle, unit contains a few thin beds of nodular limestone. Forms slope.	40	12.2
108.	Sandstone, light-yellowish-gray, fine-grained to very fine grained, micaceous. Contains limonite-replaced fossil logs and twigs. Bedding is very thin; crossbedded. Forms slight ridge.	13	4
107.	Concealed; slope; probably shale.	7	2.1
106.	Limestone, light-gray, fine-grained. Composed of minute crinoidal and other fossil fragments. Forms ledge.	2	0.61
105.	Shale, clay, gray to olive-gray, silty. Contains some thin beds of very fine grained sandstone and silty limestone. Forms slope.	20	6.1
104.	Sandstone, conglomeratic, light-brown to tan, slightly calcareous. Composed of subangular to subround, very coarse quartz sand and granules; contains a trace of weathered, yellow feldspar. Contains a few quartz pebbles up to 0.5 inch (1.25 cm) diameter. Forms small ledge.	5	1.5
103.	Concealed; slope. Float indicates interval is underlain by dark-gray shale and thin limestone.	31	9.5
102.	Limestone, gray, massive, similar to unit 97.	2	0.61
101.	Concealed; slope. Float indicates interval is underlain by shale and some shaly limestone.	33	10
100.	Sandstone, conglomeratic, pale-yellow-gray, feldspathic. Composed of angular to subround, coarse to very coarse sand and granules; 15 percent is deeply weathered, chalky-appearing, white feldspar. Contains quartz and feldspar pebbles 0.1–0.5 inch (0.3–1.3 cm) diameter. Crossbedded. Forms subdued ridge.	14.5	4.4
99.	Shale, clay, medium-gray, calcareous. Contains 2-ft (60-cm) thick bed of gray limestone near middle. Forms slope.	8	2.4
98.	Sandstone, medium-yellow-brown, medium- to coarse-grained, slightly calcareous. Forms hard, small ridge.	3	0.9
97.	Limestone, medium-gray, fine-grained. Contains crinoid columnals, brachiopods, and algal filaments and thalli. Brecciated and recemented structure. Forms massive, low ridge.	16	4.9
96.	Sandstone, light-brownish-gray, highly calcareous. Composed of angular, coarse to very coarse quartz sand. Upper two thirds contains abundant crinoid columnals and brachiopods; grades upward to sandy limestone at top. Forms ridge.	10.5	3.2
95.	Limestone, medium-gray, fine-grained, mainly structureless. Sparingly fossiliferous. Forms small ridge.	10	3
94.	Sandstone, conglomeratic, light-greenish-gray, feldspathic. Composed of angular to subround, coarse to very coarse sand and granules; 20 percent is deeply weathered, chalky-appearing, white feldspar. Contains abundant pebbles as much as 0.75 inch (1.9 cm) diameter; many of the smaller pebbles are feldspar. Crossbedded; beds are 8 inch–2 ft (20–60 cm) thick. Forms ridge.	14	4.3
93.	Concealed; slope.	20	6.1
92.	Shale, clay, medium-gray; exposed in gully.	5	1.5
91.	Limestone, gray, nodular, thin-bedded; weathers massive.	23	7
90.	Siltstone, shaly, and interbedded very fine grained sandstone. Unit is mostly shaly. Forms slope.	17	5.2
89.	Limestone, medium-brown, very sandy. Forms small ridge.	2	0.61
88.	Shale, gray, poorly exposed. Contains several 1–2-ft (30–60-cm) thick beds of gray limestone. Contains fragments of silicified fossil logs. Forms slope.	40	12.2
87.	Limestone, medium-gray, and interbedded shale and shaly limestone. Beds mainly less than 1 ft (30 cm) thick. Sparingly fossiliferous.	23	7
86.	Sandstone, pinkish-gray to yellowish-gray, weathers light-yellowish-brown. Composed of subangular to subround, medium to coarse, clean quartz sand. Bedding irregular;		

Unit	Lithology	Thickness ft	m
	beds are <1–10 inches (<2.5–25 cm) thick.	12	3.7
85.	Concealed; slope. Probably mostly shale as indicated by sparse out crops near top.	36	11
84.	Limestone, light-gray, fine-grained. Contains many irregular streaks of light-tan lacy chert. Forms small ridge.	17	5.2
83.	Siltstone, gray, calcareous, shaly. Contains beds of thin shaly lime stone. Forms slope.	15	4.6
82.	Limestone, light-yellowish-orange-weathering, silty, sparingly fossiliferous. Forms subdued ridge.	35	10.7
81.	Shale, gray, calcareous; poorly exposed; forms slope.	23	7
80.	Limestone, medium-gray, pelletal. Forms small ridge.	2	0.61
79.	Shale, gray, calcareous, and interbedded very thin limestone. Poorly exposed slop.e	25	7.6
78.	Limestone, similar to unit 76.	1.5	0.46
77.	Shale, gray, calcareous. Poorly exposed slope.	21	6.4
76.	Limestone, light-yellowish-orange-weathering, silty, sparingly fossiliferous. Forms small ridge.	2	0.61
75.	Mainly concealed; slope. Float indicates interval is mainly gray shale containing some thin nodular limestone and interbedded shale; 26 ft (8 m) above base is 1-ft (30-cm) thick bed of highly fossiliferous limestone; 39.5 ft (12 m) above base is 2-ft (60-cm) thick bed of gray pelletal limestone.	60	18.3
74.	Limestone, medium-gray, fine-grained. Moderately fossiliferous; contains brachiopods, bryozoans, crinoid columnals, and algal thalli. Beds are 2–3 ft (60–90 cm) thick. Forms massive, rounded ridge.	18	5.5
73.	Limestone, medium-gray, fine-grained. Beds are 2 inch–1 ft (5–30 cm) thick; contains calcareous shale interbeds 0.75–6 inches (2–15 cm) thick. Exposed at east side of strike canyon.	30	9.2
72.	Shale, dark-gray, calcareous; poorly exposed in bottom of strike canyon.	15.5	4.7
71.	Limestone, gray, and interbedded dark-gray shale; poorly exposed in strike canyon. Limestones, where observed, are thin; about half the unit is shale. Top of unit is medium-gray, very fine grained, fossiliferous limestone that forms a small ridge in strike canyon. Limestone about 7 ft (2.1 m) above base has abundant fusulinids. Collection f10141 contains *Beedeina* aff. *B. rockymontana*.	114	34.8
70.	Limestone, light-gray, mainly fine- to medium-grained, bioclastic; contains brachiopods, crinoid columnals, and corals. Many beds contain fine-banded algal clumps and intergrowths of algal-banded limestone between fossils. Bedding is slightly irregular; beds are mainly 0.5–1 ft (15–30 cm) thick. Contains some thin, calcareous shale partings and siliceous, brown weathering bands along bedding and laminations. Forms a massive low ridge. Fusulinids occur about 52.5 ft (16 m) above base. Collection f10140 contains *Beedeina* aff. *B. rockymontana* and *Wedekindellina* sp.	99.5	30.4
69.	Concealed; slope.	23	7
68.	Limestone, gray, fine-grained; contains abundant fragments of crinoids and brachiopods.	2	0.61
67.	Concealed; slope.	11	3.4
66.	Sandstone, conglomeratic, light-yellowish-brown-weathering. Composed of angular to subangular, very coarse quartz sand and granules; contains a trace of weathered feldspar. Contains small quartz pebbles. Forms massive ridge.	23	7
65.	Concealed; slope. Float indicates shale, siltstone, and sandstone in the interval.	202	61.6
64.	Sandstone, conglomeratic, similar to unit 57. Upper 4 ft (1.22 m) is slabby-weathering sandstone in beds 0.5–1 ft (15–30 cm) thick. Forms massive ridge.	21	6.4
63.	Concealed; slope.	19	5.8
62.	Shale, gray to light-olive-gray, poorly exposed. Contains shaly siltstone and micaceous very fine grained sandstone.	13	4
61.	Limestone, brown-weathering, silty; contains few fossils. Poorly exposed; forms slabby, low ridge.	15	4.6
60.	Concealed; slope.	83.6	25.5
59.	Limestone, light-gray, fine-grained, slightly silty. Bedding and laminations are irregular to almost nodular; beds are 1 inch–1 ft (2.5–30 cm) thick. Irregular patches of brown-weathering silicified material stand in relief on bedding. Brachiopods, bryozoans, crinoid columnals, and zaphrentid and syringoporoid corals are present sparingly. Forms a moderately resistant, irregular ridge. Fusulinids occur sparingly in upper 10 ft (3 m). Collection f10139 contains *Beedeina* aff. *B. arizonensis*.	34	10.4
Total thickness of Porvenir Formation:		1,614	492.1
Sandia Formation:			
58.	Concealed; slope.	66	20.1

[Unit 57 was traced southward downhill to point about 300 ft (90 m) north of road in canyon. Units 58 and higher were measured eastward on lower slopes of hill.]

Unit	Lithology	Thickness ft	m
57.	Sandstone, conglomeratic, pale-yel-		

Unit	Lithology	Thickness ft	m
	lowish-brown-weathering. Composed of angular to subangular, very coarse quartz sand and granules; contains a trace of yellowish-gray, weathered feldspar. Contains small quartz pebbles. Bedding irregular. Forms prominent ridge.	11	3.4
56.	Shale, gray, and interbedded thin limestone; poorly exposed on slope.	98.5	30
55.	Limestone, light-gray; forms small ridge.	2	0.61
54.	Concealed; slope.	32.5	9.9
53.	Limestone, light-gray; contains irregular, brown, siliceous bands. Forms ridge.	2.5	0.76
52.	Concealed; slope.	6	1.8
51.	Sandstone, tan, fine-grained to very fine grained, calcareous.	2.5	0.76
50.	Limestone, light-gray, fine-grained, bioclastic; contains brachiopods and bryozoans. Bedding irregular to undulatory; beds 1 inch–1 ft (2.5–30 cm) thick. Bedding and laminae marked by brown silicified bands Forms massive ridge.	29	8.9
49.	Concealed; slope.	63	19.2
48.	Sandstone, conglomeratic, light-brown. Composed of angular to subangular, very coarse sand and granules; contains small quartzite pebbles. Fine grained at top. Forms prominent ridge.	12	3.7
47.	Siltstone, gray, and interbedded thin gray limestone.	6	1.8
46.	Limestone, medium-gray, bioclastic; contains sandy lenses; thin-bedded. Forms small, irregular outcrop.	3	0.9
45.	Shale, dark-gray, poorly exposed; forms slope.	51	15.6
44.	Limestone, medium-gray, crinoidal; bedding very thin to laminated.	1.5	0.46
43.	Concealed; slope; probably shale.	25	7.6
42.	Sandstone, brown, medium-grained, silica-cemented cross-laminated, hard.	1	0.3
41.	Concealed; slope; probably shale.	9.5	2.9
40.	Shale, clay, olive-brown, silty.	1	0.3
39.	Concealed; slope; probably mostly dark-gray shale.	23	7
38.	Limestone, dark-gray, fine-grained; Forms small ledge.	1	0.3
37.	Shale, dark-gray; top half poorly exposed.	23	7
36.	Limestone, dark-gray, finely bioclastic; forms small ridge.	2	0.61
35.	Shale, dark-gray, poorly exposed on slope.	9.5	2.9
34.	Limestone, medium-gray, weathers medium olive gray; fine-grained bioclastic matrix contains large fragments of brachiopods and bryozoans. Forms ridge.	3.5	1.1
33.	Shale, dark-gray; consists of interbedded silty claystone and silt stone. Poorly exposed on slope.	29.4	9
32.	Sandstone, light-olive-brown, fine-grained, highly micaceous; beds are less than 2 inches (5 cm) thick.	5	1.5
31.	Sandstone, fine-grained, and interbedded siltstone; micaceous, very thin bedded.	10.3	3.1
30.	Sandstone, conglomeratic, light-brown-gray, weathers light brown. Composed of angular, coarse to very coarse quartz sand and granules; contains some mica and kaolinized feldspar. Contains pebbles as much as 0.25 inch (0.6 cm) diameter. Crossbedded. Forms slumped, prominent ledge and tree-covered rib on hill.	18	5.5
29.	Concealed; slope.	14.7	4.5
28.	Limestone, medium-gray, fine-grained; contains corals, brachiopods, and crinoid columnals. Forms small ledge.	3.5	1.1
27.	Concealed; slope.	25	7.6
26.	Sandstone, brown-gray-weathering. Composed of angular to subangular, coarse to very coarse quartz sand and granules. Contains limonite-replaced fossil wood. Thin bedded. Forms resistant ledge.	6	1.8
25.	Concealed; slope.	5	1.5
24.	Limestone, brown-weathering, bioclastic, poorly exposed.	1	0.3
23.	Concealed; slope. Poor exposures on slopes above are mainly dark-gray, silty clay shale.	49	15
22.	Siltstone, yellowish-gray-weathering, calcareous. Forms irregular ledge.	2	0.61
21.	Concealed; slope.	32	9.8
20.	Limestone, gray-brown-weathering, bioclastic; mainly brachiopod and crinoid debris; sandy and slightly micaceous. Forms ledge.	2	0.61
19.	Concealed; slope.	12	3.7
18.	Sandstone, olive-brown, fine-grained, thin-bedded.	1	0.31
17.	Concealed; slope.	20	6.1
16.	Siltstone, yellow-weathering, poor ly exposed.	28	8.5
15.	Concealed; slope; probably mainly shale and siltstone.	64	19.5

[Unit 14 was traced south about 500 ft (150 m) to point about 30 ft (9 m) above valley floor. Units 15 and above were measured eastward on lower slopes of valley.]

Unit	Lithology	Thickness ft	m
14.	Limestone, medium-gray, bioclastic; consists mainly of brachiopod and crinoid debris; sandy. Forms ledge.	5	1.5
13.	Concealed; slope.	10.6	3.2
12.	Siltstone, yellowish-gray-weathering, slightly micaceous. Forms ledge.	1	0.31
11.	Concealed; slope.	11	3.4
10.	Limestone, light-brownish-gray-weathering, finely bioclastic; contains many brachiopods; contains brown, rusty weathering, ferrugi-		

Unit	Lithology	Thickness ft	m
	nous silicified lenses.	3	0.9
9.	Concealed; slope.	43	13.1
8.	Limestone, similar to unit 6; highly fossiliferous; sandy and silty near top.	5	1.5
7.	Concealed; slope.	9	2.8
6.	Limestone, medium-gray, coarsely bioclastic; mainly fragments of brachiopods, crinoids, and bryozoans; contains irregular layers of brown, rusty weathering silicified lime stone. Forms ledge.	1.5	0.46
5.	Shale, clay, dark-gray, carbonaceous, micaceous; very compact and hard. Contains brachiopods. Forms poorly exposed slope.	17	5.2
4.	Concealed; slope. Float is mostly gray shale.	59.5	18.2
3.	Sandstone, brown-weathering. Composed of angular, fine to coarse quartz sand. Forms ledge.	12.5	3.8
2.	Siltstone, olive-brown, thin-bedded and thinly laminated. Grades upward near top into brown fine- to medium-grained, ferruginous quartz sandstone that contains some coarse grains.	11	3.4
1.	Sandstone, conglomeratic, light-yellowish-brown. Composed of angular to subangular, medium to very coarse, milky-appearing quartz sand and granules. Contains scattered quartzite pebbles. Silica cement. Crossbedded and cross-laminated. Forms blocky, jointed ledge.	28	8.5
Total thickness of Sandia Formation:		1,030	314.2
Arroyo Peñasco Group:			
Tererro Formation:			
	Present. See detailed description of locality 4 of sections of Arroyo Peñasco Group (p. 190).	94.9+	28.9+
Espiritu Santo Formation:			
	Not exposed at this locality. Thin basal sandstone and thin overlying carbonate rocks are present in ridges south of Manuelitas Creek.		
Precambrian rocks:			
	Metaquartzite, pink to grayish-pink, slightly micaceous, highly fractured.	Not measured	

Section I

Mora 7.5-minute quadrangle (1965). Section of Alamitos and Porvenir Formations in steeply dipping, faulted beds that crop out in low hills on north side of valley of Rito Cebolla. Locality is between 6,500 and 5,500 ft (2 and 1.7 km) northwest of New Mexico Highway 518 bridge across Rito Cebolla (shown as bridge on Highway 3 on Sapello 7.5-minute quadrangle, 1965). Measured by E. H. Baltz. Locality shown in Figures 31 and 88.

Unit	Lithology	Thickness ft	m
Sangre de Cristo Formation (lower part):			
46.	Concealed; alluvium in south-draining valley. To the north, this interval is composed of slightly gravelly thick arkoses with interbedded red and some greenish-gray shale. These rocks contain some unfossiliferous nodular limestone and thin interbeds of gray limestone. To the east, below Quaternary gravel terraces on the north side of the valley of Rito Cebolla, stratigraphically higher similar arkoses and red shale containing a few thin, unfossiliferous nodular and earthy limestone beds crop out. These rocks are estimated to be about 2,000 ft (610 m) thick.	Not measured	
45.	Sandstone, conglomeratic, light-gray, weathers light yellowish gray, feldspathic. Composed of angular to subangular, very coarse sand and granules and contains some pebbles as much as 1 inch (2.5 cm) diameter; about 20 percent of all clast sizes is unweathered pink feldspar. Crossbedded and cross-laminated; beds are 8 inch–3 ft (20–90 cm) thick. Forms ridge on north side of valley of Rito Cebolla just west of alluviated south-draining tributary valley Top and base concealed.	36	11
44.	Shale, clay, red; poorly exposed.	15	4.6
43.	Sandstone, conglomeratic, feldspathic, similar to unit 45, except that it contains distinct lenses of pebbles 0.5–1 inch (1.27–2.5 cm) diameter. Some small pebbles are unweathered pink feldspar. Forms small ridge.	19	5.8
42.	Sandstone, conglomeratic, purplish-red to yellowish-gray, feldspathic. Composed of very coarse sand and granules; contains quartz and purple clay pebbles as much as 0.75 inch (1.9 cm) across. Basal 2 ft (0.6 m) is red shale. Soft; crops out		

Unit	Lithology	Thickness ft	m
	in shallow gully.	15	4.6
41.	Sandstone, conglomeratic, light-yellowish-gray, feldspathic. Composed of angular to subangular, very coarse sand and granules; about 20 percent of clasts is angular pebbles 0.25–1 inch (0.6–2.5 cm) across.	7.5	2.3
	Thickness of measured lower part of Sangre de Cristo Formation:	92.5	28.3

[The contact of the Sangre de Cristo and Alamitos Formations probably is a fault that is poorly exposed. A few yards north of point of measurement, the lower part of unit 41 is cut out and the unit is warped eastward along a north-trending strike fault. Amount of displacement is unknown; about 2,000 ft (610 m) to the north the fault seems to die out.]

Alamitos Formation (part):

Unit	Lithology	Thickness ft	m
40.	Shale, clay, red, poorly exposed; forms slope.	7.5	2.3
39.	Sandstone, conglomeratic, olive-green, weathers greenish gray, arkosic. Clasts are very coarse sand, granules, and pebbles as large as 0.25 inch (0.6 cm). Rock is greatly sheared and slickensided internally. Some parts may be slightly mylonitized. Forms small ridge; middle part poorly exposed.	15.5	4.7
38.	Sandstone, light-greenish-gray, medium-grained, micaceous, slightly feldspathic. Thin bedded. Forms slope; poorly exposed.	4	1.2
37.	Sandstone, light-yellowish-gray, arkosic. Clasts are very coarse sand and granules; contains some greenish-gray clay. Forms small ridge.	3	0.9
36.	Shale, clay, red-weathering, poorly exposed.	7	2.1
35.	Sandstone, light-yellowish-gray, very coarse grained, arkosic; poorly exposed.	4	1.2
34.	Sandstone, light-gray to light-brown, arkosic. Composed of angular to subangular, very coarse sand and granules; many granules are pink and yellow, angular feldspar. Crossbedded and cross-laminated. Forms strong ridge; slabby weathering. Internally sheared and slickensided.	8	2.4
33.	Concealed; probably soft sandstone.	5	1.5
32.	Limestone, light-gray, weathers light brownish gray. Mainly micrite, but contains scattered streaks of quartz silt and sand and scattered fragments of brachiopods and crinoid columnals. Bedding is irregular to lumpy. Forms small ridge.	0.5	0.15
31.	Concealed; slope; float indicates unit is greenish-gray shale and thin, nodular limestone beds.	5	1.5
30.	Sandstone, light-greenish-gray, arkosic. Matrix is greenish-gray, clayey, fine sand that contains coarse sand and granules. Many coarse grains and granules are angular pink feldspar. Slightly micaceous. Forms small ridge.	3	0.9
29.	Mainly concealed; slope. Float and a few poor exposures indicate unit is gray to purplish-red shale containing thin, nodular limestone beds.	6	1.8
28.	Limestone, purplish-gray, weathers light purplish gray. Micritic matrix is slightly silty and sandy and contains scattered brachiopods and brachiopod fragments. Bedding is irregular to undulatory; beds are 1–6 inches (2.5–15 cm) thick. Forms slight ridge.	4	1.2
27.	Concealed.	3	0.9
26.	Sandstone, light-greenish-gray, medium- to very coarse-grained; contains pink feldspar granules. Forms small ridge.	3.5	1.1
25.	Sandstone, light-yellowish-gray, medium-grained, Forms slope; poorly exposed.	5	1.5
24.	Concealed; slope; probably shale.	7	2.1
23.	Shale, light-gray; unit is clayey siltstone containing a trace of muscovite. Forms slope.	11	3.4
22.	Sandstone, conglomeratic, light-yellowish-gray, feldspathic. Composed of very coarse sand and granules; contains scattered pebbles as large as 0.5 inch (1.27 cm). Some granules and pebbles are pink feldspar. Beds are 0.5–3 ft (15–90 cm) thick. Forms ridge; sharply overturned and west-dipping.	13	4
21.	Shale, purplish-gray, silty and sandy; grades into underlying unit. Forms slope; poorly exposed.	3	0.9
20.	Sandstone, purple- to olive-green-weathering, medium-grained; contains scattered coarse sand and granules; slightly micaceous. Forms small ridge.	4	1.2
19.	Sandstone, greenish-olive, coarse-grained; contains scattered granules of pink feldspar. Forms small ridge.	2.5	0.76
18.	Shale, green- to maroon-weathering; contains many purple to gray, botryoidal-limestone nodules. Forms slope; poorly exposed.	13	4
17.	Limestone, light-gray-weathering; contains silty interbeds and irregular, yellow chert stringers. Highly fossiliferous; contains brachiopods and crinoid columnals. Near middle is a 1-ft (30-cm) thick crinoidal coquina. Bedding is undulatory; beds are 1–8 inches (2.5–20 cm) thick. Forms ledge.	16	4.9
16.	Shale, clay, gray, silty. Contains some 1-inch (2.5-cm) thick beds of gray limestone. Forms slope; poorly exposed.	13.7	4.2
15.	Limestone, medium-gray, weathers light brown. About 20 percent of		

Unit	Lithology	Thickness ft	m
	unit is thin interbeds of silty gray shale. Limestone is micrite containing scattered fossil fragments; fusulinids are common in the lower part. Bedding is undulatory to nodular; beds are 1–6 inches (2.5–15 cm) thick. Forms small ridge. Fusulinid collection f10297 contains *Beedeina* aff. *B. sulphurensis*.	5	1.5
14.	Shale, clay, gray; grades downward into yellow sandy shale and interbedded shaly, very fine grained sandstone. Forms slope.	20	6.1
13.	Sandstone, conglomeratic, light-olive-brown, weathers light yellowish brown, feldspathic. Composed of coarse to very coarse sand containing granules scattered throughout; about 15 percent is yellow to pink feldspar clasts. Basal 2 ft (60 cm) contains scattered quartz and quartzite pebbles 0.5–2 inches (1.27–5 cm) diameter, and angular orange and pink feldspar pebbles as large as 0.75 inch (1.9 cm) diameter. Forms strong ridge.	17	5.2
12.	Sandstone, conglomeratic, similar to unit 13 but softer. Contains scattered orange and yellow feldspar granules and small pebbles. Near base, contains green shale pebbles. Forms poorly exposed small ledges on slope.	15.5	4.7
11.	Sandstone, conglomeratic, similar to unit 13, but soft and poorly exposed. Contains numerous angular feldspar cleavage fragments as large as 0.5 inch (1.27 cm). Grus-like appearance. Forms slope.	29	8.9
10.	Limestone, light-grayish-brown, sandy, silty, fossiliferous. Forms small ridge.	1	0.3
9.	Sandstone, light-yellowish-gray-weathering, feldspathic. Composed of angular to subangular, coarse to very coarse sand and granules; contains numerous orange and yellow feldspar clasts. Basal 2.5 ft (76 cm) is hard, greenish-gray, fine- to coarse-grained granule-bearing, conglomeratic sandstone; about 15 percent is pink, unweathered, feldspar cleavage fragments, many as large as 0.25–0.5 inch (0.6–1.27 cm). Unit forms ridge. Probable base of Alamitos Formation.	12	3.7
	Thickness of faulted (incomplete) Alamitos Formation:	266.7	81.2

[Underlying units 6 through 8 might be assigned to either the Alamitos Formation or the Porvenir Formation. They are assigned to the upper part of the Porvenir because of the weathered yellowish-gray feldspars in unit 6 and because, farther north, interbedded gray shales appear lithologically most similar to shales of the Porvenir.]

Unit	Lithology	Thickness ft	m
	Porvenir Formation (part):		
8.	Concealed; slope.	28	8.5
7.	Limestone, light-gray; upper half is a coquina of crinoid fragments; lower half is bioclastic and sandy. Forms small ridge.	2	0.61
6.	Sandstone, light-yellowish-gray, feldspathic. Composed of angular, coarse to very coarse sand and granules; contains yellow, weathered feldspar. Bedding is obscure. Soft and poorly exposed; base concealed. Lower (western) part is greatly fractured and sheared, suggesting proximity to a concealed fault.	19	5.8

[Concealed strike fault, roughly parallel to bedding, probably juxtaposes units 5 and 6.]

Unit	Lithology	Thickness ft	m
5.	Sandstone, light-yellowish-gray; mostly fine- to medium-grained and micaceous. Thin bedded to shaly. Some coarse-grained sandstone is interbedded in upper third. Unit is mostly poorly exposed; outcrop belt is littered with sandstone slabs; possibly some shale is interbedded. General lithology of unit is similar to lower part of sandstones of Fragoso Ridge exposed on upper slopes of that ridge at locality C south of Rito Cebolla.	95±	29±
4.	Concealed; alluvium in small south-draining valley. Exposures to the north indicate bedrock is mostly dark-gray shale containing thin sandstone and gray limestone interbeds. Some of the sandstones are 6–10 ft (1.8–3 m) thick.	140±	43±
3.	Limestone, medium- to dark-gray, weathers medium grayish brown. Micrite containing scattered small brachiopods and bioclastic debris. Consists of three limestone beds separated by thin, gray shale interbeds. Forms small ridge in south-draining valley.	12	3.7
2.	Sandstone, light-brownish-gray-weathering, fine- to medium-grained. Bedding is subparallel; beds are 1 inch–1 ft (2.5–30 cm) thick. Laminae are inclined south. Forms a small slabby ridge.	5	1.5
	Thickness of internally faulted (incomplete) Porvenir Formation:	301±	92±
	Sandia Formation (upper part):		
1.	Shale, dark-gray, containing interbeds of thin limestone and sandstone; poorly exposed on slopes west of south-draining valley. A grayish-tan bioclastic limestone, about 2 ft (0.6 m) thick, occurs in this unit about 70 ft (21 m) below		

Unit	Lithology	Thickness ft	m
	the top of the Sandia. This limestone is composed of crinoid-columnal and brachiopod fragments and forms a small ledge. The limestone contains scattered fusulinids; collection f10132 contains *Fusulinella* aff. *F. juncea* Thompson.	Not measured	

[At the west, the Sapello fault throws steeply dipping beds of unit 1 against anticlinally folded thick conglomeratic sandstone of the lower part of the Sandia Formation that is similar to thick conglomeratic sandstones of the lower part at San Isidro Lake south of Rito Cebolla at stratigraphic section C.]

Sections J and K

Mora 7.5-minute quadrangle (1965). Composite section of Alamitos, Porvenir, and Sandia Formations and Arroyo Peñasco Group measured across hogback ridges north of Mora River beginning about 2.7 mi (4.3 km) east of center of town of Mora. Base of section (locality J1) is about 0.95 mi (1.5 km) north of Mora River in southeast-draining headwater segment of the southernmost canyon to cut completely through hogback ridges into Precambrian rocks in southeast part of the Romero Hills. The lower (southern) part of this canyon forms the first broad, southerly trending, strike valley east of outcrops of Precambrian rocks and the highly deformed lower part of the Sandia Formation exposed along New Mexico Highway 518 in Mora River Valley. Reference section of Sandia Formation. Upper part (Section K) is a reference section of the Porvenir and Alamitos Formations; this part was measured in roadcuts and hogback ridges a short distance north of Highway 518 northwest and northeast of St. Joseph Church. Measured by E. H. Baltz, J. M. O'Neill, and M. N. Machette. Localities are shown in Figures 17, 31, 55, and 89.

Section K

Unit	Lithology	Thickness ft	m
Sangre de Cristo Formation (lower part only):			
373.	Sandstone, conglomeratic, purplish-brown-weathering, arkosic. Composed of subangular very coarse sand. Feldspars are pink orthoclase. Contains rounded to subrounded pebbles of quartz, quartzite, and schist. Forms strong, high hogback ridge.	25±	8±
372.	Shale, red-weathering, poorly exposed. Forms slope.	23	7
371.	Sandstone, conglomeratic, purplish-brown-weathering, arkosic. Composed of subangular very coarse sand. Highly arkosic; feldspars are pink orthoclase. Contains rounded to subrounded pebbles of quartz, quartzite, and schist. May contain some thin red shale interbeds. Forms strong hogback ridge. Contact with underlying unit concealed.	40	12.2
	Thickness of measured lower part of Sangre de Cristo Formation:	88±	27±
Alamitos Formation (reference section):			
370.	Concealed; slope; probably red shale.	8.8	2.7
369.	Shale, red-weathering, poorly exposed. Forms slope.	1.5	0.5
368.	Sandstone, red-brown-weathering, fine-grained to very fine grained, quartzose, micaceous. Beds are 1–6 inches (2.5–15 cm) thick; contains thin shaly partings. Grades into underlying unit. Poorly exposed; forms ridge.	3	0.9
367.	Shale, clay, medium-gray, weathers light greenish gray. Upper two-thirds is silty, micaceous, and weathers reddish-purple. Forms slope.	13	4
366.	Claystone, green, weathers yellowish green. Very thinly laminated, tending to part into slate-like plates. Bedding surfaces are smooth and contain tiny impressions of plant fragments and animal trails. Unit is relatively resistant and forms local ridges. A similar unit, possibly the same unit, was observed at places northward past Cañon del Agua, and southward past La Cañada del Guajalote.	3.5	1.1
365.	Sandstone, light-olive-gray, weathers light brown to light olive brown. Fine-grained, quartzose, micaceous. Contains green clay partings. Beds are 1–3 inches (2.5–7.6 cm) thick. Forms small ridge.	6.2	1.9
364.	Siltstone and mudstone, light-olive-gray, weathers olive brown, sandy and micaceous. Thin-bedded to shaly. Upper third contains pelecypods, brachiopods, and plant debris and is a bioturbated, poorly bedded mudstone; megafossil collection USGS 27356–PC was obtained from these beds. (Locality BM7801 in Baltz and O'Neill, 1984.) Unit forms slope; upper part well exposed in bulldozed ranch road.	44	13.4
363.	Sandstone, conglomeratic, light-reddish-gray, arkosic. Composed of angular to subangular, coarse sand and granules; about 25 percent of clasts is pink feldspar. Contains numerous rounded to subrounded		

Unit	Lithology	Thickness ft	Thickness m
	pebbles of quartz, quartzite, and schist. Forms massive, strong ridge.	29	8.9
362.	Concealed; slope.	20.8	6.3
361.	Sandstone, conglomeratic, light-grayish-brown, weathers mottled light reddish gray; arkosic. Composed of angular to subangular, very coarse sand and granules. Contains scattered small pebbles, as large as 1 inch (2.5 cm) diameter, of angular to rounded quartz and pink feldspar. Bedding is subparallel to slightly inclined; beds are 2 inch–10 ft (5 cm–3 m) thick; cross-laminated. Forms ridge.	10.6	3.2
360.	Concealed; slope.	4.3	1.3
359.	Claystone, calcareous, and some interbedded lenticular argillaceous limestone; light olive gray. Bedding is subparallel and undulatory; beds are mainly about 1 inch (2.5 cm) thick. Contains brachiopods and some pelecypods. Unit weathers to hard slabby ridge.	3.9	1.2
358.	Claystone, olive-green, thin-bedded to finely laminated. Forms poorly exposed slope.	19.5	6
357.	Limestone, light- to medium-gray. Micrite containing numerous complete and broken brachiopods (collection USGS 27163–PC); contains gastropods, bryozoans, and algal filaments. Beds in lower half are 4–6 inches (10–15 cm) thick; beds in upper half are 2–3 inches (2.5–7.6 cm) thick, undulatory, and contain shale partings. Forms irregularly weathering ridge.	3.9	1.2

[Locality of measurement offset about 1,300 ft (400 m) north in strike valley by tracing unit 357 northward. Units 357–373 were measured up east side of valley in steep hogbacks.]

Unit	Lithology	Thickness ft	Thickness m
356.	Shale, clay, light-gray to light-olive-gray. Contains pods of bioclastic limestone as much as 3 inches (7.6 cm) long. Forms slope.	6	1.8
355.	Limestone and interbedded clay shale, gray- to brown-weathering. Lower part contains clay balls as large as 1.5 inches (4 cm) diameter; upper part is mainly brown lime stone nodules in clay shale.	4.5	1.4
354.	Sandstone, conglomeratic, yellowish-olive-weathering, arkosic. Composed of angular to subangular, coarse sand and granules. Contains scattered small pebbles of angular quartz and pink feldspar. Middle third is medium grained and micaceous. Forms small ridge on west side of valley.	9.5	2.9

[Locality of measurement offset about 150 ft (46 m) north of State Highway 518 by tracing unit 354 northward. Units 354–356 were measured in outcrops at west side of broad alluviated valley.]

Unit	Lithology	Thickness ft	Thickness m
353.	Shale, clay and micaceous silt, olive-weathering. Contains lenticular arkosic sandstone to north. Grades into underlying unit. Poorly exposed near east end of roadcut.	25	7.6
352.	Sandstone, light-pinkish-tan- to olive-brown-weathering. Contains abundant pink feldspar sand and granules.	9.2	2.8
351.	Shale, clay, silty and micaceous. Weathers purplish gray to olive green.	5.3	1.6
350.	Sandstone, conglomeratic, light-pinkish-gray-weathering with purple-weathering stringer; highly arkosic. Composed of very coarse sand and granules. Contains pebbles of vein quartz and pink feldspar. Partly crossbedded. Forms ridge.	17.5	5.3
349.	Shale, clay, red-purple-weathering. Contains lenses of granule arkose near base.	4.3	1.3
348.	Sandstone, pebbly; arkose similar to unit 350. Forms ridge.	38	11.6
347.	Claystone; weathers purple with olive-green streaks. Silty and calcareous; contains argillaceous limestone nodules 0.25–2 inches (0.6–5 cm) long. Upper 2 ft (60 cm) is fine- to medium-grained, micaceous, shaly sandstone. Unit forms slope.	15.9	4.9
346.	Sandstone, purple- to light-purplish-brown-weathering, arkosic. Composed of medium to very coarse sand and granules; micaceous; contains thin siltstone partings. Beds are subparallel and are 2–8 inches (5–20 cm) thick. Grades into underlying unit. Forms irregular slabby ridge.	5	1.5
345.	Siltstone, shaly, olive-green, argillaceous, micaceous, calcareous. Contains 8-inch (20-cm) thick zone of nodular, silty limestone at base. Forms slope.	7	2.1
344.	Sandstone and interbedded siltstone, silty limestone, and thin shale; weathers dark-olive-gray.	1.8	0.55
343.	Sandstone, light-olive- to pink-brown-weathering, fine- to medium-grained. Contains lenses of granule arkose near middle. Contains some very thin silty clay interbeds. Beds are subparallel and are 0.06–1 inch (0.15–2.5 cm) thick. Forms irregular slope.	6.4	2
342.	Sandstone, conglomeratic, light-pinkish-gray-weathering, arkosic. Composed of angular to subangular, very coarse sand and granules. Contains pebbles, as large as 1 inch (2.5 cm) diameter, of vein quartz		

Unit	Lithology	Thickness ft	Thickness m
	and pink feldspar. Forms ridge.	14	4.3
341.	Siltstone, claystone, and fine-grained sandstone, interbedded; weathers olive gray; micaceous and shaly. Forms notch.	5.6	1.7
340.	Limestone, light-yellowish-olive-weathering, very silty. Contains brachiopods.	0.6	0.18
339.	Siltstone and interbedded very fine grained sandstone and some clay shale. Weathers purple to light-olive-green. Micaceous and slightly calcareous; contains a few small pods of sandy limestone. Forms slope.	15.8	4.8
338.	Sandstone, conglomeratic, light-pinkish-gray-weathering, arkosic. Composed of angular to subangular, very coarse sand and granules. Contains pebbles, as large as 1 inch (2.5 cm), of vein quartz and pink feldspar. Forms ridge.	22	6.7
337.	Shale, clay and silt, purplish-brown-weathering, highly micaceous. Middle 1.5 ft (45 cm) is marly, nodular limestone. Forms slope.	16.2	4.9
336.	Sandstone, light-purplish-brown-weathering. Coarse-grained at base, but mainly fine to medium grained; micaceous and slightly feldspathic. Middle 1–2 ft (30–60 cm) is purple to olive, micaceous siltstone and claystone. Thin bedded to shaly and crossbedded. Forms small ridge.	9.5	2.9
335.	Claystone, dark-olive-gray. Lower 1 ft (30 cm) contains limestone nodules and weathers purplish-gray. Forms slope.	5.8	1.8
334.	Limestone, nodular, light-olive-gray- to purple-weathering; contains some interbedded red clay. Nodules are micrite, 0.06–6 inches (0.16–15 cm) long. Forms slight, irregular ridge.	1	0.3
333.	Shale, clay and silt, light-purplish-red with olive streaks; slightly micaceous. Upper 1 ft (30 cm) contains reddish-brown limestone nodules as much as 6 inches (15 cm) long. Forms slope.	6.8	2
332.	Sandstone, light-purple-gray to light-olive-green, arkosic. Composed of fine to very coarse sand and granules of quartz and pink feldspar. Forms slight ridge.	3	0.9
331.	Shale, clay, dark- to light-purple-weathering, calcareous, slightly marly. Forms notch.	2	0.61
330.	Limestone, nodular, and interbedded claystone; weathers light-olive to purple. Limestone nodules are irregularly shaped and are 0.25–3 inches (0.6–7.5 cm) long. Claystone is about 20 percent of unit. Forms irregular ridge.	2.2	0.67
329.	Limestone, light-gray, weathers light purplish gray. Unit is mainly limestone nodules, 0.25–4 inches (0.6–10 cm) long, in a matrix of thinly laminated, shaly, gray limestone. Nodules are fine grained to micritic. Finely comminuted fossil fragments form much of matrix; broken and unbroken brachiopods are common floating in matrix. Contains scattered fusulinids; collection f10121 from outcrop at south side of highway contains Beedeina acme. Beds are 8 inch–1.5 ft (20–45 cm) thick and generally parallel. Forms strong ridge.	7.5	2.3
328.	Shale, calcareous, and interbedded lenticular to nodular limestone; weathers olive-gray. Forms notch.	0.6	0.18
327.	Limestone, light-gray, slightly nodular. Micrite containing some fossil fragments.	1.3	0.4
326.	Shale, clay, very-light-olive-green, marly. Contains small limestone nodules. Forms notch.	1	0.3
325.	Limestone, nodular, gray to greenish-gray with some purple staining. Contains several 1-inch (2.5-cm) thick calcareous shale beds. Undulatory bedded. Contains small fossil fragments. Forms irregular ridge.	1.7	0.52
324.	Shale, clay, dark-olive-green, weathers light olive green, calcareous. Contains many nodules of gray, dense limestone. Some nodules are primary and are in zones parallel to bedding; other nodules are secondary and located along joints. Upper fourth of unit contains lenses of limestone and nodules. Locally slope.	9.7	3
323.	Limestone, light-gray; faintly laminated micrite. Beds are 1 inch–1 ft (2.5–30 cm) thick, parallel, and slightly undulatory. Contains scattered brachiopods and algal filaments. Upper half is silty and finely laminated and contains interbeds of shaly limestone. Forms ridge.	12.3	3.8
322.	Shale, clay, olive-green. Contains thin beds of marly shale and some brachiopods. Upper part is calcareous shale and, near the top, contains thin lenses of limestone. Forms slope.	15.5	4.6
321.	Limestone, nodular, light-yellowish-olive; contains thin interbeds of gray clay shale. Nodules are recrystallized and are 1–2 inches (2.5–5 cm) thick and 2–8 inches (5–20 cm) long. Nodules contain poorly preserved indeterminate fusulinids. Upper 8 inches (20 cm) is slightly oolitic, evenly bedded, silty limestone. Unit forms small irregular ridge.	2.7	0.82
320.	Siltstone, light-olive-gray; slightly		

Unit	Lithology	Thickness ft	m
	calcareous and micaceous. Contains brachiopods. Grades into underlying unit.	1	0.3
319.	Claystone and interbedded siltstone, olive-green, purple-mottled. Bedding slightly irregular. Forms slope.	8.5	2.6
318.	Sandstone and interbedded siltstone and claystone; sandstone weathers dark purplish gray; siltstone and claystone weather olive green to purple. Sandstone is very fine grained and forms ribs about 6 inches (15 cm) thick. Unit forms irregular slope.	6	1.8
317.	Sandstone, conglomeratic, feldspathic; similar to unit 313. Forms ridge.	20.5	6.3
316.	Shale, purplish-gray; similar to unit 310. Forms slope.	16.2	5
315.	Sandstone, conglomeratic, feldspathic; similar to unit 313. Beds are 6–10 ft (1.8–3 m) thick. Grades into underlying unit. Forms minor ridge.	24	7.3
314.	Sandstone, conglomeratic, olive-green, purplish-gray near base, arkosic. Composed of coarse to very coarse sand and granules. Lower third is granules and pebbles as large as 2 inches (5 cm) diameter. Pebbles are subangular to subround and are composed of quartz, shale, and pink feldspar. Highly crossbedded; beds are 1 inch–1.5 ft (2.5–45 cm) thick. Moderately indurated.	7	2.1
313.	Sandstone, conglomeratic, yellowish-gray- to light-greenish-gray-weathering, feldspathic. Composed of coarse sand and granules; 10–20 percent of clasts is feldspar. Contains lenses of pebbles and scattered pebbles; pebbles are angular to subround and 0.1–1.5 inches (0.3–3.8 cm) diameter. Pebbles are pink feldspar, vein quartz, greenish-gray quartzite, quartz-mica schist, and shale. Essentially one massive cross-laminated bed. Forms minor ridge.	24.5	7.5
312.	Siltstone and interbedded claystone; olive- to purple-weathering. Grades into underlying unit. Forms notch.	2.5	0.75
311.	Sandstone, conglomeratic, arkosic; similar to unit 309. Forms slight ridge.	6.6	2
310.	Siltstone and some interbedded claystone; weathers dark purplish gray with olive-green-weathering streaks. Lower and middle parts contain very thin lenses of medium- to coarse-grained arkose. Grades into underlying unit. Forms slope.	9	2.8
309.	Sandstone, conglomeratic, light-pinkish-gray- to light-olive-gray-weathering, arkosic. Coarse-grained to very coarse grained; 25 percent of clasts is pink feldspar. Basal 2 ft (60 cm) is conglomerate containing pebbles as large as 1 inch (2.5 cm); upper part contains scattered stringers of pebbles. Pebbles are vein quartz and pink feldspar. Forms slight ridge.	7.2	2.2
308.	Siltstone, claystone, and clay shale; weathers olive gray and purple. Middle part contains small limestone nodules. Upper part poorly exposed. Forms slope.	13	4
307.	Siltstone and interbedded very fine grained sandstone; weathers greenish-yellow; calcareous. Contains nodules and lenses of tan to gray, fine-grained, bioclastic limestone and silty, micaceous limestone. Beds are parallel, 1–8 inches (2.5–20 cm) thick, and undulatory. Forms small ridge in roadcuts just east of small valley.	12	3.7

[Locality of measurement offset about 590 ft (180 m) south by tracing unit 307 south to roadcuts on New Mexico Highway 518 at east side of small valley. Units 307–353 measured in roadcuts to east.]

Unit	Lithology	Thickness ft	m
306.	Shale, olive-gray, poorly exposed. Contains some thin, medium-gray limestone. Brachiopods occur in some beds. Forms slope.	60.5	18.5
305.	Sandstone, light-olive-gray, fine-grained, feldspathic, micaceous. Crossbedded and finely laminated. Forms slope on east side of small gully.	12	3.7
304.	Sandstone, conglomeratic, olive- to orangish-gray, brown-mottled, arkosic. Coarse-grained to very coarse grained; contains pebbles as large as 1 inch (2.5 cm) diameter. Pink feldspar is 15–30 percent of unit and ranges from coarse sand to pebbles. Sharp, channeled contact with underlying unit. Forms a moderate ridge.	12.8	3.9
303.	Mainly concealed; slope. Part of unit is red-weathering shale.	13.5	4.1
302.	Sandstone, conglomeratic, olive- to orangish-gray, arkosic. Composed of very coarse sand, granules, and pebbles as large as 1 inch (2.5 cm) diameter. Pink feldspar is 15–30 percent of sand and pebbles. Crossbedded; beds are 6 inch–2.6 ft (15–76 cm) thick. Contains red shale interbeds as much as 3 ft (90 cm) thick. Forms strong ridge.	41.4	12.6
301.	Sandstone, light-olive-green to light-olive-brown. Fine- to medium-grained, highly micaceous, slightly feldspathic. Beds are subparallel and 0.5–8 inches (1.3–20 cm) thick. Forms several slight ridges.	15.8	4.8

Unit	Lithology	Thickness ft	m
300.	Shale, light-olive-green, poorly exposed.	6.5	2
299.	Shale, slightly reddish-gray-weathering, poorly exposed. Contains numerous limestone nodules that are 0.25–2 inches (0.6–5 cm) in maxi mum dimension. Forms notch.	12	3.7
298.	Sandstone, conglomeratic, light-orangish-gray, arkosic; similar to unit 291. Crossbedded; beds are 2 inch–2 ft (5–60 cm) thick. Forms moderate ridge. Thickness approximate.	24.5	7.5
297.	Siltstone, olive-green, micaceous. Contains thin, irregular beds of light-gray limestone and limestone concretions. Beds are 0.25–2 inches (0.6–5 cm) thick, subparallel, and undulatory. Forms small, hard ridge.	9	2.8
296.	Shale, clay, light-olive-green-weathering; silty and slightly micaceous. Contains an 8 inch (20 cm) thick brownish-gray limestone bed near top. Forms slope.	14	4.3
295.	Shale, clay, medium- to dark-gray, silty, slightly micaceous. Contains several 2 inch (5 cm) thick limestone beds that have numerous brachiopods. Forms slope on east side of gully.	21	6.4
294.	Concealed; slope overlain by slumped sandstone slabs.	29	8.9

[Locality of measurement offset about 425 ft (130 m) north along small strike valley by tracing unit 293 northward from roadcuts on New Mexico Highway 518. Units 294–306 measured in arroyos and ridges east of valley.]

Unit	Lithology	Thickness ft	m
293.	Sandstone, conglomeratic, arkosic; similar to unit 291; contains pink feldspar clasts. Beds are as much as 5 ft (1.5 m) thick in lower part and 2–6 inches (5–15 cm) thick in upper part. Forms ridge west of small alluvial valley. Top not exposed in road cut; thickness approximate.	20	6.1
292.	Siltstone and interbedded very fine grained sandstone, olive-gray, micaceous, shaly. Forms notch.	4	1.2
291.	Sandstone, conglomeratic, light-olive-gray, arkosic. Composed of angular to subangular, coarse sand and granules; contains pebbles as much as 1 inch (2.5 cm) diameter of pink feldspar, quartzite, amphibolite schist, and green shale. Upper third contains thin shale interbeds. Forms ridge.	8.5	2.6
290.	Shale, silt and clay, olive-green to splotchy purple-weathering. Forms notch.	5.6	1.7
289.	Sandstone, light-olive-gray, arkosic. Similar to unit 283. Forms strong ridge. Channels into underlying unit.	11	3.4
288.	Shale, siltstone, and very fine grained sandstone, weathers grayish red to olive green; micaceous; contains some pink feldspar granules. Forms irregular slope.	10	3
287.	Sandstone, conglomeratic, arkosic; similar to unit 283. In parts of unit, 50 percent of sand grains are pink feldspar.	1	0.3
286.	Shale, clay, green to purplish-gray, silty. Contains limestone nodules.	0.5	0.15
285.	Siltstone, greenish-gray, calcareous. About 20 percent of unit is light-gray limestone nodules that are as much as 2 inches (5 cm) diameter. Upper half is shaly. Purplish-gray near top.	3	0.9
284.	Sandstone, arkosic, and interbedded shaly sandstone and sandy shale, all slightly micaceous; weathers light-olive-gray to faintly purplish-gray. About 40 percent of unit is sandstone in lenticular beds 2 inch–1.3 ft (5–40 cm) thick; clasts are fine to very coarse sand and granules. Bedding subparallel and slightly irregular. Forms slope.	7.4	2.3
283.	Sandstone, conglomeratic, light-olive-gray, arkosic. Composed mainly of angular to subangular, coarse sand and granules. Basal 2 ft (60 cm) is conglomerate containing granules and pebbles, as large as 1 inch (2.5 cm) diameter, of pink feldspar, quartzite, and amphibolite schist. Upper part is similar, but pebbles are smaller. At places the matrix of the sandstone is chloritic green clay. Slightly inclined bedding; cross-laminated. Beds are 0.5–2.5 ft (15–75 cm) thick. Forms moderate ridge.	10.6	3.2
282.	Siltstone, greenish-gray, purple-mottled, argillaceous, slightly micaceous. Contains greenish-gray limestone nodules up to 2 inches (5 cm) diameter. Forms gentle slope.	5.6	1.7
281.	Sandstone, conglomeratic, light-greenish-gray, brown-mottled, feldspathic. Composed of angular to subangular, very coarse sand and granules; about 20 percent is pink feldspar clasts that range up to 0.25 inch (0.6 cm) diameter. Slightly inclined bedding; beds are 2–4 inches (2.5–10 cm) thick. Forms small irregular ridge.	3.4	1
280.	Siltstone, shaly, and interbedded shaly sandstone, weathers purplish red. Sandstone ranges from very fine grained and micaceous to very coarse grained. Siltstone is micaceous. Some irregular bedding and channeling in upper part. Forms gentle slope.	16	4.9
279.	Sandstone, conglomeratic, light-yellowish-gray, brown-mottled; weath-		

Unit	Lithology	Thickness ft	m
	ers light yellowish olive-green; feldspathic. Composed of angular to subangular, coarse quartz sand and granules; about 15 percent is pink to yellow feldspar clasts. Contains scattered pebbles, 0.1–1 inch (0.3–2.5 cm) diameter, that are quartz and pink feldspar. Contains several 2–4-inch (5–10-cm) thick shale beds. Subparallel to crossbedded; beds in lower part are about 3-ft (1 m) thick; beds in upper part are 2 inch–2 ft (5–60 cm) thick. Contact with underlying unit is channeled. Forms strong ridge.	11	3.4
278.	Shale, greenish-gray; lower third locally weathers red. Mainly argillaceous siltstone, middle third contains a micaceous, medium-grained sandstone bed.	2.7	0.82
277.	Sandstone, conglomeratic, light-brown with some medium-brown mottling; weathers light brownish gray. Composed mainly of angular to subangular, medium quartz sand; about 5 percent is pink to gray feldspar clasts. Contains scattered granules and lenses of granules. Upper half contains limestone nodules and stringers of quartz pebbles as much as 0.5 inch (1.3 cm) diameter. Crossbedded and cross-laminated; beds are 2 inches–2 ft (2.5–60 cm) thick. Forms low ridge at east side of small strike valley. Exposed in roadcut.	6.2	1.9
	Total thickness of Alamitos Formation:	1,041	317.7

[Locality of measurement offset about 300 ft (90 m) south to roadcuts by tracing unit 277 south from topographic saddle at head of small valley. Units 277–293 measured eastward in roadcuts at north side of New Mexico Highway 518.]

Porvenir Formation (reference section):

Unit	Lithology	Thickness ft	m
276.	Shale, clay, silty, and interbedded shaly sandstone; light-olive-gray to light-olive-brown. Mostly shale. Sandstones are fine-grained to very fine grained and micaceous; beds are as much as 2 inches (5 cm) thick. Lower half poorly exposed; contains nodules of gray, micritic, silty limestone. Near top some nodular limestones contain fusulinids; collection f10149 contains *Beedeina* aff. *B. rockymontana*, *Wedekindellina* sp., and *Bradyina* sp. Forms slope in low topographic saddle.	21.5	6.6
275.	Limestone, medium-gray, weathers light-olive-gray. Coquina composed of crinoid columnals and large brachiopods and comminuted fossil fragments. Forms slight ridge.	1.2	0.37
274.	Shale, similar to unit 272.	39	11.9
273.	Limestone, medium-gray, weathers brownish gray. Composed of fine- to coarse-grained fragments of crinoid columnals and bryozoans; as much as 20 percent is angular, coarse quartz sand. Unit is two limestone beds separated by thin shale bed. Forms slight ridge on gentle slope.	2	0.6
272.	Shale, clay, medium-gray, slightly silty, slightly carbonaceous. Weathers to chips and flakes. Forms gentle slope in saddle.	46.4	14.1

[Locality of measurement offset about 75 ft (23 m) south to gently sloping topographic saddle. Units 272–276 measured east across saddle.]

Unit	Lithology	Thickness ft	m
271.	Sandstone, light-olive-gray, fine- to medium-grained, micaceous, silty. Crossbedded and finely cross-laminated. Slabby weathering; forms small ridges.	9.1	2.8
270.	Sandstone, light-olive-gray, feldspathic. Composed of angular to subangular, medium quartz sand; micaceous; about 10 percent of sand is pink feldspar. Crossbedded and cross-laminated. Slabby weathering; forms steep slope.	31.2	9.5
269.	Concealed. Probably shale and thin sandstone.	14.7	4.5
268.	Limestone, light-gray, micritic, silty, sandy. Contains bryozoan fragments and algal filaments. Forms small ridge.	1	0.3

[Locality of measurement offset about 50 ft (15 m) to south. Units 268–271 measured eastward.]

Unit	Lithology	Thickness ft	m
267.	Concealed. Probably shale and thin sandstone.	11.5	3.5
266.	Sandstone, light-olive-gray, feldspathic. Composed of angular to subangular, very coarse sand and granules; about 15 percent is pink feldspar, with some gray feldspar and a trace of muscovite. Slightly calcareous. Crossbedded; beds are 0.5–1 ft (15–30 cm) thick. Slabby weathering; forms low ridge.	50	15.3

[Locality of measurement offset about 100 ft (30 m) north to small gully. Units 266–267 measured east along gully.]

Unit	Lithology	Thickness ft	m
265.	Concealed. Probably shale. Forms slope.	13.9	4.2
264.	Limestone, light-gray, fine-grained, very silty. Contains isolated pockets of broken brachiopods and angular quartz granules. Bedding slightly undulatory and subparallel; beds 1–3 inches (2.5–7.5 cm) thick. Blocky weathering; forms slope.	6.5	2
263.	Concealed where measured. Where exposed along strike, interval is bioclastic limestone and interbedded thin coarse-grained calcareous sandstone.	2.5	0.76

Unit	Lithology	Thickness ft	m
262.	Limestone, light-gray, very coarse grained, bioclastic. Lower part contains numerous algal filaments. Upper half contains limestone pebbles in fine-grained matrix. Contains lenses, 6–8 inches (15–20 cm) long, of quartz pebbles that are as large as 0.25 inches (0.6 cm) diameter. Forms small ridge.	6.4	2
261.	Sandstone, light-tan, locally brown-mottled. Composed of well-sorted, angular to subangular, medium to coarse quartz sand and a trace of weathered, yellowish-gray feldspar. Calcareous cement. Bedding obscure. Forms small ridge.	10	3
260.	Limestone, light-gray to light-tan, coarse-grained, bioclastic. Unit is a coquina composed of fragments of brachiopods, crinoid columnals, bryozoans, some corals, and a trace of encrusting algae. Slightly recrystallized. Upper 2 ft (60 cm) is sandy. Grades abruptly into underlying unit and forms one ridge with it. Forms strong ridge on high part of hill about 325 ft (100 m) north of New Mexico Highway 518.	10	3
259.	Limestone, light-gray to light-tan, bioclastic. Unit is very sandy; contains subangular granules and pebbles as large as 0.5 inch (1.27 cm) of quartz and weathered pink and gray feldspar. Cross-laminated; laminae are inclined toward south.	1.5	0.46
258.	Shale, clay, silty, medium-gray; weathers light olive gray. Contains interbedded clayey siltstone and a few 1–1.5-inch (2–3-cm) thick beds of calcareous sandstone and sandy limestone. Forms slope.	10	3
257.	Limestone; coquina similar to unit 251. Forms ridge.	1.5	0.46
256.	Shale, similar to units 258 and 252. Forms slope.	7	2.1
255.	Limestone; coquina similar to unit 251. Forms small ridge. Contains a few fusulinids; collection f10148 contains *Beedeina* aff. B. *joyitaensis*.	0.6	0.18
254.	Shale, similar to units 258 and 252. Forms slope.	6	1.8
253.	Limestone; coquina similar to unit 251. Forms ridge.	3	0.9
252.	Shale, clay, silty, medium-gray; weathers light olive gray. Contains interbedded clayey siltstone and a few 1-inch (2.5-cm) thick beds of calcareous sandstone and sandy limestone. Forms slope.	20	6.1
251.	Limestone, medium-brownish-gray, weathers light grayish brown. Unit is a coquina consisting mainly of broken brachiopods and small brachiopod fragments but containing also fragments of crinoid columnals and bryozoans. Contains angular to subangular, fine to coarse quartz sand and granules scattered throughout. Bedding is slightly undulatory; beds are 1–6 inches (2.5–15 cm) thick. Forms small ridge.	1.2	0.37
250.	Sandstone, and interbedded siltstone and limestone, medium-gray; weathers light olive gray. Sandstone is fine grained, highly calcareous, and contains interbedded calcareous siltstone and undulatory-bedded to nodular, gray silty fine-grained limestone. About 20 percent of unit is limestone. Brachiopods and other fossils are scarce. Bedding is parallel to subparallel; beds are 2 inch–1 ft (5–30 cm) thick. Unit has a banded appearance because limestones are slightly more resistant to weathering than other beds. Forms a bare, relatively smooth, steep slope on east wall of small canyon.	57.5	17.5
249.	Claystone, silty, dark-gray, weathers light olive brown. Unit is finely laminated but not fissile. Upper 5 ft (1.5 m) is silty sandstone that grades into overlying unit. Weathers to angular chips and forms steep slope on east side of small canyon.	35	10.7
248.	Limestone, medium-gray, weathers grayish brown. Coquina of fragments of brachiopods, crinoid columnals, and bryozoans. Fragments are as large as 1 inch (2.5 cm) and are in a matrix of finer bioclastic material. Silty and slightly sandy. Forms small ridge.	1	0.3
247.	Sandstone, light-olive-brown, fine- to medium-grained, micaceous. Near the top is 2-ft (60-cm) thick bed containing granules of pink feldspar. Unit is thin bedded, slabby weathering, and forms a slope. This unit is the top of rocks that are generally correlative with the sandstones of Fragoso Ridge of areas to the south.	12.6	3.8
246.	Sandstone, conglomeratic, feldspathic; similar to unit 237. Contains angular pebbles of weathered pink feldspar as large as 0.5 inch (1.3 cm) diameter. As much as 15 percent of some beds is feldspar. Slabby weathering; forms small ridge.	8.5	2.6
245.	Siltstone and claystone, light-olive-gray. Upper two thirds is mainly clay shale containing light-gray limestone nodules 0.25–1.5 inches (0.6–3 cm) long. Forms slope.	10.4	3.2
244.	Sandstone, brownish-olive-weathering, feldspathic. Fine- to coarse-grained; some beds contain stringers of angular clasts of pink feldspar; slightly calcareous. Beds		

Unit	Lithology	Thickness ft	m
	are 1–6 inches (2.5–15 cm) thick. Slabby weathering; forms small ridge.	14.4	4.4
243.	Mainly concealed. Float and a few small exposures indicate olive-green clay shale containing small gray limestone nodules. Forms slope.	11.6	3.5
242.	Sandstone, similar to unit 237, very coarse grained, feldspathic. Contains fragment of Calamites trunk 3 inches (7.6 cm) in diameter and 6 inches (15 cm) long. Forms strong ridge.	10.4	3.2
241.	Sandstone, light-olive-brown, fine- to medium-grained, micaceous. Beds are subparallel and about 1 inch (2.5 cm) thick. Slabby weathering; forms ledge.	7	2.1
240.	Concealed.	4.2	1.3
239.	Mainly concealed; a few small outcrops indicate mainly shale. Numerous gray limestone nodules litter the slope and are weathering from this unit. These nodules are "armored" around the outside with fusulinid tests and probably are fossil burrows with tests packed in the walls. Fusulinid collection f10147 contains *Beedeina* aff. *B. socorroensis* and *Bradyina* sp.	2.3	0.7
238.	Sandstone, olive-gray, fine-grained, shaly, poorly exposed. Forms slope.	21	6.4
237.	Sandstone, conglomeratic, light-olive-green, feldspathic. Composed of angular to subangular, very coarse sand and granules. About 10 percent is angular clasts of pink feldspar ranging from granules to pebbles as large as 0.5 inch (1.3 cm). Crossbedded; highly irregular beds; beds are 4 inch–1.5 ft (10–45 cm) thick. Appears to be a stream-channel deposit. Forms moderate slabby-weathering ridge.	15.5	4.7
236.	Concealed.	6.7	2
235.	Shale, clay, red-weathering.	2	0.61
234.	Shale, clay, olive-green. Upper 1 ft (0.3 m) is olive-green, fine-grained, micaceous, shaly sandstone. Forms slope.	4.6	1.4
233.	Sandstone, pinkish-gray, fine-grained, thin-bedded to finely laminated. Forms slope.	2	0.61
232.	Shale, clay, gray to greenish-gray in lower part, purplish-red in upper two thirds. Unit is marly; lower part contains limestone nodules 0.25–2 inches (0.6–5 cm) long. Forms slope.	8	2.4

[Units 232–243 were measured eastward along slope about half way up hill north of New Mexico Highway 518.]

Unit	Lithology	Thickness ft	m
231.	Sandstone, light-gray, weathers light orange yellow, arkosic. Composed of angular to subangular, coarse sand and granules. Contains pink feldspar granules and pebbles as large as 0.25 inch (0.6 cm). Irregularly bedded. Slabby weathering; forms slope. This unit is folded into a small anticline and a syncline and appears to be a stream-channel sandstone that thickens west and locally cuts out the underlying units down to unit 225, then thins westward. Measured in east-dipping ridges on slope above roadcut. Probably equivalent to poorly exposed slabby sandstone at east end of roadcut on New Mexico Highway 518.	22.8±	6.9±
230.	Concealed.	1	0.3
229.	Limestone, light-gray, bioclastic, medium- to coarse-grained, silty. Forms small ledge.	0.3	0.09
228.	Concealed.	1	0.3
227.	Limestone, medium-gray, micritic, silty. Contains numerous fossil fragments as much as 0.06 inch (0.16 cm) diameter. Contains fusulinids; collection f10146 contains *Beedeina* cf. *B. novamexicana* and *Wedekindellina* sp. Forms small ledge.	0.5	0.15
226.	Shale, clay, gray; poorly exposed. Forms notch.	0.5	0.15

[Unit 225 was traced back westward to central part of roadcut. Units 226–230 measured on slopes above roadcut.]

Unit	Lithology	Thickness ft	m
225.	Sandstone, light-gray, weathers light yellowish orange; medium- to coarse-grained, micaceous. Bedding is subparallel; thin bedded to finely laminated; cross-laminated. Unit is a channel sandstone that thickens westward and cuts out underlying units down to unit 222. In central part of roadcut this sandstone is gently folded and forms the prominent ledge at the top of the cut. Unit is the base of rocks generally correlative with the sandstones of Fragoso Ridge of areas to the south.	16±	4.9±
224.	Shale, silty, olive-gray-weathering. Forms notch.	0.6	0.18
223.	Limestone, medium-gray, weathers light brown. Micrite containing scattered fragments of crinoid columnals, bryozoans, and brachiopods. Collection f10133 contains the fusulinids *Beedeina* sp. and *Wedekindellina* cf. *W. coloradoensis*. Forms two small ledges separated by a 6-inch (15-cm) thick notch-forming unit of nodular lime stone and clay shale.	1.8	0.55
222.	Shale, clay, gray; contains interbedded rusty-brown weathering shaly sandstone. Forms notch. Angular unconformity apparent at base.	0.5	0.15
221.	Sandstone, silty limestone, and		

Unit	Lithology	Thickness ft	m
	sandy clay shale, interbedded. Beds are 1 inch–1.6 ft (2.5–18 cm) thick. Unit thickens eastward but is cut out westward by angular unconformity with overlying unit.	0–3	0–0.9
220.	Shale, clay, gray. Grades eastward into feldspathic-sandstone lens similar to unit 219.	2.7	0.82

[Unit 219 was correlated with thick sandstone east of small syncline and just above road level to the east. Units 220–225 measured eastward to near east end of roadcut. Above unit 219 in western part of roadcut is notch-forming, shaly, coarse-grained sandstone about 5.5 inches (13 cm) thick. This is overlain by thin, silty, brownish-gray limestone that forms a small ledge and contains fusulinids. These two units do not appear to be present above unit 219 in roadcut to east. Collection f10145 from the limestone contains *Beedeina* cf. *B. pattoni*, *Wedekindellina* sp., and *Bradyina* sp.]

Unit	Lithology	Thickness ft	m
219.	Sandstone, conglomeratic, light-gray, weathers light brownish gray, feldspathic. Composed of angular to subangular, very coarse sand and granules; about 10 percent is yellow, weathered feldspar grains. Contains lenses of angular quartz pebbles as large as 0.5 inch (1.3 cm) diameter and some feldspar pebbles. Strongly crossbedded and cross-laminated. Forms strong slabby ledge near west end of roadcut on New Mexico Highway 518.	13	4.0
218.	Shale, olive-green-weathering; mainly thinly laminated siltstone; upper 1 ft (0.3 m) is thin-bedded, fine- to medium-grained sandstone. Forms irregular slope.	21	6.4
217.	Limestone, light-gray, weathers brownish olive green. Bioclastic and sandy; lower half is nodular. Forms small ridge.	1.8	0.55
216.	Limestone, light-grayish-tan, weathers light grayish brown. Coarse-grained calcarenite containing much quartz silt and fine to very coarse sand and granules of quartz; lower part is mainly calcareous sandstone. Crossbedded and cross-laminated; probably a channel deposit. Unit forms small strong ridge. Contains fusulinids in upper 6 inches (15 cm).	3	0.9

[Unit 216 is about the stratigraphic position of fusulinid collection f10135 from sandy oolite on ridge about 600 ft (180 m) south of Mora River (locality B7611 in Baltz and O'Neill, 1984). Collection f10135 contains *Beedeina* aff. *B. arizonensis*, *Wedekindellina excentrica*, and *Fusulinella* aff. *F. dosensis*.]

Unit	Lithology	Thickness ft	m
215.	Sandstone, conglomeratic, light-orangish-gray-weathering, feldspathic. Composed of angular coarse to very coarse sand and granules of quartz and yellowish-gray, weathered feldspar; contains lenses of pebbles of angular quartz, as much as 1 inch (2.5 cm) diameter, and feldspar. Crossbedded; steeply inclined laminae in some beds indicate intra-unit channeling. Contact with underlying unit is channeled. Forms moderate ridge.	5	1.5
214.	Shale, clay, silty, gray- to brown-weathering. Bedding is contorted by differential compaction.	1	0.31
213.	Sandstone, light-yellowish-olive-gray-weathering, coarse-grained, feldspathic.	3.5	1.1
212.	Sandstone, and interbedded silty limestone; light-gray, weathers light olive gray. Sandstone is fine-grained to very fine grained and calcareous; beds are 0.25 inch–1 ft (0.6–30 cm) thick. Limestones are silty fossiliferous lenses 1 inch–1 ft (2.5–30 cm) thick. Some limestone beds grade laterally into calcareous sandstone. Unit forms slabby irregular slope because of differential weathering of sandstone and limestone. Base concealed by alluvium at east edge of broad valley. Unit is probably about 30 ft (9 m) thick, but measured partial thickness is given. Base of section K.	18.5+	5.6+
	Total thickness of Porvenir Formation:	679.9+	207+

[Locality of measurement offset about 4,000 ft (1,220 m) south–southwest by tracing unit 212 from locality J7 to outcrops at locality K just north of New Mexico Highway 518 near Mora River. Base of unit 212 is west end of locality K. Units 212–219 were measured eastward up the ridge north of culvert for irrigation ditch at east edge of broad, south-draining valley, and about 100 ft (30 meters) north of west end of roadcut. See description of locality L for supplementary description of lower part of Porvenir Formation and upper part of Sandia Formation that were measured about 2,000 ft (600 m) north of New Mexico Highway 518.]

Section J

Top of unit 211 is top of Sandia Formation and is the east end of locality J7. Unit 211 at this locality is overlain by thin-bedded, fine-grained, shaly sandstone and interbedded thin limestone of Porvenir Formation (unit 212) in a narrow syncline. These basal beds of the Porvenir are exposed again farther east in a broad saddle on the crest of a narrow anticline. Fusulinid collection f10137 from limestone of the Porvenir just above unit 212 in the syncline about 150 ft (45 m) south of J7 contains *Fusulinella* aff. *F. dosensis*, *Wedekindellina* sp., and *Bradyina* sp. Collection f10300 from similar limestone near base of the Porvenir east of the anticline contains *Beedeina* sp. as well as *Wedekindellina* sp. and *Bradyina* sp. Localities of measurement of composite section J1–J7 of Sandia Formation shown in Figure 89.

Locality J7

Unit	Lithology	Thickness ft	m
	Sandia Formation (composite reference section)		
211.	Shale, dark-gray, weathers olive gray to olive brown. Poorly exposed in saddle on drainage divide between Cañon del Agua and Mora River, but exposures along strike show unit is mainly silty, carbonaceous claystone containing some thin siltstone and sandstone. Forms slope in saddle.	100	30.5
210.	Shale, black; mainly fissile carbonaceous claystone; poorly exposed. Contains two silty limestone beds 2–4 ft (0.6–1.2 m) thick in upper 9 ft (2.7 m). Forms slope.	19	5.8
209.	Sandstone, conglomeratic, light-yellowish-brown, feldspathic; similar to unit 207. Composed of very coarse sand, granules, and pebbles. Contains some clay and siltstone interbeds. Forms low, irregular ridge.	46.7	14.2
208.	Shale and sandstone, interbedded in about equal proportions. Sandstone is olive-green weathering, fine grained, and micaceous. Shale is gray claystone and siltstone. Poorly exposed; forms slope.	7	2.1
207.	Sandstone, olive-brown, feldspathic. Basal 2 ft (0.6 m) is fine grained and thin bedded. Upper part is angular to subangular, very coarse sand and granules; about 10 percent is yellow, weathered feldspar. Crossbedded. Forms small rounded ridge.	5.2	1.6
206.	Shale, clay, silty, olive-brown, micaceous. About 20 percent of unit is fine-grained, shaly sandstone. Forms slope with numerous small sandstone ribs.	16.7	5.1
205.	Limestone, medium-gray, weathers brown; slightly silty micrite. Contains small turritellid snails, brachiopods, algal filaments, and fine organic debris; slightly fetid. Beds are as much as 6 inches (15 cm) thick. Forms slight ridge.	2.4	0.73
204.	Mostly concealed. Upper 5 ft (1.5 m) is clay shale. Forms slope.	36.7	11.2
203.	Sandstone, medium-olive-gray, weathers light olive brown. Fine- to medium-grained, micaceous; some beds contain yellow to pink feldspar granules. Contains some interbedded clayey siltstone. Beds range from finely laminated to 0.25–6 inches (0.6–15 cm) thick. Forms slope.	33	10.1
202.	Sandstone, conglomeratic, feldspathic, similar to unit 197. Medium- to coarse-grained; contains lenses of pebbles that are as large as 2 inches (5 cm) diameter; contains shaly interbeds.	2	0.61
201.	Sandstone, conglomeratic, feldspathic, similar to unit 197. Forms three small ridges.	7.5	2.3
200.	Concealed.	5.6	1.7
199.	Limestone, light-brown-gray, sandy, shaly; very coarsely recrystallized. Forms small ledges and irregular slope.	7	2.1
198.	Concealed; probably shale and shaly sandstone.	18.6	5.7
197.	Sandstone, conglomeratic, light-olive-yellow, weathers light orange brown, feldspathic. Composed of very coarse sand and granules; about 15 percent is weathered yellow feldspar. Contains pebbles as large as 1.5 inch (3.7 cm) diameter. Forms small ridge.	2	0.61
196.	Concealed.	10.7	3.3
195.	Sandstone, conglomeratic, light-orange-brown, feldspathic. Composed of angular to subangular, medium to coarse sand and granules; 5–10 percent is angular yellow feldspar. Contains scattered lenses of quartz and feldspar pebbles that are 0.25–0.5 inch (0.6–1.27 cm) in diameter. Crossbedded; beds are 0.25–2.5 inches (0.6–6.5 cm) thick. Grades into underlying unit. Blocky-weathering; forms strong ridge.	68	20.7
194.	Sandstone, light-orange-brown, fine- to medium-grained, micaceous. Bedding is inclined; finely laminated to 1-inch (2.5-cm) thick beds. Forms moderate slope.	22	6.7
193.	Mainly concealed; sparse outcrops are interbedded shale and sandy shale. Forms slope.	29	8.8
192.	Sandstone, light-brown; composed of angular to subangular, fine to medium sand; micaceous. Beds are subparallel and 0.25–1.5 inches		

Unit	Lithology	Thickness ft	m
	(0.6–3.5 cm) thick. Forms slight ridge.	2	0.61
191.	Shale and interbedded sandstone, light-grayish-brown, poorly exposed; probably mostly clay shale. Sandstone is fine grained and slightly calcareous. Shale contains a few brachiopods and gastropods. Contains thin, medium-gray limestone containing algal filaments. Forms slope.	30.4	9.3
190.	Sandstone and interbedded shale, light-brown to light-brownish-gray, poorly exposed. Sandstone is fine grained and micaceous; beds are 0.25–1 inch (0.6–2.5 cm) thick; upper part slightly thicker bedded. Shale is probably subordinate in amount to sandstone. Forms slight ridge.	24	7.3
189.	"e" sandstone, conglomeratic, light-orangish-gray, weathers light orangish brown to light reddish brown, feldspathic. Composed of angular to subangular, very coarse sand and granules. Pebbles as large as 0.5 inch (1.3 cm) are abundant, and some pebbles are as large as 1.5 inches (3.8 cm). As much as 20 percent of sand and pebbles is yellow feldspar. Upper part is crossbedded; beds are mainly 2.5 inches–3 ft (6–90 cm) thick with some thin finer-grained interbeds. Lower part is subparallel bedded. Lower 26 ft (8 m) is soft and forms discontinuously exposed small ridges with slopes between. Upper part forms persistent, strong, high ridge. Base of locality J7.	66.6	20.3

[Locality of measurement offset about 900 ft (275 m) south along "e" sandstone ridge to locality J7. Unit 189 and higher units were measured at locality J7 eastward along the drainage divide between Cañon del Agua and Mora River.]

Locality J6

Unit	Lithology	Thickness ft	m
188.	Sandstone, conglomeratic, light-yellowish-gray, slightly feldspathic. Composed of coarse sand and granules and contains feldspar pebbles. Contains shaly sandstone interbeds. Forms small ledges and intervening slopes.	9.6	2.9
187.	Sandstone, light-olive-brown, fine- to medium-grained, highly micaceous. Beds are 0.25–3 inches (0.6–7.6 cm) thick. Forms shaly appearing slope.	37	11.3
186.	Sandstone, light-yellowish-gray, feldspathic. Lower half is fine- to medium-grained, and shaly. Grades upward into very coarse-grained sandstone; about 20 percent is weathered pink feldspar.Upper part forms slight ridges.	9.6	2.9
185.	Shale, clay, medium-gray, weathers light brownish gray, poorly exposed. Outcrops are silty, calcareous claystone containing several 6-inch (15-cm) thick bioclastic limestone beds. Forms gentle slope.	50	15
184.	Concealed; slope. Exposures to south indicate unit is probably carbonaceous black shale.	50	15
183.	Limestone, light-brownish-gray, nodular, micritic to medium-grained. Contains a few brachiopods and algal filaments. Forms slope with some small poorly exposed ledges.	20	6.1
182.	Concealed; slope. Base of locality J6.	7.5	2.3

[Locality of measurement offset about 1,000 ft (300 m) north by tracing unit 181 along west side of small canyon to drainage divide between Cañon del Agua and Mora River. Units 182–188 measured eastward at locality J6 in topographic saddle on divide.]

Locality J5

Unit	Lithology	Thickness ft	m
181.	Sandstone, conglomeratic, feldspathic, similar to unit 177. Exposed in bend of small side canyon. Forms moderate ridge to north.	48	14.6
180.	Concealed; forms notch.	14.8	4.5
179.	Sandstone, conglomeratic, coarse-grained to very coarse grained; about 5 percent is white weathered feldspar. Contains pebbles as large as 0.25 inch (0.6 cm). Crossbedded. Forms moderate ridge.	5	1.5
178.	Sandstone, similar to unit 176, but thicker bedded.	33	10.1
177.	Sandstone, conglomeratic, light-		

Unit	Lithology	Thickness ft	Thickness m
	olive-gray, weathers reddish brown, feldspathic. Coarse-grained to pebbly. Crossbedded; beds are 0.5–6 ft (15 cm–1.8 m) thick. Similar to unit 175. Forms massive-weathering, moderate slope.	63	19.2
176.	Sandstone, light-olive-gray, weathers brownish gray to reddish gray. Composed of angular to subangular, fine to coarse sand; slightly micaceous; contains fossil-wood fragments. Beds are subparallel and 0.5–8 inches (1.3–20 cm) thick. Slabby weathering; forms slope.	81	24.7
175.	Sandstone, conglomeratic, light-orange-gray; upper part is feldspathic. Medium-grained to very coarse grained, becoming coarser upward. Upper part is granule conglomerate that contains pebbles, as large as 1 inch (2.5 cm) diameter, of angular, yellowish-gray orthoclase and plagioclase feldspar and rock fragments. Beds are 0.5–6 ft (15–180 cm) thick, subparallel in lower part, and crossbedded in upper part. Forms moderate, rounded ridge.	145	44.2
174.	Sandstone, light-olive-brown, weathers light gray brown. Fine- to medium-grained, micaceous. Finely laminated to 6-inch (15-cm) thick beds. Forms slope.	40.3	12.3
173.	Shale, gray, clay, poorly exposed.	7	2.1
172.	Sandstone, olive-gray-brown-weathering, fine- to coarse-grained, micaceous. Forms small ridge.	2.5	0.76
171.	Concealed; probably clay shale, siltstone, and very-fine-grained sand stone.	21	6.4
170.	Sandstone, tan, coarse-grained to granule, micaceous. Contains a trace of yellow feldspar. Beds are as thin as 1 inch (2.5 cm), but are mainly 1–1.5 ft (30–45 cm) thick. Cross-laminated and crossbedded. Forms small ridge.	11.5	3.5
169.	Shale, gray, poorly exposed. Upper third of unit is fissile claystone containing a few 1-inch (2.5-cm) thick beds of limestone concretions.	32	9.8
168.	Sandstone, conglomeratic, yellowish-gray, weathers reddish gray to brown. Composed of angular to subangular, medium to coarse sand; micaceous. Contains scattered pebbles as much as 0.25 inch (0.6 cm) diameter. Crossbedded and cross-laminated. Forms small, inconspicuous ridge.	8	2.4

[Locality of measurement offset about 100 ft (30 m) south along alluviated strike valley, still at locality J5. Units 168–181 measured eastward in small southwest-trending canyon tributary to strike valley.]

Unit	Lithology	Thickness ft	Thickness m
167.	Concealed by alluvium in bottom of strike valley.	91	27.8
166.	Sandstone, conglomeratic, tan, weathers light brown gray. Composed of angular to subangular, coarse sand and granules; contains scattered pebbles 0.25 inch (0.6 cm) in diameter; micaceous. Beds are 2–3 inches (5–7.6 cm) thick; mildly inclined crossbedding. Forms inconspicuous ridge on west side of arroyo in strike valley.	10	3
165.	Sandstone, light-olive-gray, medium-grained, micaceous. Beds are 0.25–2.5 inches (0.6–6.5 cm) thick; finely laminated. Forms poorly exposed, low, slabby ridge; probably contains shaly interbeds in upper half.	34	10.4
164.	Sandstone, conglomeratic, light-tan, weathers light gray. Composed of very coarse quartz sand and granules containing scattered pebbles as large as 1.5 inches (3.1 cm) diameter. Beds are 4 inches–2 ft (10–60 cm) thick; slightly inclined crossbedding. Forms moderate ledge.	5.5	1.7
163.	Concealed; probably shale.	20	6.1
162.	Sandstone, conglomeratic, light-brown, weathers light gray, feldspathic. Very coarse grained to pebbly; contains pebbles as large as 1.5 inches (3.8 cm) diameter. About 10 percent is angular yellowish-gray feldspar ranging from granules to pebbles 0.25 inch (0.6 cm) diameter. Lower part contains limestone pebbles as large as 1.5 inch (3.8 cm) diameter. Cross-laminated and crossbedded. Forms rounded ledge.	19	5.8
161.	Limestone, gray-brown, weathers light orange brown. Medium- to coarse-grained. Contains gastropods and brachiopod fragments. Finely laminated to 3-inches (7.6-cm) thick beds. Poorly exposed; forms small ridge.	15.6	4.8
160.	Concealed; probably calcareous shale.	33	10.1
159.	Limestone, light-gray, fine-grained. Fine laminae probably are algal bands. Locally mostly recrystallized and vuggy. Forms small ledge.	5	1.5
158.	Concealed; slope.	20.5	6.3
157.	Limestone, light-gray, micritic. Forms small ledge.	5.5	1.7
156.	Sandstone, conglomeratic, light-gray. Composed of angular to subround, very coarse sand and granules with a few scattered small pebbles. Slightly calcareous. Forms inconspicuous ridge.	3.5	1.1
155.	Sandstone, olive-gray, fine-grained, highly micaceous, thin bedded. Forms slight, slabby ridge.	10	3
154.	Concealed; slope; probably shaly		

Unit	Lithology	Thickness ft	m
	sandstone and shale.	37	11.3
153.	Sandstone, yellowish-gray and brown-mottled, weathers pinkish gray. Composed of subangular to subround, coarse sand and granules; about 5 percent is weathered yellow feldspar. Beds are 1 inch–1 ft (2.5–30 cm) thick, and irregular to crossbedded. Forms slabby inconspicuous ridge.	18	5.5
152.	Limestone, medium-gray, weathers light brown gray. Micrite with silty and sandy laminae; partly algal. Forms small ridge.	13	4
151.	Concealed; slope.	54	16.5
150.	Sandstone, conglomeratic, light-yellowish-gray, weathers light gray brown, feldspathic. Composed of subrounded, medium to very coarse sand and granules; about 10 percent is angular yellowish-pink feldspar clasts ranging up to 0.25 inch (0.6 cm) diameter. Beds are 6 inches–1 ft (15–30 cm) thick and subparallel to crossbedded. Forms inconspicuous ridge.	11	3.4
149.	Sandstone, olive-gray, weathers medium gray brown. Fine-grained and highly micaceous. Finely laminated to thin bedded. Forms slabby ridge.	9	2.7
148.	Concealed; slope. Nearby outcrops of unit are shale and fine-grained micaceous sandstone.	68	20.7
147.	Sandstone and shale, similar to unit 145; poorly exposed; forms slope.	35	10.7
146.	Sandstone, light-yellowish-gray; composed of coarse sand and granules; slightly feldspathic. Forms small ridge just east of top of large hogback. Thins northward and becomes inconspicuous. Base of locality J5.	5.4	1.6

[Locality of measurement offset about 1,600 ft (490 m) north along top of high hogback ridge by tracing unit 145 to locality J5. Units 146–167 measured eastward down slopes into large strike valley.]

Locality J4

Unit	Lithology	Thickness ft	m
145.	Sandstone, brownish-gray, fine- to medium-grained, slightly micaceous; contains fossil-wood fragments. Beds are 1–2 inches (2.5–5 cm) thick. Poorly exposed; probably contains some interbedded shale. Forms notch just east of high part of hogback ridge.	35.4	10.8
144.	"d" sandstone, conglomeratic, light-yellowish-gray, weathers light yellowish brown, slightly feldspathic. Composed of subangular to subround, coarse sand and granules; about 5 percent is weathered yellowish-gray feldspar clasts ranging up to 0.25 inch (0.6 cm) diameter. Contains scattered quartz pebbles ranging up to 1 inch (2.5 cm) diameter. Beds range from 3 inches–6 ft (7.6–180 cm) thick. Unit is mildly crossbedded; local intra-unit channels occur. Upper part forms strong, high hogback ridge. Lower part is less resistant, and base is concealed by talus.	133.5±	40.7±
143.	Concealed; slope mantled by talus blocks from above. Probably mainly shale.	70	21.4
142.	Sandstone, medium-brownish-gray. Very coarse grained at base, but grades upward into fine- to medium-grained, silty, micaceous sandstone containing pods of coarse sand. Beds are 0.5–8 inches (13–20 cm) thick.	2	0.61
141.	Limestone, light- to medium-gray, micritic, fossiliferous; slightly fetid. Forms slight ridge.	4	1.2
140.	Shale, clay, medium-gray; forms slope.	62	18.9
139.	Limestone, medium-gray, weathers light brownish gray. Micritic; slightly fetid; unfossiliferous. Lower half contains some shaly limestone. Forms small ridge.	1.2	0.37
138.	Shale, similar to unit 136. Forms slope.	24.5	7.5
137.	Limestone, dark-gray, weathers yellowish orange; unfossiliferous.	0.5	0.15
136.	Shale, clay, medium-gray, weathers light greenish gray. Forms slope.	2.2	0.67
135.	Siltstone and claystone, interbedded; light-gray to light-olive-gray. Upper half is mainly claystone with interbedded thin shaly sandstone. Forms slope.	10.6	3.2
134.	Sandstone, light-yellowish-gray, fine-grained, highly micaceous, slightly calcareous. Finely laminated to 1-inch (2.5-cm) thick beds, sub parallel. Forms slabby ridge.	2.3	0.7
133.	Sandstone, light-brownish-gray, weathers light brown. Mainly fine- to medium-grained and micaceous.		

Unit	Lithology	Thickness ft	m
	Contains some shale and some interbedded coarse-grained sandstone lenses with pebbles as large as 0.5 inch (1.3 cm) diameter.	8	2.4
132.	Shale, clay, dark-gray, weathers light gray. Near the top is a light-gray, dense, slightly fetid limestone that is 0.5–1.5 ft (15–45 cm) thick. Unit forms slope.	4.8	1.5
131.	Sandstone, light-grayish-brown, fine- to medium-grained, very micaceous. Beds are 2–8 inches (5–20 cm) thick; irregular to cross bedded. Forms slight ridge.	2.3	0.7
130.	Shale, clay, medium-gray, weathers light gray. Slightly calcareous; contains some 1-inch (2.5-cm) thick beds of limestone nodules. About 5 ft (1.5 m) below top of unit is a 2-ft (60-cm) thick limestone bed. Unit forms slope.	43	13.1
129.	Limestone, medium-gray, weathers light grayish orange. Micrite; no fossils observed. Forms small ridge.	0.7	0.21
128.	Shale, clay, medium-gray, slightly calcareous near top. Forms slope.	4.3	1.3
127.	Sandstone, conglomeratic, greenish-gray, weathers brownish gray. Composed of angular to subangular, coarse sand containing pebbles of quartz and rock fragments; contains some weathered feldspar. Forms slight ridge.	1	0.3
126.	Sandstone, light-olive, weathers medium brownish gray. Very fine grained, silty, highly micaceous, slightly calcareous. Slightly inclined crossbedding. Forms slight ridge.	6	1.8
125.	Shale, dark-gray, carbonaceous. Forms slope.	5	1.5
124.	Sandstone, light-olive-green, weathers medium brownish gray. Very fine grained, silty, micaceous, slightly calcareous. Slightly inclined crossbedding. Forms slight ridge.	1.2	0.37
123.	Shale, dark-gray, weathers olive brown. Mainly micaceous siltstone; contains lenticular 2–6-inches 5–15-cm) thick beds of fine- to coarse-grained sandstone. Forms slope.	18	5.5
122.	Shale, clay, carbonaceous, and clayey coal. Forms slope.	2.5	0.76
121.	Sandstone, conglomeratic, light-olive-brown, slightly feldspathic. Medium- to coarse-grained; contains stringers of small pebbles. Beds are 3 inches–1 ft (7.6–30 cm) thick; mildly inclined crossbedding. Forms slight ridge.	10.5	3.2
120.	Sandstone, conglomeratic, light orangish brown, slightly feldspathic. Coarse-grained; grades upward into finer sand; contains pebbles of quartz, rock fragments, and feldspar; about 5 percent is feldspar. Contains thin shaly interbeds. Channeled contact with underlying unit. Forms slight ridge.	5	1.5
119.	Shale, clay, medium-brownish-gray, micaceous, carbonaceous, slightly calcareous. Forms slope. Exposed in bulldozed cut on ranch road.	13.5	4.1
118.	Sandstone, light-olive-gray, weathers brownish gray. Fine- to medium-grained with some very coarse grained beds; micaceous; contains fossil-plant fragments. Beds are 0.5–3 inches (1.3–7.6 cm) thick; slightly inclined crossbedding. Exposed in bulldozed cuts on ranch road above stream channel in strike valley.	2	0.61
117.	Concealed interval in bottom of strike valley. Slumped debris probably rests on sandy shale, shale, and some thin limestone which were observed in this interval to the north. Base of locality J4.	102	31.1

[Locality of measurement offset about 1,600 ft (490 m) south by tracing unit 116 down strike valley to locality J4. Units 118–119 were measured eastward in ranch road and units 120–145 were measured up gulleys on slope on east side of valley at locality J4.]

Locality J3

Unit	Lithology	Thickness ft	m
116.	Sandstone, conglomeratic, feldspathic. Similar to unit 114, but lower half is thinner bedded. Forms persistent strong ridge that is topographically a little lower than unit 114.	25	7.6
115.	Concealed; probably shale. Forms persistent notch between units 116 and 114.	37	11.3
114.	"c" sandstone, conglomeratic, light-brown, weathers light tan gray, feldspathic. Composed of angular to subangular, coarse sand and granules; about 10 percent is white feldspar. Contains lenses of vein-quartz pebbles. Beds are mainly 3.2–6 ft (100–180 cm) thick, but range down to 4 inches (10 cm) thick; beds are subparallel. Forms strong, high, hogback ridge.	41	12.5

Unit	Lithology	Thickness ft	Thickness m
113.	Shale, gray; poorly exposed on slope along bulldozed ranch road on north side of canyon.	28	8.5
112.	Shale, clay, medium-gray, weathers light gray, silty, calcareous. Exposed in bulldozed roadcut east of dam for livestock pond, and at outcrops west of dam. Forms slope and valley.	150	45.8
111.	Limestone, dark-gray, weathers light brown gray. Micrite; carbonaceous; contains a few brachiopod fragments. Beds are 3–8 inches (7.6–20 cm) thick. Forms small ridge on west side of valley west of live stock pond.	2	0.61
110.	Shale, clayey silt, medium-brownish-gray, slightly calcareous. Poorly exposed on slope west of livestock pond. Underlain by ledge-forming, coarse-grained sandstone that is tentatively correlated with unit 109. Base of section J3.	50	15.3

[Rocks above unit 109 at locality J2 are mainly concealed eastward to the massive hogback of "c" sandstone, which is unit 114 above. The concealed interval is about 220 ft (67 m) thick. Locality of measurement was offset about 3,000 ft (915 m) by tracing the "c" sandstone from locality J2 south to locality J3 where an east-trending segment of canyon cuts across the hogback. Unit 110 at locality J3 is underlain by a sandstone tentatively correlated with unit 109. Units 110–116 were measured eastward across the valley and north side of the east-trending segment of canyon at locality J3.]

Locality J2

Unit	Lithology	Thickness ft	Thickness m
109.	Sandstone, light-olive-brown, weathers light greenish gray, slightly feldspathic. Composed of angular to subangular, medium to coarse sand; contains a trace of white feldspar. Beds are 1.5–8 inches (3.5–20 cm) thick; moderately inclined cross-bedding. Forms low ridge in topographic saddle.	15	4.6
108.	Limestone, similar to unit 106; fetid	7	2.1
107.	Concealed; slope.	10	3.1
106.	Limestone, medium-gray, weathers light olive brown to reddish brown. Composed mainly of fragments of crinoid columnals; contains algal filaments. Forms small ledge.	3	0.9
105.	Concealed; slope. Exposures of unit to the south are gray clay shale.	52	15.9
104.	Sandstone, light-orange-brown, weathers medium brown gray. Fine- to medium-grained, micaceous, finely laminated. Beds are 1–5 inches (2.5–13 cm) thick; slightly inclined crossbedding. Forms slight ridge.	5	1.5
103.	Concealed; slope.	29	8.8
102.	Sandstone, medium-olive-brown, weathers brownish gray. Very fine- to medium-grained, micaceous. Poorly exposed middle part is shaly. Beds are 0.5–3 inches (1.3–7.6 cm) thick; laminae are ripple marked. Forms slight ridge in saddle.	32.6	9.9
101.	Shale, limy silt and clay, gray to black, poorly exposed. Forms slope in saddle.	31	9.5
100.	Sandstone, light-olive-gray, weathers light brown gray, calcareous. Composed of angular to subangular, coarse sand and granules. Beds are 0.5–2 ft (15–60 cm) thick; cross-laminated. Forms small ledge.	2	0.61
99.	Limestone, medium-gray, weathers light orange gray. Fine-grained; contains silty interbeds; upper 4 ft (1.2 m) contains three bioclastic beds. Slightly fetid. Beds are 0.25–4 inches (0.6–10 cm) thick and subparallel. Forms slight irregular ridges.	25	7.6
98.	Concealed; slope. Probably mainly shale.	68	20.7
97.	Shale, silt, medium-gray, weathers brown gray, moderately calcareous. Forms slope.	6	1.8
96.	Limestone, medium-gray, weathers light brown gray. Bioclastic, medium- to coarse-grained, sandy; contains brachiopods and bryozoans. Beds are 1–6 inches (2.5–15 cm) thick; contains thin shaly interbeds. Forms small slabby ridges.	16.5	5
95.	Concealed.	34	10.4
94.	Limestone, medium-gray, fine-grained, dense. Contains small brachiopods and algal filaments. Forms small ridge.	5	1.5
93.	Concealed.	66	20.1
92.	Sandstone, light-brown, weathers light brownish gray. Medium- to coarse-grained; slightly micaceous. Beds are (10–30 cm) thick and parallel. Forms slight ridge.	4.5	1.4
91.	Concealed; probably shale.	8.3	2.5
90.	Sandstone, light-olive-gray, fine- to medium-grained, silty, micaceous. Beds are 1–6 inches (2.5–15 cm) thick, subparallel, and finely laminated. Poorly exposed; forms slope.	2	0.61
89.	Concealed; east-facing slope.	37.5	11.4
88.	"b" sandstone, conglomeratic, light-gray, light-brown-mottled. Composed of subangular to subround,		

Unit	Lithology	Thickness ft	Thickness m
	coarse quartz sand and granules; upper part contains lenses of vein-quartz pebbles 0.25–1 inch (0.6–2.5 cm) diameter. Beds are 3 inches–3 ft (7.6–60 cm) thick with thinner, fine-grained sandstone interbeds; moderately inclined cross-laminations. Forms strong, high, hogback ridge.	50.5	15.4
87.	Concealed interval in topographic saddle.	96	29
86.	Limestone, medium-gray, micritic; contains crinoid columnals, brachiopods, and some algal encrustations; slightly fetid. Forms slight ridge.	1.5	0.46
85.	Shale, clay, light-olive-gray; contains trace of mica and some brachiopods. Poorly exposed in saddle	43	13.1
84.	Limestone, similar to unit 82.	1.8	0.5
83.	Concealed.	25	7.6
82.	Limestone, dark-gray, weathers brown gray, micritic; contains brachiopods and algal filaments. Forms slight ridge.	2	0.61
81.	Concealed; probably shale.	22	6.7
80.	Sandstone, conglomeratic, light-yellowish-gray, weathers light yellow brown. Composed of subangular to subround, very coarse sand and granules; contains scattered quartz pebbles as large as 0.5 inch (1.27 cm) diameter. Beds are 3 inches–1 ft (7.6–33 cm) thick; crossbedded and cross-laminated. Forms slabby moderate ridge.	23.5	7.2
79.	Concealed.	48	14.6
78.	Limestone, similar to unit 76, but not fetid.	1	0.3
77.	Concealed; probably shale.	30	9.2
76.	Limestone, medium-gray, weathers light brown gray, fine-grained, fossiliferous, fetid. Beds are 0.5–1 ft (15–30 cm) thick and undulatory. Middle part poorly exposed. Forms slight ridge.	13.5	4.1
75.	Concealed; probably mostly shale.	23	7
74.	Sandstone, similar to unit 72. Forms slight ridge.	2	0.61
73.	Concealed; probably mostly gray shale as indicated by exposures 100 ft (30 m) to south.	66	20.1
72.	Sandstone, olive-gray, fine-grained, micaceous. Beds are 2–8 inches (5–20 cm) thick, subparallel, and finely laminated. Forms slabby ridge.	6.5	2
71.	Concealed; probably shale and shaly sandstone. Forms flat surface on topographic saddle. Locality of measurement offset to south along strike several times during measurement of this unit.	44	13.4
70.	Sandstone, light-olive-gray, weathers light orange. Composed of medium to coarse sand containing scattered granules. Beds are 0.25–10 inches (0.6–25 cm) thick; crossbedded and cross-laminated. Forms low ridge.	20	6.1
69.	Limestone, medium-gray, weathers light yellowish gray, medium-grained, bioclastic. Contains brachiopods and crinoid columnals. Beds are 0.25–6 inches (0.6–15 cm) thick, parallel, and undulatory. Contains numerous thin shaly limestone interbeds. Forms low slabby ridge.	43.5	13.1
68.	Shale, calcareous; contains some thin beds of limestone that contain crinoid columnals. Poorly exposed; forms slope on topographic saddle.	29.5	9.0
67.	Limestone, light-grayish-tan, silty, fossiliferous; contains scattered grains of coarse, angular quartz sand. Lenses of coarse-grained calcareous and noncalcareous sandstone are interbedded with limestone. Entire unit is highly crossbedded and cross-laminated. Forms a low, massive-weathering ridge.	7.3	2.2
66.	Shale, clay, gray, calcareous and silty; contains several thin beds of silty gray limestone. Poorly exposed on slope.	42	12.8
65.	Limestone, medium- to dark-gray, fine-grained, bioclastic. Forms slight ridge.	0.8	0.24
64.	Sandstone, shaly, and interbedded siltstone; orange-gray, slightly micaceous. Poorly exposed; forms slight ridge at west edge of topographic saddle.	14	4.3
63.	Concealed; probably mostly shale. Forms irregular slope west of topographic saddle along major southeast-trending drainage divide. Base of locality J2.	53	16.2

[Locality of measurement was offset about 2,400 ft (730 m) north by tracing the "a" sandstone (unit 62) north to a high, southeast-trending topographic saddle and drainage divide at locality J2. Units 63–88 were measured southeastward along the top of this drainage divide; units 89–109 were measured southeastward down a slope and along a lower drainage divide and saddle at locality J2.]

Locality J1

Unit	Lithology	Thickness ft	m
62.	"a" sandstone, conglomeratic, light-gray, weathers light orangish brown. Composed of angular to subround, coarse sand and granules; slightly feldspathic. Contains scattered quartzite pebbles ranging up to 0.5 inch (1.3 cm) diameter. Beds are 1 inch–1.5 ft (2.5–45 cm) thick and nearly parallel. Locally, parts of unit are slightly crossbedded. Forms resistant, low but prominent ridge at east side of main stream channel in south-draining strike valley. Measured north of point where channel cuts across the ridge.	13.3	4.1
61.	Interval mainly concealed by alluvium and stream-terrace deposits in south-draining strike valley; probably mostly shale. Measured by offsetting south along strike at several places. Interval measured is about 240 ft (73 m); however, scanty exposures to south indicate small local anticline and syncline that duplicate part of section. True thickness estimated.	150±	45±
60.	Shale, clay, medium-gray, weathers reddish brown; contains a few pods of sandstone near base. Forms slope.	45	13.7
59.	Sandstone, brown-weathering, fine- to medium-grained; middle third is shaly. Mildly inclined cross-lamination. Forms slight ridge.	5.2	1.6

[Locality of measurement of above units was offset about 200 ft (60 m) to the south from point where stream channel of southeast-trending canyon bends south into strike valley.]

Unit	Lithology	Thickness ft	m
58.	Shale, clay, gray, silty; contains a few 1-ft (30-cm) thick sandstone beds. Forms slope. Poorly exposed along north side of canyon.	54	16.5
57.	Sandstone, similar to unit 51. Forms small blocky ridge.	12.5	3.8
56.	Concealed.	36	11
55.	Sandstone, conglomeratic, similar to unit 51. Forms small ridge.	13	4
54.	Mainly concealed. Sparse outcrops indicate unit is mainly dark-gray shale with some thin interbeds of sandstone. Forms slope.	42	12.8
53.	Sandstone, yellowish-brown, medium- to coarse-grained. Beds are 2 inches–2.5 ft (5–76 cm) thick; crossbedded. Forms slight ridge.	16	4.9
52.	Shale, clay, medium-gray, weathers brownish gray; silty and micaceous. Forms slope.	15	4.6
51.	Sandstone, conglomeratic, light-yellowish-gray, weathers medium gray. Composed of angular to subangular, very coarse quartz sand and granules; contains scattered quartz pebbles ranging up to 0.25 inch (0.6 cm) diameter. Slightly calcareous. Beds are 0.5–3 ft (15–90 cm) thick; slightly inclined cross-bedding. Forms strong ridge.	22	6.7
50.	Shale, clay, dark-gray, weathers medium gray; fissile but hard. Contains brachiopods. Forms slope.	24	7.3
49.	Limestone, light-gray, weathers light brownish gray. Bioclastic; very coarse grained; contains nodular-weathering layers of brachiopods. Forms small ridge.	6.2	1.9
48.	Sandstone and interbedded shale. Sandstone is tan, reddish-brown-weathering, fine- to medium-grained, and crossbedded. Shale is black, platy, and contains thin coaly interbeds. A coal bed, 4 inches–2 ft (10–60 cm) thick, occurs between sandstone beds in lower part of unit. Upper part is mainly shale. Forms irregular slope.	44	13.4
47.	Siltstone, purplish-gray, weathers reddish brown, very hard. Beds are 0.5 inch–1 ft (1.3–30 cm) thick; slightly crossbedded. Platy-weathering; forms small ridge.	5.4	1.6
46.	Concealed; probably mainly shale.	26	7.9
45.	Sandstone, light-tan, weathers light brownish gray, coarse-grained to very coarse grained. Beds are 0.5 inch–2 ft (1.3–60 cm) thick; mildly inclined crossbedding. Forms ridge	34	10.4
44.	Shale, clay, dark-gray, weathers. light olive gray. Contains several 0.1-inch (0.3-cm) thick beds of highly fossiliferous gray limestone and a few nodular limestone beds. Upper third contains 2.5-ft (76-cm) thick brown-weathering siltstone. Brachiopods of probable Morrowan age are abundant in upper part (collection USGS 27164–PC). Forms gullied slope on north wall of canyon.	48	14.6
43.	Limestone, gray, bioclastic; locally a crinoidal coquina. Forms small ridge.	4	1.2
42.	Shale, clay, dark-gray. Forms slope.	5	1.5
41.	Sandstone, olive-gray, weathers reddish brown. Composed of fine quartz sand containing many scattered quartz granules. Forms minor ridge.	6	1.8
40.	Concealed; probably mainly shale.	26.5	8.1
39.	Sandstone, light-orangish-gray, weathers light grayish brown. Composed of angular to subangular, coarse quartz sand and granules; contains a trace of yellowish-gray feldspar. Upper part is fine grained. Forms ridge.	34	10.4
38.	Concealed.	7	2.1
37.	Sandstone, light-olive-gray, weath-		

Unit	Lithology	Thickness ft	m
	ers light brownish gray, fine-grained to very coarse grained; contains fossil wood fragments. Slightly inclined crossbedding; beds are 1 inch–3 ft (2.5–90 cm) thick. Forms ridge.	5.2	1.6
36.	Concealed; probably thin-bedded sandstone and interbedded shale.	16	4.9
35.	Sandstone, light-yellowish-gray, weathers light brownish gray; medium-grained. Forms ridge.	13	4
34.	Sandstone, fine- to medium-grained, and interbedded shale; very poorly exposed.	24.4	7.4
33.	Limestone, gray, bioclastic; coarse-grained crinoid coquina. Forms small ridge.	2.5	0.76
32.	Sandstone, medium-grayish-brown.	2	0.61
31.	Shale, clayey silt, light-olive-gray.	5.7	1.7
30.	Limestone, medium-gray, bioclastic, medium-grained; contains numerous brachiopods and fragments of crinoid columnals. Contains thin shale interbeds near middle. Forms small ridge.	2.5	0.76
29.	Shale, clayey silt, light-olive-gray, poorly exposed. Upper third contains much thin-bedded, fine-grained sandstone and some 1–2-inch (2.5–5-cm) thick limestone beds. Forms slope.	34.5	10.5
28.	Concealed; probably mainly shale.	12	3.7
27.	Limestone, similar to unit 21.	3	0.9
26.	Concealed.	7	2.1
25.	Limestone, bioclastic; crinoidal coquina; similar to unit 21.	17.3	5.3
24.	Concealed.	10	3
23.	Limestone, similar to unit 21; poorly exposed.	8.2	2.5
22.	Concealed.	16.5	5
21.	Limestone, medium-gray, weathers dark grayish brown, bioclastic, coarse-grained, silty. Upper 2 ft (60 cm) is crinoidal coquina. Forms ridge.	15.5	4.7
20.	Shale containing some fine-grained sandstone interbeds; unit is poorly exposed on a slope littered with slumped sandstone blocks. Exposures higher on north wall of canyon shown that unit is tectonically thickened along steeply plunging minor fold. Thickness estimated.	39	11.9
19.	Shale, clay, dark-gray, slightly silty. Forms slope. Tectonically thickened along steeply plunging minor fold; true thickness determined.	55.5	16.9
18.	Sandstone, similar to unit 16; crossbedded stream-channel deposit. Forms small ridge.	1.5	0.46
17.	Shale, medium-gray; weathers to notch.	8.7	2.7
16.	Sandstone, light-brown, weathers light tan gray, medium-grained; contains thin shale partings. Beds are 2 inches–2 ft (5–60 cm) thick; crossbedded. Forms several small ridges.	32	9.8
15.	Sandstone, conglomeratic, light-greenish-gray, weathers light yellowish brown. Composed of medium to coarse sand containing scattered granules. Contains scattered granules and small pebbles of chloritized schist. Beds are 2 inches–3 ft (5–90 cm) thick; bedding indistinct. Forms ridge.	6	1.8
14.	Shale, clay, light-brownish-gray. Poorly exposed.	1	0.3
13.	Claystone, medium-gray, weathers light olive brown, silty, hard; lower part slightly calcareous; contains brachiopods. Forms small ridge.	4.8	1.5
12.	Concealed; poor exposures on north wall of canyon are mainly greatly sheared shale and thin sandstone. Mapping north and south of locality of measurement indicates that a major west-dipping reverse fault (Romero fault) probably occurs within this unit. Amount of stratigraphic separation on this fault is not known, but is estimated to be at least 500–600 ft (150–180 m) on the basis of exposures of this part of the Sandia Formation south of Mora River. However, the separation, stratigraphic and structural, might be considerably greater. Measured thickness.	131+	40+
Total thickness of Sandia Formation:		5,029+	1,532+
Arroyo Peñasco Group:			
Tererro Formation:			
Cowles Member:			
11.	Siltstone and fine-grained silty sandstone, light-olive-gray; contains thin claystone partings. Bedding is very thin to laminated. Forms slope.	9.5	2.9
10.	Limestone, light-yellowish-gray, weathers light gray; very fine grained, silty; slightly nodular Forms slight ridge.	1.6	0.5
9.	Siltstone, light-yellowish-gray, calcareous.	5	1.5
8.	Limestone, light-tan-gray, weathers light brownish gray; fine-grained silty calcarenite. Crossbedded and cross-laminated; thin silicified zones along crossbeds and laminae stand out in relief on weathered sur face. Forms ledgy slope.	20	6.1
Manuelitas Member:			
7.	Limestone, light-gray, mainly micritic. Contains streaks of translucent pink to light-gray chert, and small masses of pink to gray oolitic chert. Contains fragments of crinoid columnals. Bedding obscure. Forms massive ridge.	47	14.3

Unit	Lithology	Thickness ft	m
	Macho Member:		
	Absent.	0	0
	Total thickness of Tererro Formation:	83.1	25.3
	Espiritu Santo Formation:		
6.	Concealed; slope.	7.5	2.3
5.	Sandstone, light-pink, weathers light gray. Composed of well-sorted, medium quartz sand and scattered quartz granules.	1	0.3
4.	Limestone, light-gray, weathers light purplish brown. Contains scattered, angular, quartz granules; several interbeds, as much as 5 inches (12 cm) thick, are medium- to coarse-grained quartz sandstone.	4.5	1.4
3.	Sandstone, conglomeratic, light-yellowish-gray, weathers light gray. Composed of medium to coarse quartz sand containing scattered granules; basal 1 inch (2.5 cm) contains angular vein-quartz pebbles as large as 0.25 inch (0.6 cm) diameter. Forms inconspicuous ridge. Probably the Del Padre Sandstone Member.	2	0.6
	Total thickness of Espiritu Santo Formation:	15.0	4.6
	Precambrian rocks:		
2.	Concealed.	1	0.3
1.	Quartz-mica schist, light-gray; exposed on north wall of canyon. Traced north from locality of measurement, these rocks are seen to be angularly unconformable with the overlying Espiritu Santo Formation. Base of locality J1.	Not measured	

[Base of section at locality J1 is in southeast-draining deep canyon at east side of Romero Hills. Units 2–58 were measured eastward, mainly on the north side of the stream channel in this canyon. At places the units were measured at good exposures in the bottom of the canyon.]

Section L

Mora 7.5-minute quadrangle (1965). Auxiliary section of lower part of Porvenir Formation and upper part of Sandia Formation, east wall of south-draining canyon about 2,000 ft (600 m) north of New Mexico Highway 518. Locality is in hogback ridges north of Mora River about 1.6 mi (2.6 km) northwest of La Cueva. Locality shown in Figure 89. Section documents some lateral lithologic variations of the lower part of the Porvenir and upper part of the Sandia between locality J7 and locality K. Measured by E. H. Baltz.

Unit	Lithology	Thickness ft	m
	Porvenir Formation (lower part)		
22.	Sandstone, conglomeratic, light-grayish-pink-weathering, feldspathic. Matrix is angular to subangular, very coarse sand and granules; about 15 percent is weathered, pink and yellow feldspar clasts. Contains angular-shaped, but rounded, pebbles of quartz and feldspar that are mainly 0.25–0.5 inch (0.6–1.27 cm) diameter but range up to 1 inch (2.5 cm) diameter. Crossbedded; beds are 0.5–2.5 ft (15–76 cm) thick. Forms strong slabby hogback ridge and east-facing dip slope.	31+	9.4+
21.	Shale, light-olive-gray; interbedded silty claystone and clayey siltstone. Forms notch that is followed northward by ranch road on top of ridge. Lower third concealed. South of locality, lower half of unit grades into coarse-grained sandstone.	42	12.8

[Unit 20 was correlated to ridge at the east and the above section continues east in steeply dipping beds east of axis of small anticline.]

Unit	Lithology	Thickness ft	m
20.	Limestone, light-gray, weathers light tannish gray. Bioclastic; medium- to coarse-grained debris is mainly fragments of crinoid columnals; contains fine to very fine quartz sand. Oolitic; oolites are as large as 0.03 inch (0.08 cm) diameter. Fusulinids are abundant and are scattered throughout. Lower third of unit has interbeds of very fine-grained sandstone; beds are parallel to subparallel and 0.5–2 ft (15–60 cm) thick. Upper third is crossbedded; beds are 2 inches–2.5 ft (5–76 cm) thick. Unit forms strong ledge locally; a short distance to the north it is cut out by a stratigraphically higher gravelly sandstone. Unit 20 also disappears southward. Farther south, similar lenses of fusulinid-bearing oolitic limestone interbedded with sandstone occur in similar stratigraphic position on the ridge about 500 ft (150 m) south of Mora River and on a ridge about 1,500 ft (450 m) south of La Cañada del Guajalote. Fusulinid collection		

Unit	Lithology	Thickness ft	m
	f10293 from the oolitic limestone at section L contains *Beedeina* aff. *B. arizonensis*, *Wedekindellina* sp., and *Bradyina* sp.	15	4.6
19.	Sandstone, light-gray, weathers light yellowish olive. Fine-grained to very fine grained, calcareous. Contains lenses of brown-weathering, silty limestone scattered throughout. Limestone lenses are 1–6 inches (2.5–15 cm) thick and 2–10 ft (0.3–3 m) long. Some limestone beds grade laterally into calcareous sandstone. Limy layers contain a few brachiopods. Forms slabby-weathering, irregular ledge with many notches. Unit persists northward and lies on the Sandia Formation at the top of section J. Persists southward where it contains a greater proportion of fossiliferous limestone and is unit 212 at base of Porvenir at section K.	30	9.2
	Thickness of lower part of Porvenir Formation:	18	36
	Sandia Formation (upper part):		
18.	Siltstone and very fine-grained sandstone, olive-gray-weathering; probably contains some interbeds of gray clay shale. Bedding is thin and indistinct. Grades into unit 19. Forms slope.	10.7	3.3
17.	Shale, dark-gray, weathers medium gray; mainly silty claystone. Contains fossil wood-twig impressions and small brachiopods. Forms slope on east wall of canyon; weathers to small chips and flakes.	55	16.8

[Locality of measurement of the above units was offset about 200 ft (60 m) northward to avoid area of tectonic thickening of unit 17 in small syncline and anticline.]

Unit	Lithology	Thickness ft	m
16.	Sandstone, yellowish-gray-weathering, feldspathic. Composed of angular to subangular granules of quartz and feldspar in greenish-gray clay matrix; about 20 percent of clasts is yellow feldspar. Bedding highly irregular; beds are 0.5–1 ft (15–30 cm) thick. Forms small ledge.	9.2	2.8
15.	Shale, similar to unit 13. Contains thin- to shaly-bedded, fine-grained sandstone in middle third. Forms slope on top of a ledge.	15.4	4.7
14.	Sandstone, conglomeratic, light-olive-gray, weathers olive brown, arkosic. Lower part is very coarse sand and granules; grades upward into medium to coarse sand in upper half. Lower part contains pink, angular, feldspar granules and pebbles as large as 0.25 inch (0.6 cm) diameter. Highly crossbedded. Forms small slabby-weathering ledge.	4	1.2
13.	Shale, clay and silt, yellowish-gray-weathering. Forms slope.	6	1.8
12.	Sandstone, light-olive-gray, weathers light olive tan, feldspathic. Basal 3 ft (0.9 m) is fine to medium grained; grades upward into angular to subangular, coarse sand and granules. About 10 percent is pink feldspar clasts. Crossbedded; beds are 1–2 ft (30–60 cm) thick and are gently inclined to each other. Contact with underlying unit slightly channeled. Forms strong ledge.	12	3.7
11.	Sandstone, brown-weathering, fine-grained, micaceous, shaly; contains interbeds of gray clay shale. Forms slight ledges.	4	1.2
10.	Shale, clay, dark-gray, weathers medium gray. Contains 1-inch (2.5-cm) thick carbonaceous shale bed at base and several thin carbonaceous shale beds near middle. Contains 1-ft (30 cm) thick, dark-brown, gastropod-bearing limestone 12 ft (3.7 m) above base. Forms slope.	22	6.7
9.	Limestone, medium-gray, weathers brownish gray; fine-grained, bioclastic, silty. Contains brachiopods and small gastropods. Beds are parallel but undulatory and 4 inches–1 ft (10–30 cm) thick. About 30 percent of lower half is interbeds of calcareous shale that are 1–4 inches (2.5–10 cm) thick. Forms small, blocky ledge.	9.8	3
8.	Shale, clay, dark-gray, weathers medium gray. Hard, slightly calcareous, silty. Contains small brachiopods. Forms slope.	7.5	2.3
7.	Sandstone, light-olive-gray, fine- to medium-grained, slightly feldspathic, micaceous.	1	0.3
6.	Sandstone, conglomeratic, light-yellowish-olive-green, arkosic. Matrix is argillaceous fine to medium sand; contains angular granules and pebbles, as large as 0.25 inch (0.6 cm) diameter, of quartz and gray feldspar. Forms small ledge.	1	0.3
5.	Sandstone, greenish-gray, similar to unit 3. Grades into overlying and underlying units. Weathers to notch.	4	1.2
4.	Sandstone, conglomeratic, light-olive-gray, weathers gray, arkosic. Matrix is angular, very coarse sand and granules. About 30 percent is angular pebbles of quartz and pink feldspar as much as 0.5 inch (1.27 cm) diameter. Contains lenses and scattered, angular-shaped but rounded, quartz and pink feldspar pebbles 0.5–1 inch (1.27–2.5 cm) diameter. Unit contains some green clay. Forms strong ledge in bottom		

Unit	Lithology	Thickness ft	m
	of canyon.	25	7.6
3.	Sandstone, light-olive-gray, fine- to medium-grained, micaceous, slightly feldspathic. Cross-laminated. Poorly exposed.	7	2.1
2.	Shale, and interbedded shaly sandstone, light-olive-yellow-weathering; unit is mostly silty clay shale; sandstone is fine- to medium-grained. Forms slope on west bank of arroyo in bottom of canyon. Poorly exposed.	21	6.4
1.	Concealed; slope below ledge of massive sandstone that crops out west of arroyo in canyon bottom.	Not measured	
	Partial thickness of Sandia Formation.	214.6	65.4

[Base of section is at west side of sinuous segment of arroyo in bottom of canyon. Section was measured eastward up the east wall of the canyon.]

Section M

Ojitos Frios 7.5-minute quadrangle (1961). Section of Alamitos Formation on east limb of Ojitos Frios anticline, 0.85 mi (1.35 km) south–southeast of Ojitos Frios. Locality is about 700 ft (215 m) southwest of point where Tecolote Creek makes sharp bend to the east. Base of section is on southeast-facing hillslopes; section was measured southeast across northeast-draining arroyos and up slopes to the southeast. Measured by E. H. Baltz. Locality shown in Figure 55.

Unit	Lithology	Thickness ft	m
	Sangre de Cristo Formation (lower part)		
18.	Siltstone and interbedded, intergrading sandstone; dark-reddish-brown. Calcareous; parts of matrix of sandstone are sandy to silty limestone containing scattered, angular, granules of quartz and some pink feldspar. Contains subangular to subround pebbles, 0.25–3 inches (0.6–7.6 cm) diameter, of chocolate-brown calcareous siltstone and silty limestone. Crossbedded and cross-laminated; beds are 2 inches–3 ft (5–90 cm) thick. Foreset laminae are inclined mainly south–southeast. Forms first prominent ridge east of valley.	12	3.7
17.	Sandstone, feldspathic, similar to unit 14. Forms small ledge.	2	0.61
16.	Shale, clay, red, soft. Forms slope.	22	6.7
15.	Mainly concealed; slope. Float and sparse exposures indicate unit probably is mainly red shale containing brown, dense, unfossiliferous lime stone concretions.	12	3.7
14.	Sandstone, conglomeratic, very light yellowish gray, feldspathic. Composed of angular to subangular, very coarse quartz sand and granules; about 10 percent is pink angular clasts of feldspar. Contains a few lenses of pebbles as large as 1 inch (2.5 cm) diameter; pebbles are angular to subangular quartz, feldspar, and some gray limestone. Crossbedded and cross-laminated; beds are 1–10 inches (2.5–25 cm) thick. Bedding and laminae are inclined south–southeast. Forms small ledge; upper half is soft and may contain some shaly interbeds. This unit thickens and thins laterally; it can be traced more than a mile southward past the lower part of Cañon Pino Real. To the north it is locally poorly exposed but seems to be a persistent basal sandstone of the Sangre de Cristo Formation from Ojitos Frios north and north east.	8	2.4
	Thickness of lower part of Sangre de Cristo Formation:	56	17.1
	Alamitos Formation:		
13.	Shale, silty clay, red; contains a few concretions of gray limestone. Forms slope; poorly exposed.	7.5	2.3
12.	Concealed; alluvium in small north-draining valley. Good exposures in south wall of Cañon Pino Real, about 0.7 mi (1.13 km) to the south, show this unit is mainly red shale.	28	8.5
11.	Shale, clay, red-weathering; contains nodules of dense, gray, limestone that are 0.25–1 inch (0.6–2.5 cm) diameter. Base is conformable with underlying unit; however, as traced westward through poor exposures to vicinity of axis of Ojitos Frios anticline, underlying units apparently wedge out and unit 11 is on Porvenir Formation.	7.5	2.3
10.	Conglomerate, light-gray- to white-weathering. Clasts are irregular, discoid, and round, pebbles of gray limestone 0.25–2 inches (0.6–5 cm) across. Pebbles are densely packed and have a rude layering. Contains a minor amount of greenish-gray to		

Unit	Lithology	Thickness ft	m
	red clay shale as matrix; matrix is deformed slightly by differential compaction. Unit is cemented loosely by calcium carbonate. Forms small ledges on both sides of northeast-draining arroyo. Probably wedges out westward beneath Quaternary colluvial cover.	5	1.5
9.	Limestone, light-gray, finely bioclastic. Contains abraded and nonabraded fusulinids and broken but not abraded, thick-shelled brachiopods. Forms hard ledge in bottom of northeast-draining arroyo. Lenses out 10 ft (3 m) to west. Fusulinid collection f10275 contains *Triticites* (*Leptotriticites*) sp.	0.5	0.15
8.	Limestone, light-gray, nodular, fine- to medium-grained, bioclastic. Forms hard ledge in bottom of northeast-draining arroyo. Lenses out about 8 ft (2.4 m) to the west. Contains fusulinids; collection f10275 contains *Triticites* (*Leptotriticites*) sp. and *Ozawainella* sp.	0.7	0.21
7.	Limestone nodules or pebbles, gray, micritic; gray shale matrix.	0.5	0.15
6.	Shale, clay, purplish-gray, flaky; lenticular. Exposed in northeast-draining arroyo.	0.55	0.17
5.	Conglomerate, light-gray-weathering. Clasts are gray, fine-grained, rounded pebbles of limestone ranging from 0.25–4 inches (0.6–10 cm) diameter; most pebbles are 1 inch (2.5 cm) or less in diameter. Some parts are rudely bedded; beds are 2–4 inches (5–10 cm) thick. Matrix is micritic calcium carbonate. Forms weak ledge exposed along and in northeast-draining arroyo. Probably wedges out westward beneath Quaternary colluvial cover.	4	1.2
4.	Shale, clay, slightly marly; lower third weathers maroon; upper part is light-olive-gray. Upper part contains scattered, irregularly shaped gray limestone concretions 0.25–2 inch (0.6–5 cm) across. Top concealed. Probably wedges out westward beneath Quaternary colluvial cover.	7.5	2.3
3.	Sandstone, conglomeratic, medium-gray to light-brownish-gray, feldspathic, highly calcareous. Composed of angular, coarse to very coarse quartz sand and granules that contain scattered, angular quartz pebbles and pink feldspar pebbles as large as 0.1 inch (0.3 cm) diameter; about 5 percent of all grain sizes is pink feldspar. Sandstone grades laterally and vertically into very sandy bioclastic limestone. Crossbedded; beds are 1–8 inches (2.5–20 cm) thick. Forms soft ledge on east-facing slope; wedges out at south end of exposure. Probably a channel sandstone similar to basal sandstone of Alamitos farther north.	5	1.5
	Total thickness of Alamitos Formation:	66.8	20.3
	Porvenir Formation (upper part):		
2.	Concealed; slope.	12	3.7
1.	Limestone, light-gray, dense to partly recrystallized. Contains scattered corals, brachiopods, and crinoid columnals. Massive weathering; forms low ledge on southeast-sloping hill.	10+	3+
	Partial thickness of Porvenir Formation:	22+	6.7+

Section N

San Geronimo 7.5-minute quadrangle (1961). Section of Alamitos Formation measured in Dead Horse Canyon in Santa Fe National Forest about 2.6 mi (4.2 km) southwest of San Geronimo. Base of section is in middle (main) branch of canyon in NW¼SW¼ sec. 2 T15N R14E. Top of section is in the northwest branch of canyon in NE¼NE¼ sec. 3 T15N R14E. Measured by E. H. Baltz and D. A. Myers. Locality shown in Figure 55.

Unit	Lithology	Thickness ft	m
	Sangre de Cristo Formation (lower part)		
21.	Sandstone, conglomeratic, arkosic, similar to unit 15. Caps broad, highest topographic bench that extends about 1,300 ft (400 m) south from lower slopes of Fisher Hill.	6±	1.8±
20.	Shale, clay, red, silty; contains some small gray limestone nodules. Forms slope; poorly exposed.	7	2.1
19.	Limestone, gray, micritic, partly recrystallized; unfossiliferous. Forms small ledge.	4	1.2
18.	Shale, clay, red, silty; contains some small gray limestone nodules. Forms slope; poorly exposed.	10	3
17.	Limestone, gray, micritic, partly recrystallized; unfossiliferous. Forms prominent ledge.	8	2.4
16.	Mainly concealed; float indicates unit is mainly red shale containing small, gray limestone nodules. Forms slope.	35	10.7

Unit	Lithology	Thickness ft	Thickness m
15.	Sandstone, conglomeratic, light-yellowish-gray, arkosic, coarse-grained. Contains much angular, pebble-sized, pink feldspar. Forms ledge.	13	4
14.	Mainly concealed. A few poor exposures indicate unit is mostly red shale. Forms slope on north side of northwest fork of Dead Horse Canyon.	80±	24±

[Unit 13 was traced north–northwest about 2,300 ft (700 m) to northwest fork of Dead Horse Canyon. Units 14–21 were measured northward from canyon along the fence marking the section line between secs. 2 and 3, T15N R14E.]

Unit	Lithology	Thickness ft	Thickness m
13.	Sandstone, light-brownish-gray to light-yellowish-brown, feldspathic. Composed of angular to subangular, very coarse sand and granules; contains round to subangular pebbles as large as 1 inch (2.5 cm) diameter. About 10 percent of clasts is pink and weathered yellow feldspar. Forms moderate ridge that constricts middle fork of Dead Horse Canyon.	10	3
12.	Mainly concealed. Small, poor exposures along slopes of north-draining gully just south of middle fork of Dead Horse Canyon indicate unit probably is mainly red shale containing some gray limestone nodules.	70	21
11.	Sandstone, feldspathic, coarse-grained. Forms small ledge along north-draining gully south of middle fork of Dead Horse Canyon. Farther north this unit thickens considerably and forms a prominent ledge.	1	0.3
	Thickness of measured lower part of Sangre de Cristo Formation:	244±	74±
	Alamitos Formation:		
10.	Limestone, lavender-gray-weathering, coarsely bioclastic, sandy. Upper part contains pink feldspar granules scattered throughout. Bedding is thin to very thick. Forms a blocky prominent ledge.	10	3
9.	Concealed.	5	1.5
8.	Sandstone, reddish-purple, very fine grained. Forms slope; poorly exposed.	1	0.3
7.	Limestone, gray, fine-grained, bioclastic, sandy; contains some brown, hackly-weathering chert. Forms small ledge.	2	0.61
6.	Shale, clay, light-olive-green, silty; contains 1–3-inch (2.5–7.6-cm) thick lenses and nodules of gray limestone scattered throughout. About 70 percent is shale.	12	3.7
5.	Limestone, medium-gray, bioclastic. Bedding is undulatory; beds are 1–3 inches (2.5–7.6 cm) thick. Forms small ledge.	6	1.8
4.	Concealed.	13	4
3.	Limestone, gray to purplish-gray, coarse-grained, bioclastic. About 20 percent is angular to subangular granules of quartz and pink feldspar. Medium to thick bedded.	7	2.1
	Total thickness of Alamitos Formation:	56	17
	Porvenir Formation (upper part):		
2.	Limestone, gray, slightly nodular, thin bedded. Contains interbeds of siltstone 1–6 inches (2.5–15 cm) thick. Forms irregular ledges.	16	4.9
1.	Limestone gray; forms strong ledge.	10	3
	Partial thickness of Porvenir Formation:	26	7.9

[Base of section is on the north wall of bottom of middle fork of Dead Horse Canyon at east end of a major covered interval in Porvenir Formation. Units 1–10 were measured eastward in the canyon. Uppermost part of Porvenir here appears to be stratigraphically a little below the "marker" zone that may have been cut out by unconformity with Alamitos Formation. Farther west, lower part of Porvenir is in contact with Precambrian rocks along El Barro fault.]

Section O

El Porvenir 7.5-minute quadrangle (1961). Section of Alamitos Formation, exposed as east-dipping beds in north wall of narrow canyon of upper part of Cabo Lucero Creek in Santa Fe National Forest. SW¼NE¼ sec. 9 T16N R14E. About 2.2 mi (3.5 km) west–southwest of Blue Haven Camp that is along upper Tecolote Creek. Measured by E. H. Baltz and D. A. Myers. Locality shown in Figure 55.

Unit	Lithology	Thickness ft	Thickness m
	Sangre de Cristo Formation (lower part)		
20.	Poorly exposed. Red shale units that contain some dense, gray, botryoidal limestone concretions and interbedded thick feldspathic sandstone beds similar to unit 19. Careful search of about 200 ft (60 m) of these beds did not disclose any marine fossils or lithologies similar to Alamitos Formation. This unit		

Unit	Lithology	Thickness ft	m
	and unit 19 are the lower part of the Sangre de Cristo Formation, as mapped here by Baltz (1972).	Not measured	
19.	Sandstone, conglomeratic, light-yellowish-brown, feldspathic. Composed of angular to subangular, coarse sand and granules; contains small pebbles as much as 0.5 inch (1.27 cm) diameter. Pebbles are white vein quartz and pink feldspar. Forms prominent massive ridge.	25±	7.6±
	Alamitos Formation:		
18.	Concealed; talus slopes on east side of deep, south-draining canyon	98	30
17.	Shale, clay, silty, greenish-gray; contains thin interbeds of nodular limestone. Forms slope on west side of deep, south-draining canyon.	4.1	1.3
16.	Limestone, gray, forms small ledge	1	0.3
15.	Shale, clay, purplish-gray; contains thin beds of limestone nodules.	8	2.4
14.	Shale and interbedded thin, gray limestone. Forms slope.	11.4	3.5
13.	Limestone, gray; contains many large brachiopods including wide-winged spirifers as much as 2 inch (5 cm) across. Forms strong ridge.	5.5	1.7
12.	Concealed.	46	14
11.	Sandstone, purplish-gray-weathering, feldspathic. Composed of angular, coarse sand; contains pink feldspar clasts. Beds are subparallel and 1–6 inches (2.5–15 cm) thick. Grades into underlying unit. Forms ridge.	49.5	15
10.	Limestone, gray. Upper half is silty and sandy; upper third contains scattered clasts of angular, coarse sand and a trace of yellowish-gray-weathered feldspar. Becomes sandy limestone near top. Forms ridges.	17	5.2
9.	Concealed.	8.5	2.6
8.	Limestone, gray; forms ledge.	10.5	3.2
7.	Shale, clay, gray; contains some nodular gray limestone. Forms slope.	23	7
6.	Shale, clay, yellowish-gray, silty; contains 1-ft (30-cm) thick lenses of arkosic sandstone.	7.4	2.3
5.	Sandstone, conglomeratic, greenish-gray, arkosic. Composed of angular to subangular, coarse sand containing abundant granules and small pebbles of unweathered angular, pink feldspar. Forms slight ledge.	1	0.3
	Total thickness of Alamitos Formation:	290.9	88.8
	Porvenir Formation (upper part):		
4.	Shale, gray, calcareous.	5	1.5
3.	Limestone, gray, fine- to coarse-grained, bioclastic. Contains angular, coarse, translucent quartz sand scattered throughout. Cross-laminated. Forms ledge. Probably the "marker" zone of the upper part of the Porvenir Formation.	3	0.9
2.	Shale, clay, gray, calcareous; contains nodular gray limestone.	2.5	0.76
1.	Limestone, gray, medium-grained; bioclastic, contains fusulinids. Fusulinid collection f10310 contains *Beedeina* aff. *B. sulphurensis*. Forms small ledge.	3	0.9
	Partial thickness of Porvenir Formation:	13.5	4.1

[Porvenir Formation immediately below unit 1 is a thick unit of calcareous shale containing some thin, gray limestone beds. Overall lithology of Porvenir to the west is similar to the type locality south of Canovas Canyon, including the thick, ledge-forming limestones of the lower 600 ft (180 m).]

Section P

El Porvenir 7.5-minute quadrangle (1961). Partial section of Alamitos Formation in road cuts, U.S. Forest Service road, east of lower part of Canovas Canyon. NW¼ sec. 24 T17N R14E. Base of section is at lowest exposures on east side of Canovas Canyon about 2,200 ft (670 m) southwest of Western Life Camp, which is in valley of Gallinas Creek just east of Santa Fe National Forest boundary. Measured by E. H. Baltz and D. A. Myers. Locality shown in Figures 55 and 81.

Unit	Lithology	Thickness ft	m
	Sangre de Cristo Formation (lower part):		
49.	Sandstone, conglomeratic, light-orangish-brown- to reddish-brown-weathering, arkosic. Composed of angular to subangular, very coarse sand, granules, and pebbles as large as 0.5 inch (1.3 cm) diameter; about 30 percent of granules and pebbles is pink feldspar. Crossbedded and cross-laminated, but weathers massive. Forms prominent ledge cropping out along middle of straight segment of road. Overlain by thin red shale and succeeding thick arkoses.	25+	7.6+
	Alamitos Formation:		
48.	Shale and sandstone, purplish-red- and red-weathering. Upper third is red-weathering clay shale; middle		

Unit	Lithology	Thickness ft	m
	third is red clay shale containing nodular limestone; lower third is dark-purplish-red, fine- to medium-grained, micaceous sandstone interbedded in micaceous, silty, sandy shale.	37	11.3
47.	Shale, clay, and interbedded limestone. Shale is light greenish gray and weathers red. About half of unit is gray and greenish-gray limestone. Limestone is irregularly bedded, bioclastic and highly fossiliferous; contains brachiopods, bryozoans, and crinoid columnals. Megafossil collection USGS 27504–PC. Unit forms slope.	8	2.4
46.	Sandstone, very coarse grained, arkosic, slightly calcareous. Forms small ledge.	2	0.6
45.	Shale, silty and sandy, light-olive-brown, weathers red.	6.5	2
44.	Concealed; small side valley at west side of road.	23	7
43.	Sandstone, conglomeratic, light-orangish-brown, arkosic. Composed of angular to subangular, very coarse sand and granules; contains some subangular pebbles 0.25–0.5 inch (0.6–1.27 cm) diameter. About 25 percent of clasts is pink feldspar. Unit is crossbedded but weathers massive. Forms prominent ridge; outcrops generally are slumped.	13	4
42.	Shale, gray, calcareous, and interbedded light-gray, dense, bioclastic limestone. Poorly exposed at head of small gully west of road.	10	3
41.	Limestone, light-gray, fine- to coarse-grained, bioclastic. Contains interbeds of calcareous clay shale in beds 2–6 inches (5–15 cm) thick. Bedding slightly irregular; beds 8 inches–1 ft (20–30 cm) thick.	3	0.9
40.	Shale, light-gray; contains two 1-ft (30-cm) thick beds of coarse bioclastic limestone formed of fragments of crinoid columnals, brachiopods, and bryozoans. Mega fossil collection USGS 27503–PC.	4	1.2
39.	Shale, light-olive-gray; lower third weathers reddish purple. Contains scattered limestone concretions 0.25–1 inch (0.6–2.5 cm) diameter.	14	4.3
38.	Concealed; small valley.	40	12.2
37.	Sandstone, conglomeratic, tan, feldspathic. Composed of very coarse sand and granules; about 15 percent of sand and granules is pink feldspar. Contains a few small clay pebbles. Contains 3-ft (0.9 m) thick lens of purple shale near middle Forms slight ledge.	30	9.2
36.	Shale, silty, purple, clayey.	15	4.6
35.	Sandstone, purple-weathering, feldspathic, micaceous; crossbedded. Soft.	35	10.7
34.	Mainly concealed. Upper 20 ft (6.4 m) exposed in road cut is red, silty clay shale containing a few 1-inch (2.5-cm) thick arkosic sand stone beds.	72	22
33.	Sandstone, conglomeratic, pinkish-tan, feldspathic. Composed of angular to subangular, very coarse sand, granules, and small pebbles up to 0.5 inches (1.27 cm) diameter. About 20 percent of sand, granules, and pebbles is pink feldspar. Forms ledge.	13	4
32.	Shale, varicolored. Lower third is olive-gray silty clay; middle third is purplish-red shale containing 1–2-inch (2.5–5-cm) limestone nodules; upper third is purple, sandy, micaceous shale.	24	7.3
31.	Siltstone, olive-gray. Upper 5 ft (1.5 m) contains three 4–8-inch (10–20-cm) thick, fine-grained, silty limestone beds.	17	5.2
30.	Limestone, gray, medium-grained, silty. Forms small ledge.	1.5	0.46
29.	Shale, clay, light-olive-gray, silty.	7	2.1
28.	Limestone, light-olive-gray, fine-grained, dense. Contains a few brachiopod fragments and scattered medium grains of feldspar sand.	1.5	0.46
27.	Shale and nodular limestone, light-purplish-gray. About 40 percent is limestone; nodules are1–3 inches (2.5–7.6 cm) diameter.	3	0.9
26.	Limestone, light-brownish-gray, fine-grained, bioclastic. Contains fragments of crinoid columnals, bryozoans, brachiopods, and ostracodes. Forms two small ledges.	3	0.9
25.	Siltstone, light-yellowish-gray; upper half is shaly. About 20 percent of unit is light-olive-gray nodules of limestone, which are 1–2 inches (2.5–5 cm) thick and 2–6 inches (5–15 cm) long. Forms slight ledge.	7	2.1
24.	Shale, clay, light-olive-gray, silty. Soft.	10	3
23.	Limestone, light-gray, fine-grained, bioclastic; contains algal filaments. Forms small ledge.	1	0.3
22.	Claystone. Lower third is red-weathering, silty, micaceous, and contains a few small limestone concretions. Upper part is olive gray, silty, and contains lenses of very fine grained, micaceous sandstone.	28	8.5
21.	Sandstone, feldspathic, similar to unit 19. Contains thin lenses of red, silty shale.	7	2.1
20.	Shale, purplish-weathering, silty, micaceous.	6	1.8
19.	Sandstone, light-pinkish-yellow, feldspathic. Composed of subround to angular, coarse to very coarse sand and granules. About 20 per-		

Unit	Lithology	Thickness ft	m
	cent is pink feldspar granules. Forms resistant ledge.	11.5	3.5
18.	Claystone, grayish-tan; soft. Forms slope.	9	2.7
17.	Sandstone, greenish-gray, arkosic, fine- to medium-grained, dense; siliceous cement. Contains angular granules of pink feldspar.	1	0.3
16.	Limestone, gray, nodular; contains thin interbeds of purple clay shale.	2.5	0.76
15.	Claystone, light-olive-gray, silty, calcareous. Contains scattered 1–2-inch (2.5–5-cm) limestone nodules mainly concentrated along joints at high angle to bedding.	10	3
14.	Limestone, medium-gray, fine- to coarse-grained, bioclastic, slightly micaceous. Bedding is irregular to slightly nodular; beds are 4 inches–1.5 ft (10–45 cm) thick. About 15 percent of unit is thin interbeds of gray, calcareous, clay shale.	4.7	1.4
13.	Shale, clay, light-olive-gray, silty; contains scattered limestone concretions as much as 6 inches (15 cm) diameter.	2.5	0.76
12.	Limestone, light-tan-gray, mainly oolitic, partly bioclastic. Contains some medium to coarse quartz sand and a trace of feldspar. Contains ostracodes and fragments of brachiopods. Forms small ledge.	3	0.9
11.	Sandstone, light-yellowish-gray. Matrix is fine to coarse sand; contains lenses and scattered clasts of pink feldspar sand and granules. Crossbedded. Upper third is silty and shaly.	5	1.5
10.	Shale, clay, reddish-brown- to light-greenish-gray-weathering, silty. Contains small silty limestone nodules.	5	1.5
9.	Sandstone, fine- to coarse-grained, arkosic. Forms small ledge.	0.7	0.21
8.	Limestone, light-gray, bioclastic. Composed mainly of fragments of crinoids and brachiopods. Contains coarse quartz sand and granules. Lower half forms hard ledge; upper half is irregular bedded and less resistant.	1.5	0.46
7.	Limestone, light-greenish-gray, fine- to coarse-grained, bioclastic. Contains bryozoans, brachiopods, and crinoid columnals; contains much quartz sand and granules. Bedding is irregular to nodular; beds are <1–8 inches (<2.5–20 cm) thick. Contains 0.25 inch (0.6 cm) thick interbeds of calcareous clay shale.	7	2.1
6.	Shale, light-yellowish-gray; unit is interbedded siltstone, very fine grained sandstone, and a few thin claystone beds. About 20 percent is silty, slightly micaceous, limestone nodules scattered along some beds. Unit contains a few brachiopods and crinoid columnals.	17	5.2
5.	Shale and interbedded limestone, light-olive-brown- and gray-weathering. Lower third is mainly gray, nodular, bioclastic, silty, sandy limestone in beds 6 inches–1 ft (15–30 cm) thick; about 30 percent is interbeds of gray, silty, micaceous shale. Upper two thirds is about 70 percent shale containing thin silty, sandy limestone interbeds. Limestone contains some thick-shelled brachiopods.	16	4.9
4.	Siltstone, light-olive-gray, shaly; contains brachiopods and ostracodes.	3	0.9
3.	Sandstone, conglomeratic, light-yellowish-gray, feldspathic. Composed of angular to subangular, coarse to very coarse sand. Contains angular granules of pink feldspar. Contains rounded pebbles of limestone and vein quartz 0.25–1.5 inches (0.6–3.8 cm) diameter. Slightly inclined crossbedding; beds are 1–2 ft (30–60 cm) thick. Forms ledge.	13	4
2.	Limestone, gray, nodular. Beds are 6–8 inches (15–20 cm) thick. About 20 percent of unit is gray, calcareous, clay shale interbeds.	3	0.9
1.	Concealed; probably red shale and thin, nodular limestone beds.	7+	2.1+
	Partial thickness of Alamitos Formation:	563.9	171.6+

[Base of section is at side road leading up east side of Canovas Canyon; section continues east in cuts on main Forest Service road. Base of Alamitos Formation is exposed at places on the west side of Canovas Canyon. (See Fig. 81.) Base of unit 1 is estimated to be about 150 ft (45 m) stratigraphically above base of formation.]

Appendix III

Descriptions of localities of fusulinid collections

(Quadrangles referenced are USGS 7.5-minute topographic series except as noted.)

USGS Number	Description
f10121	Alamitos Formation. Mora County, Mora quadrangle (1965). Road cut, south side of New Mexico Highway 518; 950 ft due east of St. Joseph Church. Gray calcarenite 8 ft below top of ledgy limestone that underlies redbeds. About 600 ft above base of formation. Field locality M7601 in Baltz and O'Neill (1984). Stratigraphic section K, unit 329 (Figs. 65, 89).
f10122	Porvenir Formation, San Miguel County, El Porvenir quadrangle (1961). Roadcuts, U.S. Forest Service Johnson Mesa road, sec. 23 T17N R14E. From 114 ft below top of formation. Stratigraphic section D, unit 111 (Figs. 33, 81).
f10123	Porvenir Formation. See f10122 for locality. About 28 ft below top of formation, stratigraphic section D, unit 120 (Fig. 33).
f10124	Alamitos Formation. See f10122 for locality. From 25 ft above base of formation, stratigraphic section D, unit 127 (Figs. 33, 62).
f10125	Porvenir Formation. See f10122 for locality. From 35 ft above base of formation stratigraphic section D, unit 52 (Fig. 33).
f10126	Porvenir Formation. See f10122 for locality. From 90 ft above base of formation, stratigraphic section D, unit 62 (Fig. 33).
f10127	Porvenir Formation. See f10122 for locality. From 200 ft above base of formation, stratigraphic section D, unit 67 (Fig. 33).
f10128	Alamitos Formation. San Miguel County, El Porvenir quadrangle (1961). South of Canovas Canyon. Limestone nodules in bed and cuts of abandoned road at about 7,880 ft altitude. About 40 ft below top of formation. Locality shown in Figure 81. Locality projected to stratigraphic section P (Fig. 62).
f10129	Alamitos Formation. San Miguel County, Sapello quadrangle (1965). Northwest of Sapello. Ledge-forming limestone in roadcut north side of New Mexico Highway 94. Locality shown in Figure 86.
f10130	Alamitos Formation. See f10129 for locality. Silty shaly limestone about 75 ft west of and stratigraphically below f10129. Field locality M7621 in Baltz and O'Neill (1986).
f10131	Porvenir Formation. San Miguel County, Sapello quadrangle (1965). About 1.5 mi northwest of Manuelitas. About 16 ft above base of formation in bioclastic crinoidal limestone. Locality shown in Figure 83. Locality projected to stratigraphic section E1, unit 10 (Fig. 39). Field locality B7602 in Baltz and O'Neill (1986).
f10132	Sandia Formation. Mora County, Mora quadrangle (1965). Bluffs 300 ft north of Rito Cebolla. About 75 ft below top of formation in 1–2-ft-thick bioclastic limestone above massive sandstone. Locality shown in Figure 88. Field locality B7605 in Baltz and O'Neill (1984). Stratigraphic section I, unit 1 (Fig. 46). (Also in sec. C, Fig. 22.)
f10133	Porvenir Formation. Mora County, Mora quadrangle (1965). Road cut on New Mexico Highway 518 north of St. Joseph Church. From 1.5-ft-thick shaly limestone 85 ft above base of formation. Field locality B7606 in Baltz and O'Neill (1984). Stratigraphic section K, unit 223 (Figs. 46, 89).
f10134	Alamitos Formation. Mora County, Mora quadrangle (1965). About 5,700 ft S8°W from St. Joseph Church at bottom of northeast-draining canyon 1,800 ft south of La Cañada del Guajalote. Limestone near middle of formation. Field locality B7610 in Baltz and O'Neill (1984).
f10135	Porvenir Formation. Mora County, Mora quadrangle (1965). About 600 ft south of Mora River and about 50 ft east of crest of low northeast-trending ridge. From 2–3-ft-thick calcareous sandstone in lower part of formation. Correlated to stratigraphic section K, unit 216, (Fig. 46). Locality shown in Figure 89. Field locality B7611 in Baltz and O'Neill (1984).
f10136	Alamitos Formation. San Miguel County, Montezuma quadrangle (1961). North of mouth of Canyon Alto and Gallinas Creek. At top of ridge 2,600 ft N54°W from Sagrado Corazon Church. Sandy limestone about 50 ft above base of formation. Stratigraphic section 1 (Figs. 33, 82).
f10137	Porvenir Formation. Mora County, Mora quadrangle (1965). About 4,400 ft N14°E from St. Joseph Church. Thin sandy limestone in basal part of formation. Locality shown in Figure 89. Field locality B7704 in Baltz and O'Neill (1984). Stratigraphic section J7. See section J headnote (Fig. 26).
f10138	Alamitos Formation. San Miguel County, Sapello quadrangle (1965). North side of gully about 75 ft east of dam for irrigation lake; 2,650 ft S44°W from bench mark 6989 on New Mexico Highway 94 northwest of Sapello. Thin limestone and interbedded thin shale in middle(?) part of formation. Field locality B7705 in Baltz and O'Neill (1986).
f10139	Porvenir Formation. San Miguel County, Rociada quadrangle (1965). Southeast of Rociada in bluffs north of Manuelitas Creek. Limestone 30 ft above base of formation. Locality shown in Figure 87. Field locality M7614 shown in Baltz and O'Neill (1986). Stratigraphic section H, unit 59 (Fig. 39).
f10140	Porvenir Formation. See f10139 for locality. Limestone about 505 ft above base of formation, stratigraphic section H, unit 70 (Fig. 39). Field locality M7615 in Baltz and O'Neill (1986).
f10141	Porvenir Formation. See f10139 for locality. From top of thin limestone 550 ft above base of formation, stratigraphic section H, unit 71 (Fig. 39).
f10142	Porvenir Formation. See f10139 for locality. From 90 ft below top of formation, stratigraphic section H, unit 116 (Figs. 39, 63). Locality shown in Figure 87. Field locality M7617 in Baltz and O'Neill (1986).
f10143	Porvenir Formation. See f10139 for locality. From 14 ft below top of formation, stratigraphic section H, unit 118 (Figs. 39, 63).
f10144	Alamitos Formation. See f10139 for locality. From 77 ft above base of formation, stratigraphic section H, unit 120 (Figs. 39, 63).
f10145	Porvenir Formation. Mora County, Mora quadrangle (1965). North side of New Mexico Highway 518 north of St. Joseph Church. About 75 ft above base of formation, stratigraphic section K, from locally present limestone between units 219 and 220 (Figs. 46, 89).
f10146	Porvenir Formation. See f10145 for locality. About 95 ft above base of formation, stratigraphic section K, unit 227 (Fig. 46).
f10147	Porvenir Formation. See f10145 for locality. Limestone nodules about 170 ft above base of formation, stratigraphic section K, unit 239 (Fig. 46).

USGS Number	Description
f10148	Porvenir Formation. See f10145 for locality. About 375 ft above base of formation, stratigraphic section K, unit 255 (Fig. 46).
f10149	Porvenir Formation. See f10145 for locality. About 6.5 ft below top of formation, stratigraphic section K, unit 276 (Fig. 46).
f10150	Porvenir Formation. Mora County, Holman quadrangle (1965). Roadcut on New Mexico Highway 518, 150 ft north of Taos–Mora County line and bench mark 9469. Gray limestone in zone of shaly limestone and dark gray shale that is transitional between Porvenir Formation and underlying Sandia Formation.
f10151	Porvenir Formation. See f10150 for locality. Roadcut on southeast side of Highway 518, a few feet southwest of bench mark 9469. Light-gray limestone in lower part of Porvenir Formation about 65 ft stratigraphically above f10150.
f10152	Porvenir Formation. San Miguel County, Montezuma quadrangle (1961). Hill south of Montezuma. About 45 ft above base of formation, stratigraphic section G, unit 27 (Figs. 33, 85).
f10153	Porvenir Formation. See f10152 for locality. Bioherm in quarry, about 210 ft above base of formation, stratigraphic section G, unit 47 (Fig. 33).
f10154	Porvenir Formation. See f10152 for locality. From quarry, about 230 ft above base of formation, stratigraphic section G, unit 50 (Fig. 33).
f10155	Porvenir Formation. See f10152 for locality. From 360 ft above base of formation, stratigraphic section G, unit 71 (Fig. 33).
f10156	Porvenir Formation. See f10152 for locality. From about 470 ft above base of formation, stratigraphic section G, unit 82 (Fig. 33).
f10157	Alamitos Formation. San Miguel County, Montezuma quadrangle (1961). South of Montezuma; 3,750 ft S13°E from bench mark 6744 on New Mexico Highway 65. From about 95 ft above base of formation, stratigraphic section G, unit 101 (Figs. 62, 85).
f10274	Alamitos Formation. San Miguel County, Ojitos Frios quadrangle (1961). About 100 ft north of New Mexico Highway 283; 3,850 ft N75°W from small pond at Agua Zarca. Sandy arkosic limestone on south-facing hillside.
f10275	Alamitos Formation. San Miguel County, Ojitos Frios quadrangle (1961). South of Ojitos Frios; 3,400 ft S20°E from road crossing on Tecolote Creek at Ojitos Frios. Lens of nodular bioclastic limestone, 0–8 inches thick, enclosed in limestone-pebble conglomerate in upper part of formation. Stratigraphic section M, units 8 and 9 (Figs. 55, 59).
f10277	Alamitos Formation. San Miguel County, El Porvenir quadrangle (1961). Hill west of Tecolote Creek, 1,400 ft S16°E from bench mark 7055 on road to Blue Haven Camp. Bioclastic limestone, 2 ft thick, which locally is a fusulinid coquina. About 130 ft below top of formation.
f10278	Alamitos Formation. San Miguel County, San Geronimo quadrangle (1961). Northwest of San Geronimo on county road; 550 ft N40°W from bench mark 6887. Reddish-gray limestone in upper part of formation.
f10283	Porvenir Formation. San Miguel County, Sapello quadrangle (1965). About 3 mi west of Sapello. North of New Mexico Highway 266 on spur 1,800 ft due east of hill 7371; on east side of ravine tributary to Sapello River. Limestone about 10 ft above base of formation. Field locality M7622 in Baltz and O'Neill (1986). Projected to stratigraphic section 5 (Fig. 22).
f10284	Porvenir Formation. Mora County, Mora quadrangle (1965). On Fragoso Ridge at approximate altitude 7,840 ft. Sandy bioclastic and oolitic limestone about 640 ft above base of formation. Locality shown in Figure 84. Field locality M7624 in Baltz and O'Neill (1984). Stratigraphic section F, unit 34 (Fig. 46).
f10285	Porvenir Formation. See f10284 for locality. Thin grayish-red silty limestone in wood-haulers road on crest of ridge at approximate altitude 7,760 ft. About 900 ft above base of formation (Fig. 46). Locality shown in Figure 84. Field locality M7625 in Baltz and O'Neill (1984). Stratigraphic section F, unit 48.
f10286	Sandia Formation. San Miguel County, Montezuma quadrangle (1961). Hill slope north of New Mexico Highway 65, southeast of Gallinas; about 30 ft west of bench mark 7099 and 50 ft above bench mark. About 70 ft below top of formation. Same locality as f13151, stratigraphic section 1 of Porvenir Formation (Figs. 33, 82).
f10287	Alamitos Formation. Mora County, Mora quadrangle (1965). In southeast-draining arroyo about 1,800 ft north of Rito Cebolla; 5,480 ft N57°W from bench mark 7053, which is near southeast corner of quadrangle. Ridge of 2-ft-thick limestone in bottom of arroyo. Field locality B7603 in Baltz and O'Neill (1984).
f10288	Alamitos Formation. Mora County, Mora quadrangle (1965). East-draining canyon about 6,300 ft north of Rito Cebolla; 5,850 ft S61°W from bench mark 7038 which is on New Mexico Highway 518. Thin, wavy-bedded cherty limestone that forms small ledge on north side of valley about 15 ft west of red arkose ledges of Sangre de Cristo Formation. Field locality B7604 in Baltz and O'Neill (1984).
f10289	Alamitos Formation. Mora County, Mora quadrangle (1965). About 4.5 mi. southeast of Mora; 8,650 ft N34°W from Brother of Jesus Mission. Thin limestone on slope about 30 ft east of crest of a ridge. Field locality B7607 in Baltz and O'Neill (1984).
f10290	Porvenir Formation. Mora County, Mora quadrangle (1965). About 4.5 mi southeast of Mora; 7,800 ft N39°W from Brother of Jesus Mission. Limestone in cut on ranch road north of earth dam on north side of small valley. Field locality B7608 in Baltz and O'Neill (1984).
f10291	Porvenir Formation. Mora County, Mora quadrangle (1965). North end of Fragoso Ridge at approximate altitude 7,200 ft on jeep trail. Oolitic limestone about 20 ft above base of formation. Locality shown in Figure 84. Field locality B7613 in Baltz and O'Neill (1984). Stratigraphic section F, unit 12 (Figs. 22, 46).
f10292	Porvenir Formation. San Miguel County, Sapello quadrangle (1965). North side of ridge south of Cañon del Horno; 6,700 ft N82°W from church at San Isidro Cemetery. From 8-ft-thick yellowish-gray weathering micritic limestone about 130 ft below top of formation. Field locality B7701 in Baltz and O'Neill (1986). Position traced to strati-

USGS Number	Description
	graphic section E3, unit 33 (Figs. 39, 83).
f10293	Porvenir Formation. Mora County, Mora quadrangle (1965). About 2,300 ft north of Mora River north of St. Joseph Church. Sandy, oolitic gray limestone 30 ft above base of formation. Field locality B7703 in Baltz and O'Neill (1984). Stratigraphic section L, unit 20 (Figs. 26, 89).
f10294	Alamitos Formation. Mora County, Mora quadrangle (1965). In Cañon del Agua, north of Mora River. Light-gray dense limestone that forms massive ledge and waterfall. Locality shown in Figure 89. Field locality B7706 in Baltz and O'Neill (1984).
f10295	Porvenir Formation. Same locality as f10285.
f10296	Porvenir Formation. Same locality as f10284.
f10297	Alamitos Formation. Mora County, Mora quadrangle (1965). North side of Rito Cebolla. Small ridge of medium-gray limestone and silty gray shale. Locality shown in Figure 88. Field locality B7713 in Baltz and O'Neill (1984). Stratigraphic section I, unit 15 (Fig. 65).
f10298	Porvenir Formation. San Miguel County, El Porvenir quadrangle (1961). Cut in Forest Service road on ridge east of Long Ranch; SW¼SE¼ sec. 13 T17N R14E. Limestone, 1.3-ft-thick, about 33 ft below top of formation. Locality shown in Figure 81. Stratigraphic section 7 (Fig. 62).
f10299	Alamitos Formation. See f10298 for locality. Thin bioclastic limestone about 75 ft above base of formation.
f10300	Porvenir Formation. Mora County, Mora quadrangle (1965). About 1 mi north of Mora River. Limestone at base of formation in topographic saddle east of small anticline. (See section J7 headnote.) Locality shown in Figure 89. Stratigraphic section J7 (Fig. 26).
f10301	Alamitos Formation. San Miguel County, Sapello quadrangle (1965). Northwest of Sapello. Ridge-forming limestone, 4.5-ft-thick, containing large brachiopods, and exposed in southeast-draining arroyo. About 150 ft above base of formation. Locality shown in Figure 86. Field locality B7907 in Baltz and O'Neill (1986). Stratigraphic section 9 (Fig. 63).
f10302	Porvenir Formation. San Miguel County, Sapello quadrangle (1965). Northwest of Sapello. Limestone ledge on north bank of southeast-draining arroyo. Probably 160 ft above base of formation. Locality shown in Figure 86. Field locality B7908 on Baltz and O'Neill (1986). Stratigraphic section 3 (Fig. 39).
f10303	Porvenir Formation. Mora County, Lucero quadrangle (1966). About 2,800 ft N85°W from road junction at cemetery at Los Cisneros. Low ridge of bioclastic, sandy oolitic limestone just south of creek near north bend in road. Basal(?) part of formation.
f10304	Porvenir Formation. Mora County, Mora quadrangle (1965). Top of northeast-trending ridge, 2,100 ft north of Cañon del Agua. Light gray, sandy, bioclastic limestone, 1–2 ft thick, that underlies massive ridge-forming arkose in lower part of formation. Locality shown in Figure 89. Field locality B7709 in Baltz and O'Neill (1984).
f10305	Porvenir Formation. Mora County, Mora quadrangle (1965). About 12,600 ft N27°E from St. Joseph Church. Small ridge of silty to sandy, bioclastic, crossbedded limestone, about 5 ft thick that is basal part of formation. Field locality B7710 in Baltz and O'Neill (1984).
f10306	Sandia Formation. San Miguel County, Villanueva 15-minute quadrangle (1960). North side of canyon, west of large clearing, NE¼ SW¼ sec. 21 T14N R15E. Two-ft-thick ledge of fractured cherty limestone, about 10 ft east of probable fault contact with Precambrian granite. About 75 ft below top of Sandia Formation. Near locality of stratigraphic section 1 (Figs. 55, 58).
f10307	Sandia Formation. Mora County, Montezuma quadrangle (1965). In Sanguijuela Arroyo just east of bench mark 7291 and north of county road. Lower part of south-facing hillside. Prominent ledge of limestone about 120 ft below top of formation.
f10308	Porvenir Formation. San Miguel County, Ojitos Frios quadrangle (1961). Roadcut 35 ft south of and above New Mexico Highway 283; 13,300 ft N67°W from small pond at Agua Zarca. Six-inch thick siliceous limestone about 15 ft above base of formation.
f10309	Porvenir Formation. San Miguel County, Ojitos Frios quadrangle (1961). East side of Cañon Mesteño. Road cut at north side of New Mexico Highway 283 1,900 ft S70°E from bench mark 7034 (San Geronimo road junction). Sandy limestone of "marker" zone near top of formation.
f10310	Porvenir Formation. San Miguel County, El Porvenir quadrangle (1961). Near bottom of Cabo Lucero Creek west of Blue Haven Camp; 1.6 mi S81°W from Trujillo Ranch house. Thin sandy limestone about 5 ft below top of formation. Stratigraphic section O, unit 1 (Figs. 55, 58).
f10311	Porvenir Formation. San Miguel County, Villanueva 15-minute quadrangle (1960). Limestone quarry at north side of road between Bernal and Blanchard; 5,600 ft N20°W from Starvation Peak. Coquinoid bed of fusulinids on floor of quarry.
f10312	Porvenir Formation. San Miguel County, Rociada quadrangle (1965). Ridge north of Sapello River in SE¼ sec. 33 T19N R14E (projected); 200 ft south of bench mark 8883 at about 8,870 ft altitude. Bioclastic limestone about 35 ft above base of formation. Field locality B8001 in Baltz and O'Neill (1986).
f10313	Porvenir Formation. San Miguel County, Rociada quadrangle (1965). Near east end of ridge between Sparks and Maestas Creeks at approximate altitude 8,460 ft; 3,200 ft N60°W from bench mark 8000, which is near mouth of Sparks Creek. Limestone about 80 ft above base of formation. Field locality B8003 in Baltz and O'Neill (1986).
f10314	Porvenir Formation. Mora County, Rociada quadrangle (1965). South side of ridge north of Sparks Creek at approximate altitude 8,720 ft; 6,500 ft N20°W from bench mark 8000, which is near mouth of Sparks Creek. Bioclastic limestone about 35 ft above base of formation. Field locality B8004 in Baltz and O'Neill (1986).
f10315	Porvenir Formation. Santa Fe County, Tesuque quadrangle (1953, revised 1977). North side of Rio Nambe about 300 ft upstream from picnic area west of Nambe falls and dam. Estimated 80–120 ft above

USGS Number	Description
	base of formation. Sparse fusulinids in ledge of limestone that dips 35–40° into bed of river.
f10316	Porvenir Formation. Santa Fe County, Glorieta quadrangle (1953). East side of ravine 0.39 mi N56°W from bench mark 6610, which is at junction of ravine with Galisteo Creek and Atchison, Topeka, and Santa Fe railroad tracks. Limestone nodules in calcareous shale about 40 ft below top of formation.
f10317	Alamitos Formation. Santa Fe County, Rosilla Peak quadrangle (1961). Northwest of Pecos. From unit 9 of stratigraphic section 97 of Sutherland (1963, p. 66).
f10318	Alamitos Formation. Same locality as f10317; from unit 11 of stratigraphic section 97 of Sutherland (1963).
f10319	Alamitos Formation. San Miguel County, North San Ysidro quadrangle (1966). Center of sec. 24 T14N R13E, about 1.2 mi northwest of San Juan on east side of meander loop of Pecos River. Sandy, bioclastic, oolitic limestone about 20 ft below top of formation. Pecos River section described in text (p. 107).
f10320	Alamitos Formation. See f10319 for locality. Bioclastic limestone that forms a strong ledge below green-gray shale at north side of meander loop of Pecos River. About 60 ft below top of formation. Pecos River section described in text (p. 107).
f10321	Alamitos Formation. San Miguel County, Villanueva 15-minute quadrangle (1960). SW¼ sec. 35 T14N R15E. Low embankment immediately north of Interstate Highway 25, about 1,000 ft west of crossover road to Bernal. (South of old U.S. Highway 84–85 shown in quadrangle.) Brown-weathering sandy bioclastic limestone about 1 ft thick and about 13 ft above base of formation. Bernal section described in text (p. 107).
f10322	Alamitos Formation. Same locality as f10321. Brown limestone that weathers to thin broken plates. About 7 ft above base of formation and just west of f10321.
f10323	Alamitos Formation. San Miguel County, Villanueva 15-minute quadrangle (1960). SW¼ sec. 35 T14N R15E, about 600 ft southwest of locality f10321. Small outcrop of purplish-gray bioclastic limestone in grass-covered field about 300 ft southwest of water well, which is just south of Interstate Highway 25.
f10324	Alamitos Formation. San Miguel County, Ojitos Frios quadrangle (1961). About 4,900 ft S5°E from bench mark 7233, which is on New Mexico Highway 283 at head of La Cañada del Alto de la Reunion. Light-gray bioclastic limestone that forms small bench west of main arroyo in the Cañada and just east of axis of La Reunion syncline. About 75 ft above base of formation.
f10325	Alamitos Formation. San Miguel County, Sapello quadrangle (1965). In ditch at north side of sharp bend in New Mexico Highway 266, about 900 ft southwest of junction of Highways 266 and 94. Cherty, greenish-gray limestone about 50 ft above basal arkose of formation. Locality shown in Figure 86. Field locality B7601 in Baltz and O'Neill (1986).
f10326	Alamitos Formation. Same locality as f10138. Field locality B7705 in Baltz and O'Neill (1986).
f10327	Alamitos Formation. Area of f10275, near stratigraphic section M. Sparse fusulinids in anthill on calcareous shale interbedded in limestone.
f10328	Alamitos Formation. See f10321 for locality. About 75 ft north of Interstate Highway 25, and just south of highway boundary fence. Small outcrop of purplish-gray sandy bioclastic limestone; probably same bed as f10321.
f10334	Porvenir Formation. Mora County, Holman quadrangle (1965). Projected sec. 29 T21N R14E. North rim of Osha Canyon; 4,100 ft N26°W from junction of stream in Osha Canyon and North Fork of Rio la Casa. Cut in Forest Service road at about altitude 9,900 ft. Bioclastic limestone, 15 ft thick, that is basal part of Porvenir Formation. Basal limestone is underlain by thick gray shale of Sandia Formation, and is overlain by a 40-ft-thick gray shale, overlain, in turn, by more limestone of the Porvenir.
f10335	Porvenir Formation. San Miguel County, Villanueva 15-minute quadrangle (1960). Northwest of Bernal, near middle of sec. 8 T14N R15E. Limestone about 35 ft above base of formation on low ridge southwest of southeast-draining canyon in which abandoned coal mine is located. Stratigraphic section A, unit 12 (Figs. 17, 20).
f10337	Porvenir Formation. San Miguel County, Villanueva 15-minute quadrangle (1960). Northwest of Bernal in SE¼SE¼ sec. 21 T14N R15E. Near bottom of south wall of large east-draining canyon east of sharp kink in ranch road. About 6 ft below top of sandstone and sandy limestone in lower part of "marker" zone and about 95 ft below top of formation. Stratigraphic section 1 (Figs. 55, 58).
f10338	Porvenir Formation. San Miguel County, Rociada quadrangle (1965). North side of Sapello River; 1,700 ft N13°E from NW corner of sec. 18 T18N R15E. Limestone 30–35 ft above base of formation on ridge at about altitude 7,680 ft. Field locality B8101 in Baltz and O'Neill (1986).
f10339	Porvenir Formation. San Miguel County, Rociada quadrangle (1965). Northwest of Rociada. West side of deep northeast-draining canyon about 2,500 ft SW of confluence with Maestas Creek. About 7,100 ft N84°E from NE corner sec. 30 T19N R14E. Top of thin-bedded limestone on wood haulers road about 100 ft above base of formation. Field locality B8105 in Baltz and O'Neill (1986).
f10340	Porvenir Formation. San Miguel County, Sapello quadrangle (1965). Topographic bench north of deep southeast-draining canyon 3,300 ft N10°E from Highway 266 bridge at Las Tusas. Limestone about 35 ft above base of formation. Field locality B7911 in Baltz and O'Neill (1986).
f10341	Porvenir Formation. San Miguel County, Sapello quadrangle (1965). Ridge north of Sapello River 1,500 ft N32°W from Highway 266 bridge at Las Tusas. About 20 ft above base of formation. Field locality 7912 in Baltz and O'Neill (1986).
f10343	Porvenir Formation. Mora County, Lucero quadrangle (1966). About 2,100 ft west of road junction, which is at cemetery at Los Cisneros. Low ridge of gray limestone about 100 ft north of dirt road. About 15 ft below top of Porvenir and overlying massive basal arkose of Alamitos Formation. Stratigraphic section 4 on Plate 3.

USGS Number	Description
f10344	Porvenir Formation. Mora County, Mora quadrangle (1965). East side of narrow north-draining canyon about 900 ft south of La Cañada del Guajalote. About 5,500 ft S14°W from St. Joseph Church. Top of 30-ft-thick sandy bioclastic limestone near base of formation. Field locality B7609 in Baltz and O'Neill (1984).
f10345	Alamitos Formation. Same locality as f10130.
f10346	Alamitos Formation. Same locality as f10129.
f13143	Porvenir Formation. San Miguel County, El Porvenir quadrangle (1961). SE¼ sec. 23 T17N R14E. Abandoned road on ridge south of Canovas Canyon at locality of stratigraphic section 6 (Figs. 58, 62, 81). Sandy bioclastic limestone near top of "marker" zone about 95 ft below top of formation.
f13144	Alamitos Formation. See f13143 for locality. Limestone about 60 ft above base of formation. Stratigraphic section 6 (Figs. 58, 62, 81).
f13150	Sandia Formation. See f10286 for locality. Four-inch-thick limestone interbedded in gray shale above thick sandstone. About 95 ft below top of formation. Stratigraphic section 3 of Sandia Formation (Figs. 17, 21).
f13151	Sandia Formation. See f10286 for locality. About 40 ft below top of formation. Stratigraphic section 3 of Sandia Formation (Figs. 17, 21).
f13153	Porvenir Formation. See f10286 for locality. Top of bench-forming limestone about 85 ft above base of formation. Stratigraphic section 1 of Porvenir Formation (Figs. 33, 82).
f13154	Porvenir Formation, San Miguel County, Montezuma quadrangle (1961). About 0.8 mi NNW of Cañon Alto. From 8-ft-thick unit of limestone and interbedded shale about 1,000 ft northwest of Sagrado Corazon Church. About 280 ft below top of formation. Stratigraphic section 1 (Figs. 33, 82).
f13156	Porvenir Formation. San Miguel County, Montezuma quadrangle (1961). Northwest of Gallinas. About 1,900 ft NNW from bench mark 7149, which is on New Mexico Highway 65. Sandy limestone about 40 ft below top of formation at locality of megafossil collection 24484–PC, stratigraphic section 1 of Porvenir Formation (Figs. 33, 82).
f13160	Porvenir Formation. San Miguel County, Rociada quadrangle (1965). SE¼ sec. 8 T18N R14E. About 1,000 ft north of Beaver Creek Cabin. Near top of ledge-forming limestone about 300 ft above base of formation. Locality f13160 in Baltz and O'Neill (1986). Stratigraphic section 2 (Figs. 31, 39).
f13161	Porvenir Formation. San Miguel County, Rociada quadrangle (1965). NE¼ sec. 8 T18N R14E. About 2,900 ft north of Beaver Creek Cabin near top of ridge. Ledge-forming thick limestone about 980 ft above base of formation. Locality 13161 in Baltz and O'Neill (1986). Stratigraphic section 2 (Figs. 31, 39).
f13167	Alamitos Formation. San Miguel County, Sapello quadrangle (1965). North of Manuelitas Creek, about 2,000 ft north of Cañoncito. Thin limestone about 210 ft above base of formation at locality of stratigraphic section 8 (Figs. 55, 63).
f13212	Alamitos Formation. Same as locality f10128.
f13213	Alamitos Formation. San Miguel County, El Porvenir quadrangle (1961). SE¼ sec. 23 T17N R18E. Outcrop of thin limestone on north side of Johnson Mesa road near junction with road to Mineral Hill. About 70 ft below top of formation. Stratigraphic section 6 (Figs. 58, 62, 81).
f13215	Alamitos Formation. San Miguel County, El Porvenir quadrangle (1961). Limestone ridge north of Gallinas Creek east of Santa Fe National Forest boundary. About 1,900 ft northeast of Western Life Camp. Locality shown in Figure 81. Projected stratigraphic position is near middle of formation at locality of stratigraphic section 7 (Fig. 62).
f13216	Alamitos Formation. San Miguel County, El Porvenir quadrangle (1961). SE¼ sec. 13 T17N R14E; about 100 ft north of Forest Service road. Sandy limestone about 40 ft above base of formation. Stratigraphic section 7 (Figs. 62, 81).
f13217	Porvenir Formation. San Miguel County, El Porvenir quadrangle (1961). SW¼NE¼ sec. 13 T17N R14E. Ridge about 2,500 ft NNW from Western Life camp. Limestone in medial part of formation.
f24347	Alamitos Formation. Same locality as f13167.
f24353	Porvenir Formation, San Miguel County, Montezuma quadrangle (1961). Head of deep canyon north of Gallinas Creek, northwest of Hot Springs. About 6,500 ft NNW of bench mark 6851, which is on New Mexico Highway 65. Limestone near east end of ridge at about altitude 8,000 ft. About 15 ft above base of formation. Stratigraphic section B, unit 27 (Figs. 17, 21).

Plates

PLATES 1–5—In pocket
PLATES 6–14—Following pages

PLATE 6—Desmoinesian fusulinids from the lower part of the Alamitos Formation and the Porvenir Formation at composite stratigraphic section G, (Fig. 85), south of Montezuma. (Unretouched photographs, x 10, except where indicated)

Figures	
1–4	USGS f10157. *Beedeina* cf. *B. sulphurensis* (Ross and Sabins), 1965. Slides 5, 1, 2, 8; USNM 486061, 486062, 486063, 486064.
5	USGS f10156. *Beedeina* sp. Slide 3; USNM 486065
6–8, 10	USGS f10155. *Beedeina* aff. *B. rockymontana* (Roth and Skinner), 1930. Slides 5, 1, 4, 3; USNM 486066, 486067, 486068, 486070.
9	USGS f10155. *Wedekindellina* cf. *W. minuta* (Henbest), 1928. (× 20). Slide 13; USNM 486069.
11, 13	USGS f10154. *Beedeina* cf. *B. rockymontana* (Roth and Skinner), 1930. Slides 2, 8; USNM 486071, 486073.
12	USGS f10154. *Wedekindellina* sp. Slide 6; USNM 486072.
14, 17	USGS f10153. *Beedeina* aff. *B. rockymontana* (Roth and Skinner), 1930. Slides 8, 3; USNM 486074, 486077.
15	USGS f10153. *Wedekindellina* sp. indet. Slide 7; USNM 486075.
16	USGS f10153. *Frumentella?* sp. (× 50). Slide 12; USNM 486076.
18, 20	USGS f10152. *Beedeina insolita* (Thompson), 1948. Slides 1, 7; USNM 486078, 486080.
19, 21	USGS f10152. *Fusulinella* sp. (× 20). Slides 3, 2; USNM 486079, 486081.

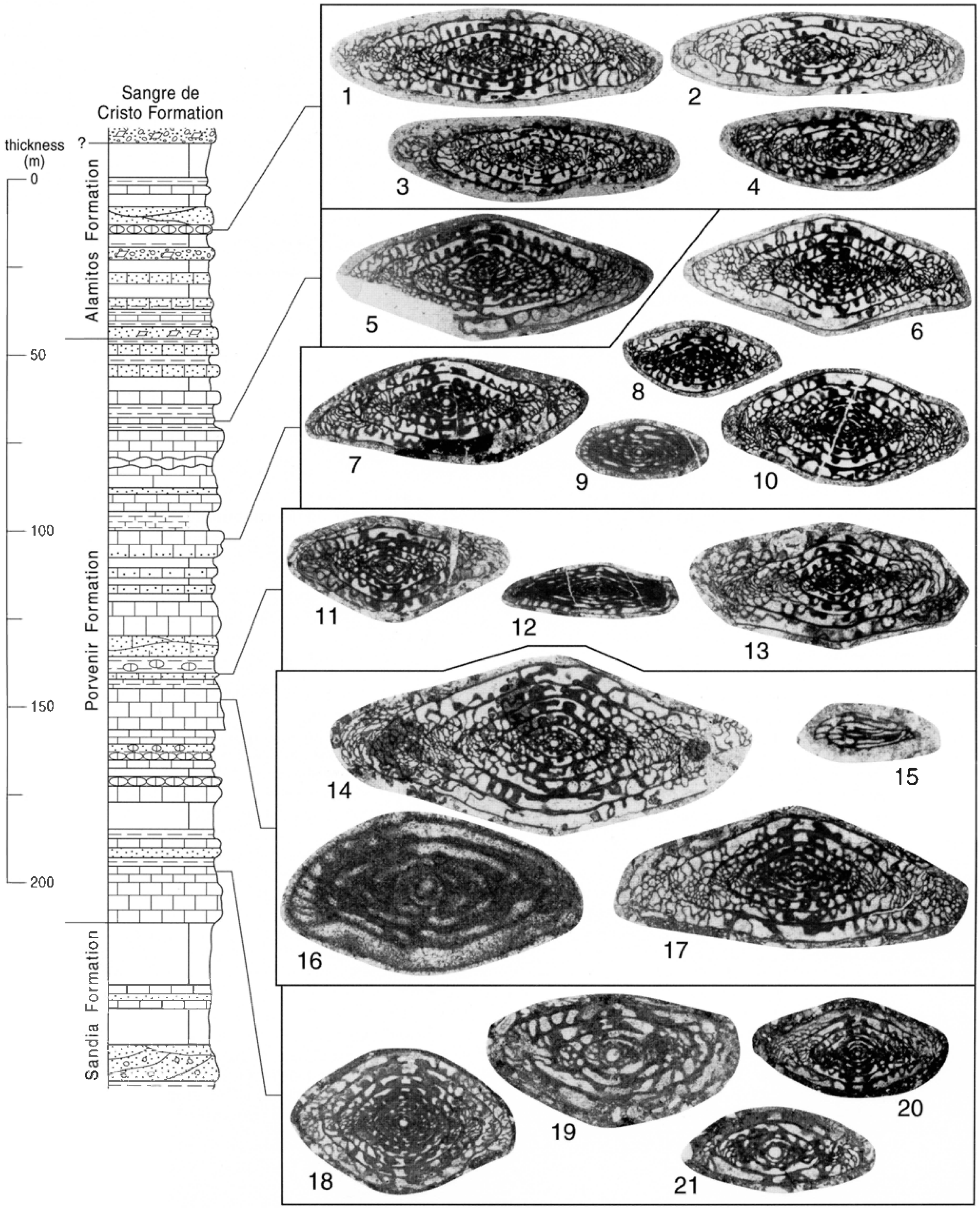

Sangre de Cristo Formation
thickness (m)
?
0
50
100
150
200
Alamitos Formation
Porvenir Formation
Sandia Formation
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

PLATE 7—Miscellaneous Permian, Upper Pennsylvanian, and Desmoinesian fusulinids from the Alamitos Formation. (Unretouched photographs, x 10 except where indicated)

Figures

1–4 USGS f10128. *Triticites* aff. *T. creekensis* Thompson, 1954. Slides 2, 3, 6, 5; USNM 486082, 486083, 486084, 486085. Wolfcampian.

5–8 USGS f10129. *Beedeina* aff. *B. sulphurensis* (Ross and Sabins), 1965. Slides 11, 9, 5, 8; USNM 486086, 486087, 486088, 486089. Desmoinesian.

9–15 USGS f10130. *Beedeina* aff. *sulphurensis* (Ross and Sabins), 1965. Slides 5, 6, 8, 7, 9, 11, 10; USNM 486090, 486091, 486092, 486093, 486094, 486095, 486096. Desmoinesian.

16, 17 USGS f13215. *Triticites nebrascensis* Thompson, 1934. Slides 9, 22; USNM 486097, 486099. Missourian.

18–20 USGS f10138. *Beedeina sulphurensis* (Ross and Sabins), 1965. Slides 4, 1, 3; USNM 486098, 486100, 486101. Desmoinesian.

21 USGS f10138. *Plectofusulina*? sp. (x 50). Slide 6; USNM 486102. Desmoinesian.

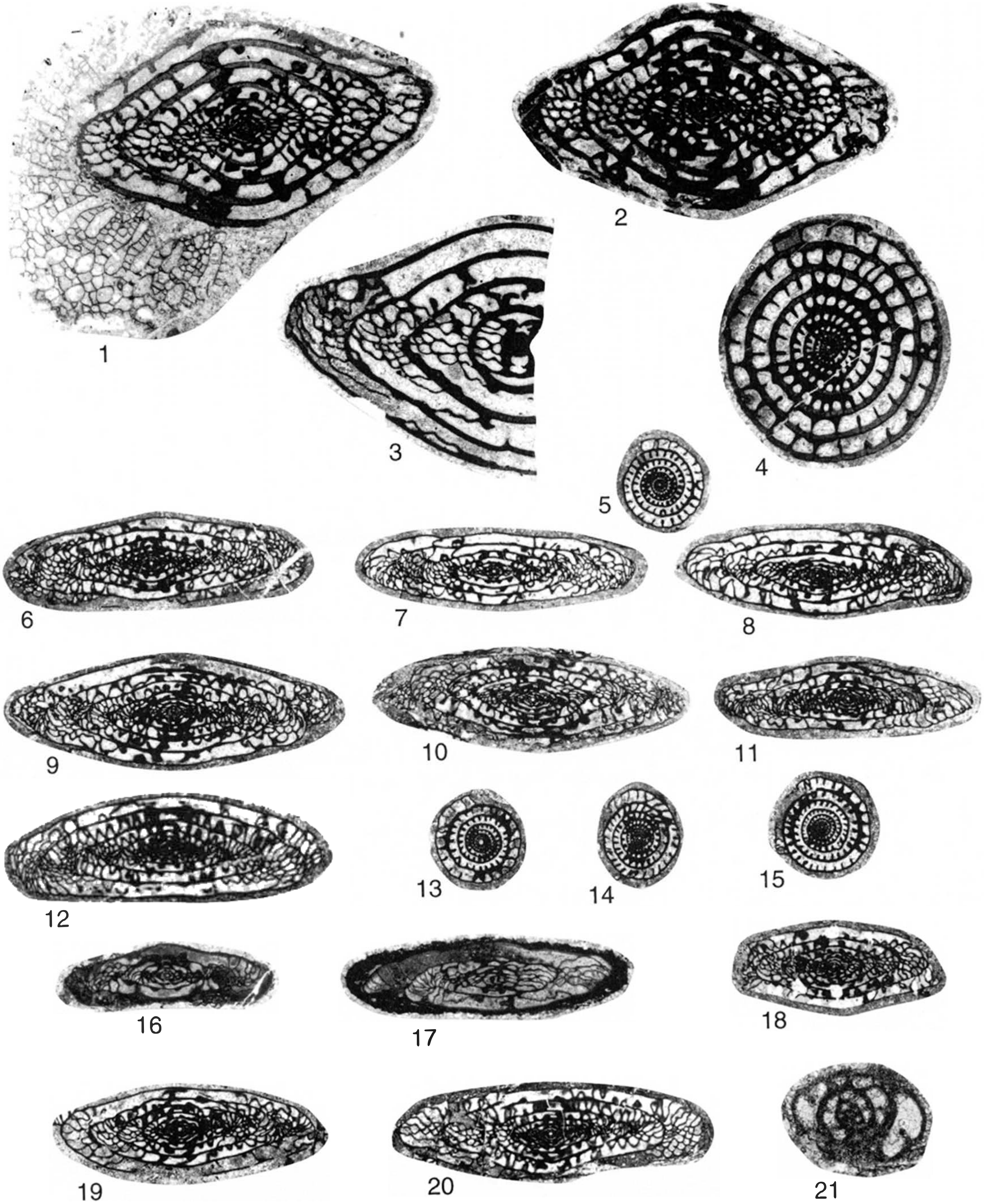

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

PLATE 8—Desmoinesian fusulinids from the Alamitos and Porvenir Formations at stratigraphic section H, (Fig. 87), Manuelitas Creek southeast of Rociada. (Unretouched photographs, x 10, except where indicated)

Figures

1–4 USGS f10144. *Beedeina sulphurensis* (Ross and Sabins), 1965. Slides 5, 12, 13, 10; USNM 486103, 486104, 486105, 486106.

5–8 USGS f10143. *Beedeina* cf. *B. sulphurensis* (Ross and Sabins), 1965. Slides 7, 3, 6, 4; USNM 486107, 486108, 486109, 486110.

9–12 USGS f10142. *Beedeina* aff. *B. sulphurensis* (Ross and Sabins), 1965. Slides 3, 1, 6, 8; USNM 486111, 486112, 486113, 486114.

13–16 USGS f10141. *Beedeina* aff. *B. rockymontana* (Roth and Skinner), 1930. Slides 2, 4, 7, 5; USNM 486115, 486116, 486117, 486118.

17, 18 USGS f10140. *Beedeina* aff. *B. rockymontana* (Roth and Skinner), 1930. Slides 8, 6; USNM 486119, 486120.

19, 20 USGS f10140. *Frumentella*? sp. (x 50). Slides 10, 9; USNM 486121, 486122.

21–24 USGS f10139. *Beedeina* aff. *B. arizonensis* (Ross and Sabins), 1965. Slides 7, 1, 6, 8; USNM 486123, 486124, 486125, 486126.

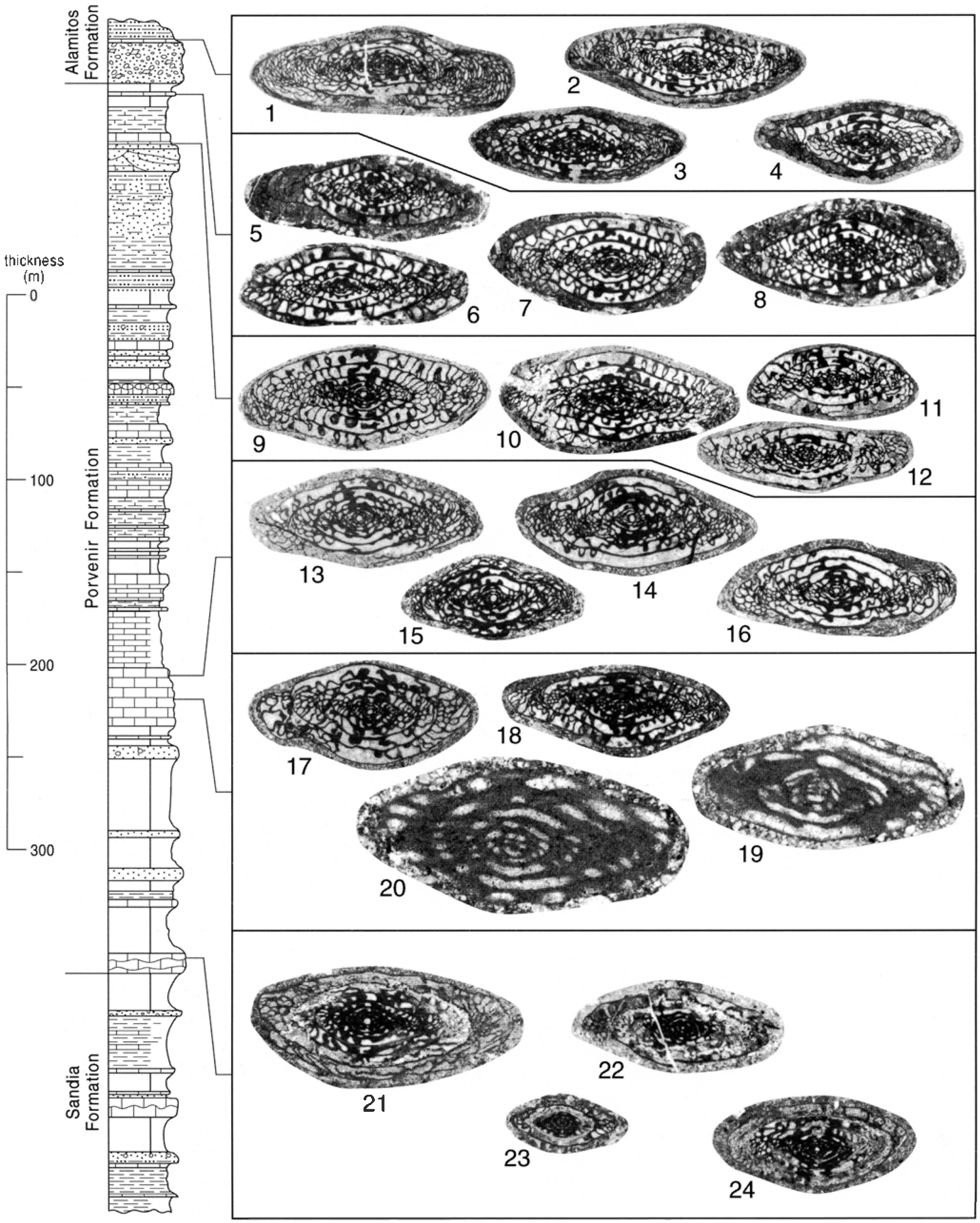

Alamitos Formation
Porvenir Formation
Sandia Formation
thickness (m)
0
100
200
300
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

PLATE 9—Desmoinesian fusulinids from the lower part of the Alamitos Formation and the type section of the Porvenir Formation at stratigraphic section D, (Fig. 81), Johnson Mesa road. (Unretouched photographs, x 10)

Figures

1–4 USGS f10124. *Beedeina sulphurensis* (Ross and Sabins), 1965. Slides 5, 2, 1, 4; USNM 486127, 486128, 486129, 486130.

5–8 USGS f10123. *Beedeina* aff. *B. sulphurensis* (Ross and Sabins), 1965. Slides 5, 1, 3, 7; USNM 486131, 486132, 486133, 486134.

9–11 USGS f10122. *Beedeina* sp. Slides 2, 1, 3; USNM 486135, 486136, 486137.

12–14 USGS f10127. *Beedeina* aff. *B. rockymontana* (Roth and Skinner), 1930. Slides 12, 4, 3; USNM 486138, 486139, 486140.

15–18 USGS f10126. *Beedeina* aff. *B. apachensis* (Ross and Sabins), 1965. Slides 6, 1, 2, 3; USNM 486141, 486142, 486143, 486144.

19–21 USGS f10125. *Beedeina* cf. *B. insolita* (Thompson), 1948. Slides 4, 6, 5; USNM 486145, 486146, 486147.

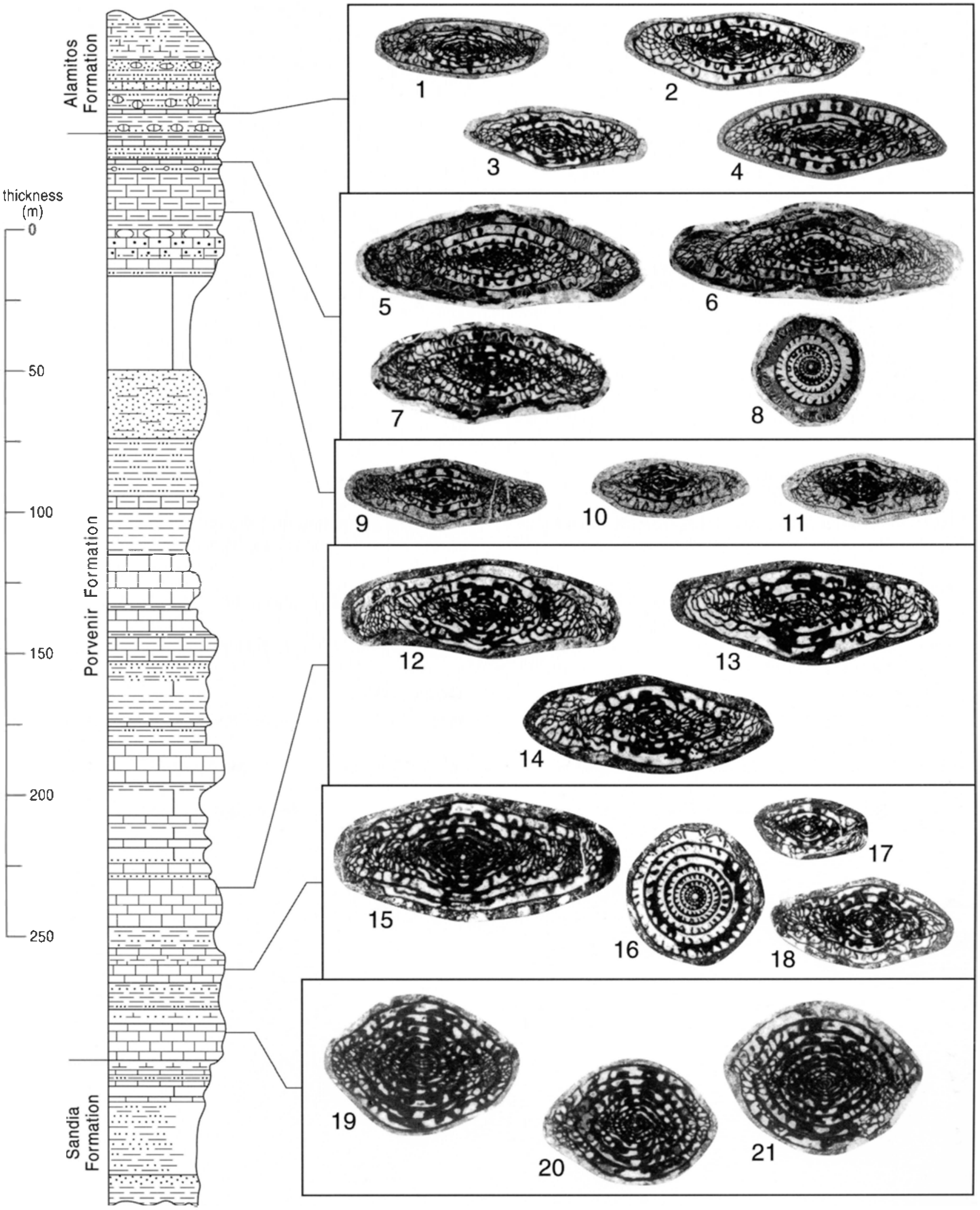

Alamitos Formation
thickness (m)
0
50
100
150
200
250
Porvenir Formation
Sandia Formation
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

PLATE 10—Desmoinesian fusulinids from the Alamitos and Porvenir Formations at stratigraphic section K, (Fig. 89), north side of Mora River. (Unretouched photographs, x 10 except where indicated)

Figures

1–3 USGS f10121. *Beedeina acme* (Dunbar and Henbest), 1942. Slides 1,2,3; USNM 486148, 486149, 486150.

4, 6 USGS f10149. *Beedeina* aff. *B. rockymontana* (Roth and Skinner), 1930. Slides 9, 6; USNM 486151, 486152.

5 USGS f10149. *Wedekindellina* sp. Slide 7; USNM 486153.

7 USGS f10149. *Beedeina*? sp. Probably reworked from older beds. Slide 7; USNM 486154.

8–12 USGS f10148. *Beedeina* aff. *B. joyitaensis* Stewart, 1970. Slides 1, 4, 3, 2, 5; USNM 486155, 486156, 486157, 486158, 486159.

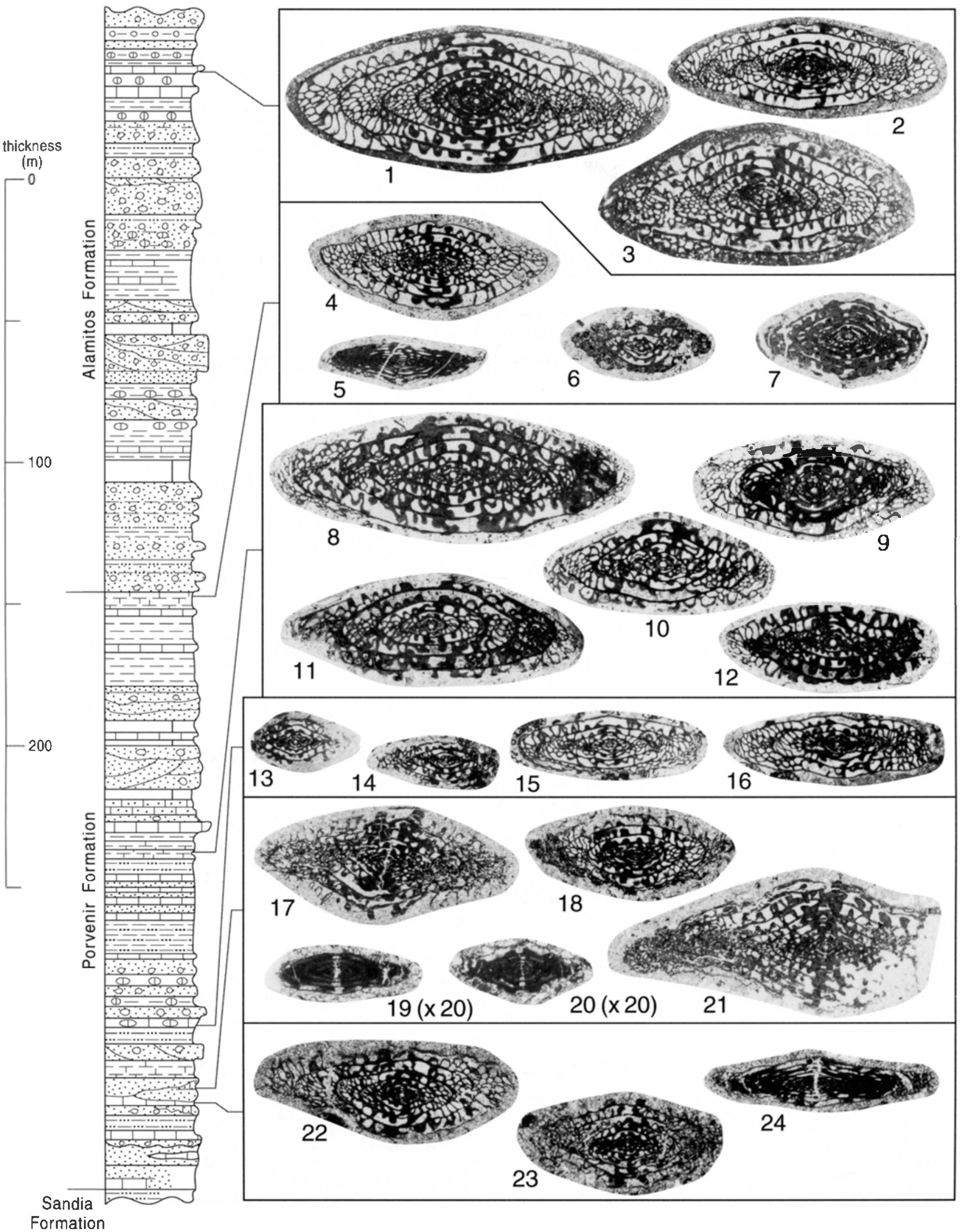
13–16 USGS f10147. *Beedeina* aff. *B. socorroensis* (Needham), 1937. Slides 1, 2, 3, 4; USNM 486160, 486161, 486162, 486171.

17, 18, 21 USGS f10146. *Beedeina* cf. *B. novamexicana* (Needham), 1937. Slides 4, 3, 2; USNM 486163, 486164, 486165.

19, 20 USGS f10146. *Wedekindellina* sp. (x 20). Slides 7, 5; USNM 486166, 486167.

22, 23 USGS f10133. *Beedeina* sp. Slides 6, 4; USNM 486168, 486169.

24 USGS f10133. *Wedekindellina* cf. *W. coloradoensis* Roth and Skinner, 1930. Slide 2; USNM 486170.



thickness
(m)
0
100
200
Alamitos Formation
Porvenir Formation
Sandia
Formation
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19 (x 20)
20 (x 20)
21
22
23
24

PLATE 11—Desmoinesian fusulinids and miscellaneous fossils from the Porvenir Formation at stratigraphic section K, (Fig. 89), Mora River. (Unretouched photographs, x 10)

Figures

1	USGS f10149. Fecal(?) pellets in a brachiopod shell from near the top of the Porvenir Formation. Slide 5; USNM 486172.
2	USGS f10147. *Beedeina* sp. accreted around a subcylindrical object. The object probably is a filled burrow. Section cut normal to the long axis. Slide 5; USNM 486173.
3, 4	USGS f10145. *Beedeina* cf. *B. pattoni* (Needham), 1937. Slides 1, 2; USNM 486174, 486175.
5	USGS f10145. *Wedekindellina* sp. Slide 3; USNM 486176.
6–8	USGS f10135. *Beedeina* aff. *B. arizonensis* (Ross and Sabins), 1965. Slides 2, 3, 4; USNM 486177, 486178, 486179.
9, 10	USGS f10135. *Wedekindellina excentrica* Roth and Skinner, 1930. Slides 8, 9; USNM 486180, 486181.

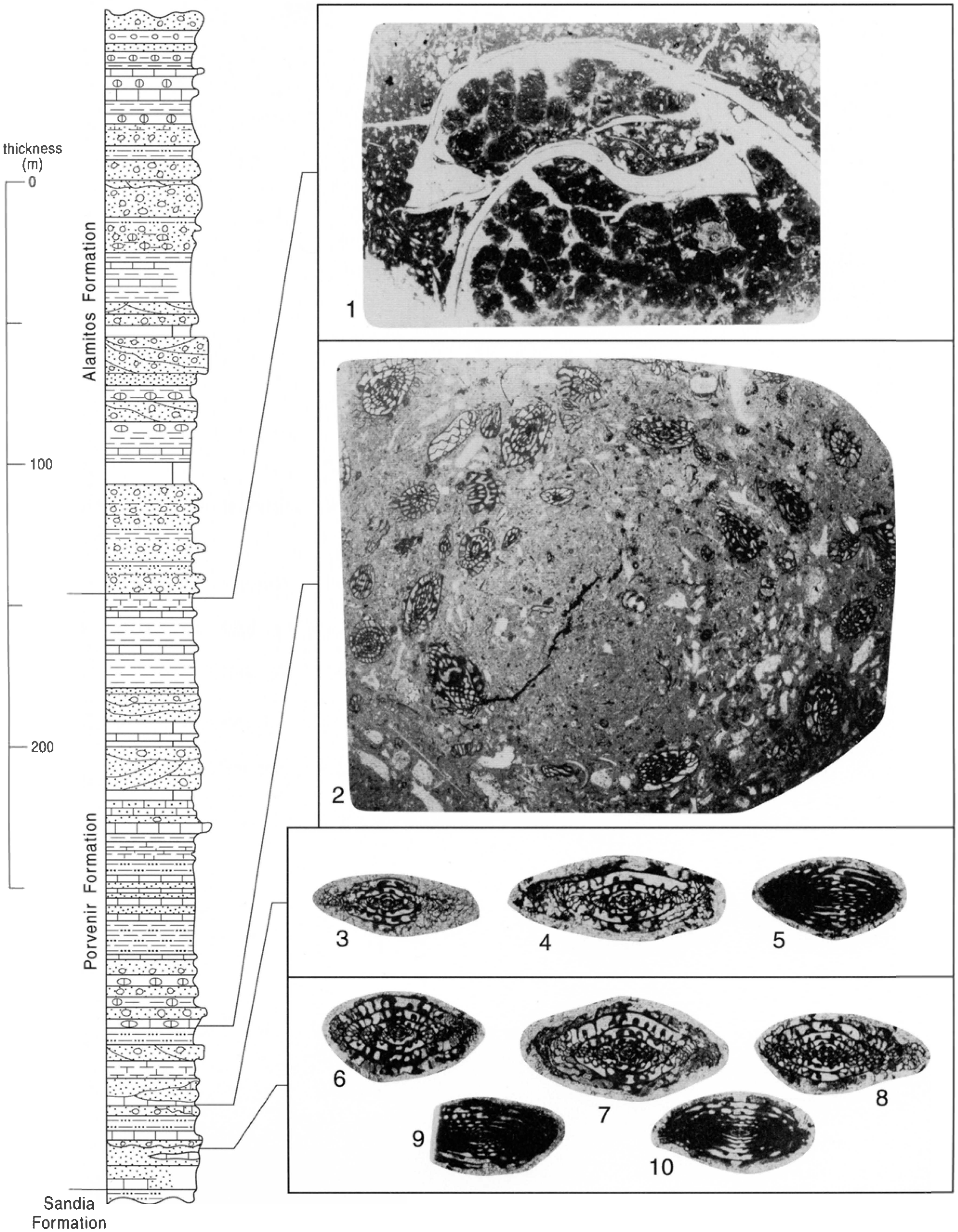

thickness
(m)
0
100
200
Alamitos Formation
Porvenir Formation
Sandia
Formation
1
2
3
4
5
6
7
8
9
10

PLATE 12—Miscellaneous Desmoinesian and Atokan fusulinids. (Unretouched photographs, x 10, except where indicated)

Figures

1–5	USGS f10134. *Beedeina acme* (Dunbar and Skinner), 1942. Slides 1, 10, 14, 9, 6; USNM 486182, 486183, 486184, 486185, 486186. Alamitos Formation. Desmoinesian.
6–9	USGS f13217. *Beedeina* sp. Slides 3, 4, 1, 2; USNM 486187, 486188, 486189, 486190. Porvenir Formation. Desmoinesian.
10	USGS f10136. *Beedeina* sp. Slide 1; USNM 486191. Alamitos Formation. Desmoinesian.
11, 12	USGS f10136. *Plectofusulina* sp. (x50). Slides 2, 1; USNM 486192, 486193. Alamitos Formation. Desmoinesian.
13–16	USGS f10137. *Fusulinella* aff. *F. dosensis* Ross and Sabins, 1965. Slides 1, 2, 6, 3; USNM 486210, 486194, 486195, 486196. Porvenir Formation. Desmoinesian.
17	USGS f10137. *Wedekindellina*? sp. Slide 5; USNM 486197. Porvenir Formation. Desmoinesian.
18–21	USGS f10131. *Fusulinella* aff. *F. oakensis* Ross and Sabins, 1965. Slides 5, 6, 2, 4; USNM 486198, 486199, 486200, 486201. Porvenir Formation. Early Desmoinesian or late Atokan.
22–25	USGS f10132. *Fusulinella* aff. *F. juncea* Thompson, 1948. Slides 1, 5, 9, 6; USNM 486202, 486203, 486204, 486205. Sandia Formation. Atokan.
26–29	USGS f13150. *Fusulinella* sp. Slides 2, 1, 3, 4; USNM 486206, 486207, 486208, 486209. Sandia Formation. Atokan.

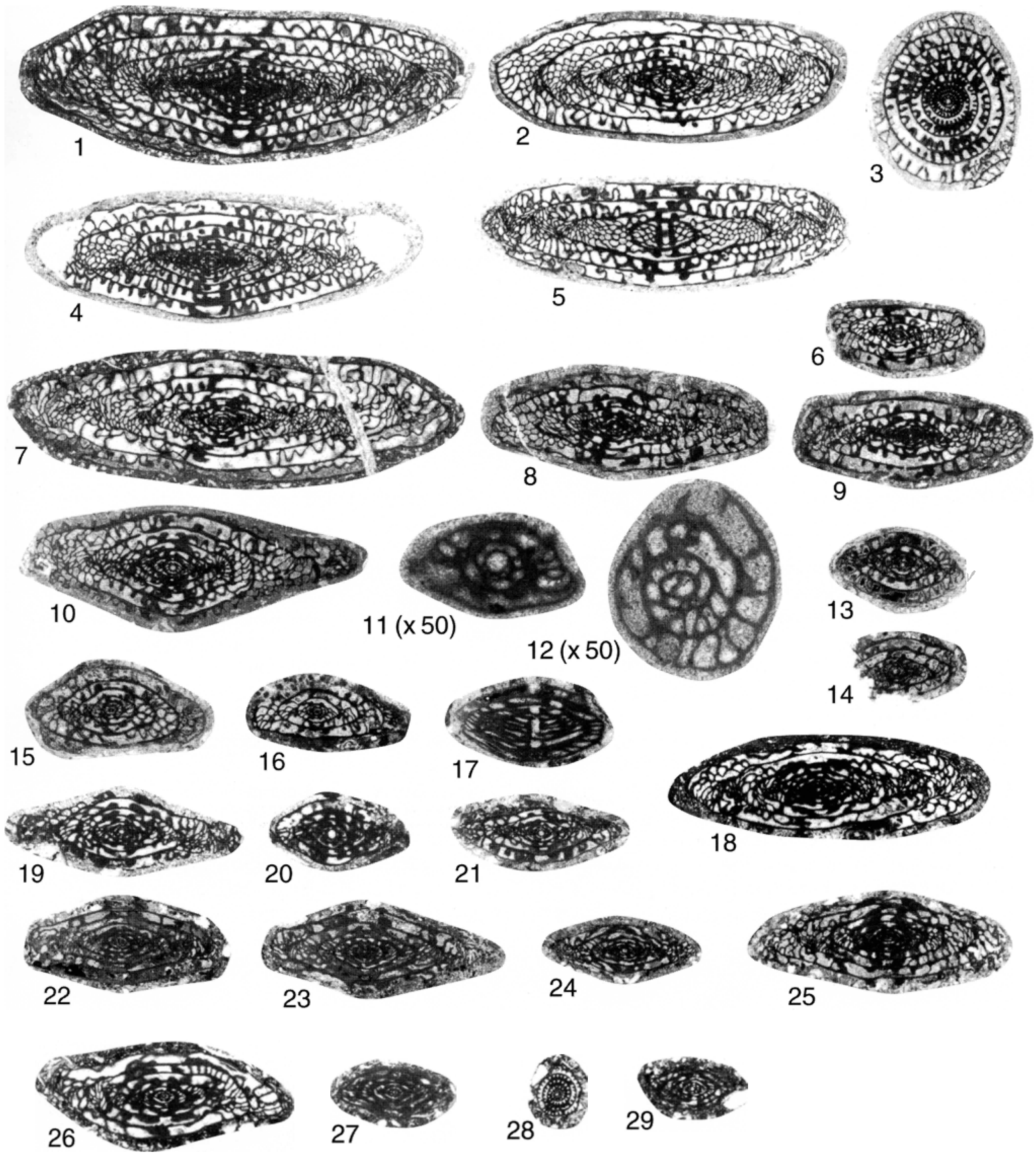

1
2
3
4
5
6
7
8
9
10
11 (x 50)
12 (x 50)
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29

PLATE 13—Miscellaneous Pennsylvanian and Early Permian fusulinids. (Unretouched photographs, x 10 except where indicated)

Figure	
1–4	USGS f10327. *Triticites (Leptotriticites)* sp. Slides 3, 6, 5, 1; USNM 486211, 486212, 486213, 486214. Alamitos Formation. Wolfcampian.
5–9	USGS f10275. *Triticites (Leptotriticites)* sp. Slides 1, 19, 17, 7, 15; USNM 486215, 486216, 486217, 486218, 486219. Alamitos Formation. Wolfcampian.
10, 11	USGS f10278. *Triticites* cf. *T. creekensis* Thompson, 1954. Slides 5, 11; USNM 486220, 486221. Alamitos Formation. Wolfcampian.
12–15	USGS f10277. *Triticites* aff. *T. coronadoensis* Ross and Tyrrell, 1965. Slides 4, 3, 7, 5; USNM 486222, 486223, 486224, 486225. Alamitos Formation. Virgilian.
16, 17	USGS f10151. *Beedeina* sp. Slides 3, 4; USNM 486226, 486227. Porvenir Formation. Early Desmoinesian.
18, 19	USGS f10151. *Plectofusulina* sp. (x 50). Slides 12, 9; USNM 486228, 486229. Porvenir Formation. Early Desmoinesian.
20–22	USGS f10150. *Beedeina* aff. *B. portalensis* (Ross and Sabins), 1965. Slides 7, 8, 2; USNM 486230, 486231, 486232. Porvenir Formation. Early Desmoinesian.
23–25	USGS f10150. *Plectofusulina* sp. (x 50). Slides 14, 17, 12; USNM 486233, 486234, 486235. Porvenir Formation. Early Desmoinesian.

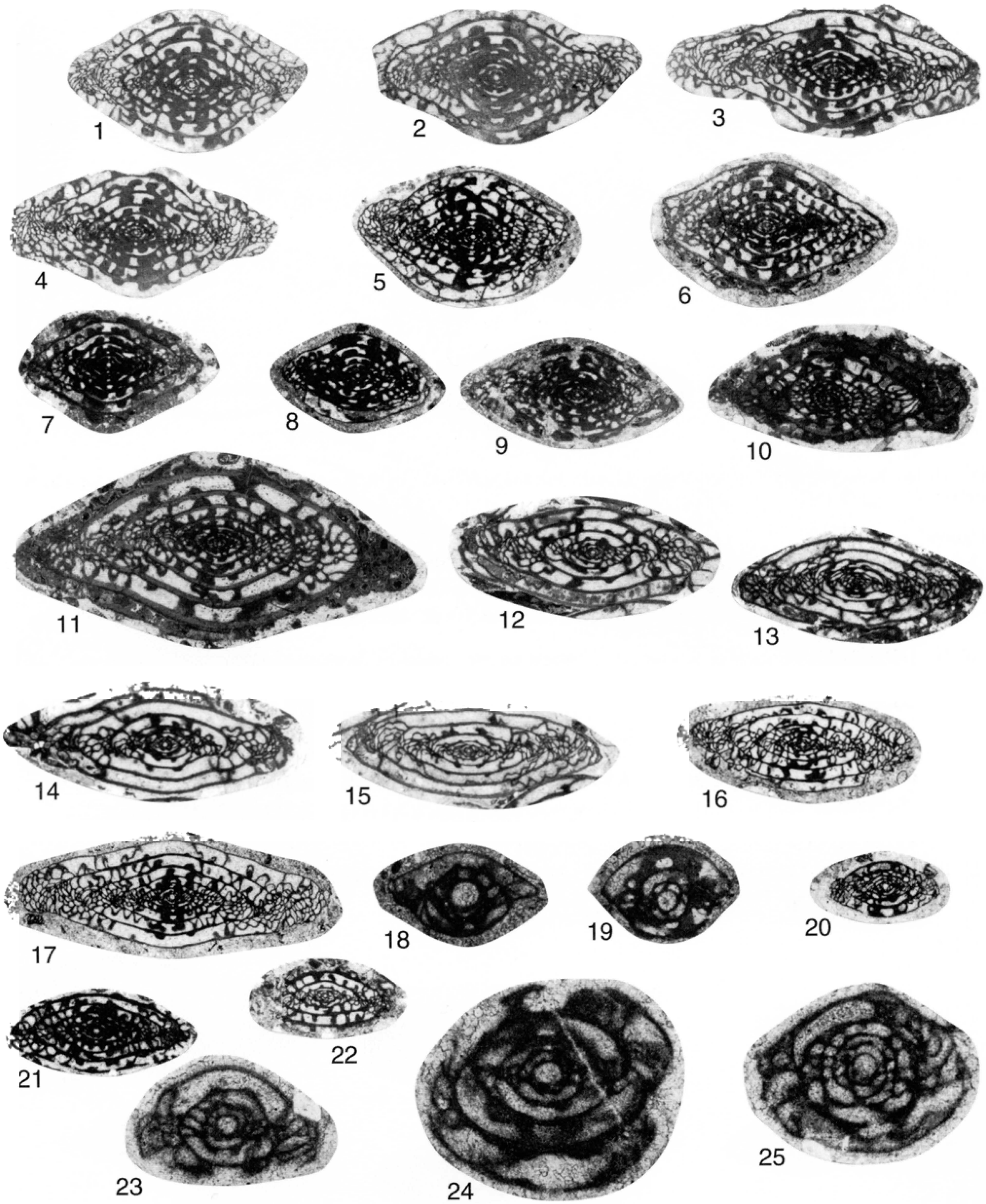
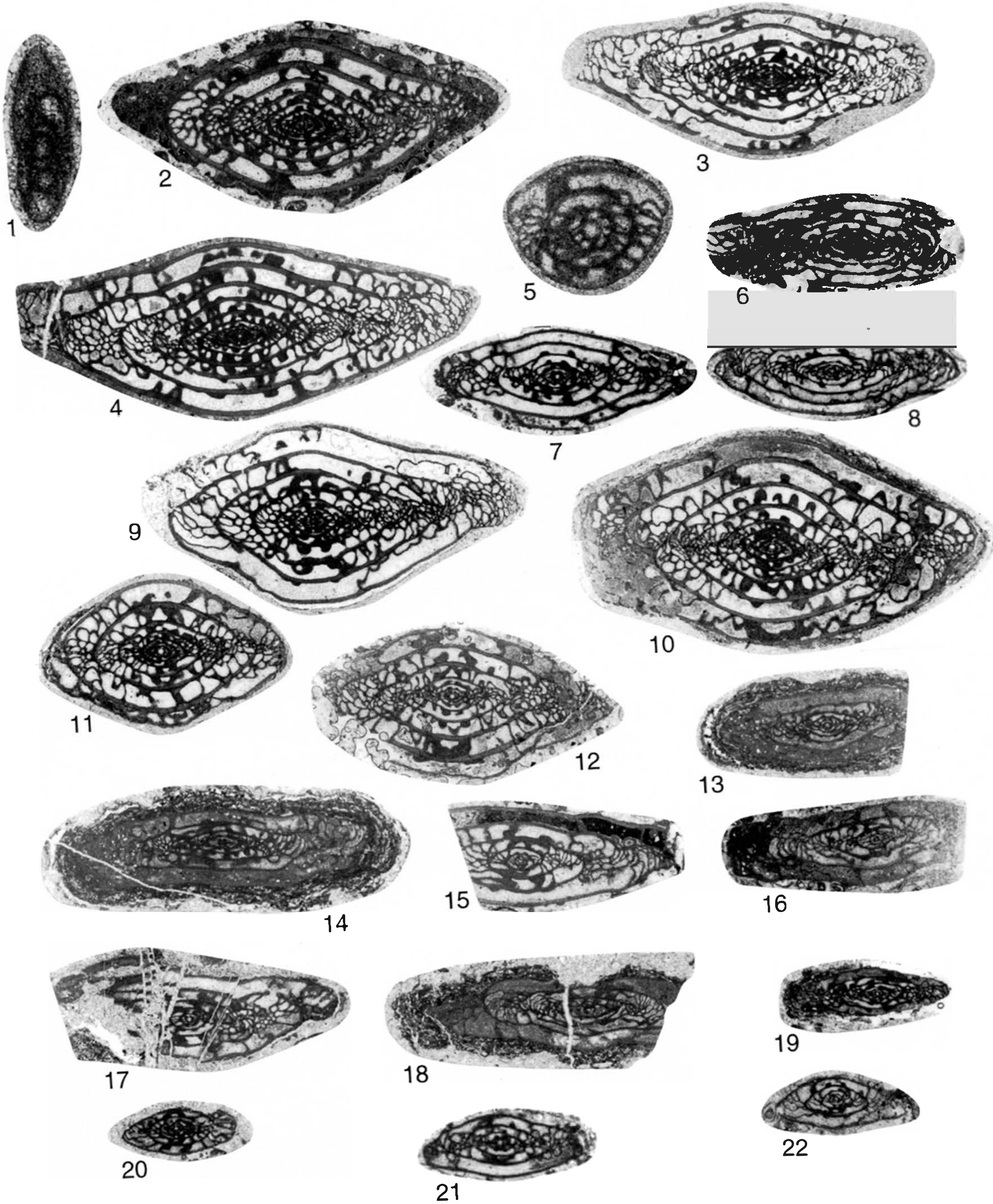

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

PLATE 14—Early Permian and Late Pennsylvanian fusulinids from Alamitos Formation. (Unretouched photographs, x 10 except where indicated)

Figures	
1	USGS f10275. *Ozawainella* sp. (x 100). Slide 29; USNM 486236. Wolfcampian.
2	USGS f10278. *Triticites creekensis* Thompson, 1954. Slide 4; USNM 486221. Wolfcampian.
3, 4	USGS f10320. *Triticites* aff. *T. whetstonensis* Ross and Tyrrell, 1965. Slides 1, 3; USNM 486237, 486238. Virgilian.
5	USGS f10320. *Oketaella* sp. (x 50). Slide 5; USNM 486239. Virgilian to Wolfcampian.
6–8	USGS f10277. *Triticites* aff. *T. coronadoensis* Ross and Tyrrell, 1965. Slides 2, 7, 5; USNM 486240, 486224, 486225. Virgilian.
9–12	USGS f10319. *Triticites bensonensis* Ross and Tyrrell, 1965. Slides 7, 5, 4, 1; USNM 486241, 486242, 486243, 486244. Virgilian.
13, 14	USGS f10322. *Triticites* aff. *T. ohioensis* Thompson, 1936. Slides 2, 3; USNM 486245, 486246. Missourian.
15, 16	USGS f10328. *Triticites* cf. *T. ohioensis* Thompson, 1936. Slides 2, 3; USNM 486247, 486248. Missourian.
17–20	USGS f10321. *Triticites* cf. *T. ohioensis* Thompson, 1936. Slides 4, 1, 3, 2; USNM 486249, 486250, 486251, 486252. Missourian.
21, 22	USGS f10323. *Triticites* aff. *T. celebroides* Ross, 1965. Slides 3, 1; USNM 486253, 486254. Missourian.


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

Selected conversion factors*

TO CO VERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, μm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-2}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{-1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	
U.S. gallons, gal	3.785	
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{-3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}

TO CO VERT	MULTIPLY BY	TO OBTAI
Pressure, stress		
lb in^{-2} (=lb/in^2), p i	7.03×10^{-2}	kg cm^{-2} (kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{-2}	mm of Hg (at 0°C)
inches of Hg (at 0°C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	$m^2 sec^{-1}$
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British th rmal units BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahr nheit)
°F - 32	5/9	°C (Celsius)

Divide by the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929

Editor ancy Gilson

Drafter: Rebecca J. Titus

Typeface: Palatino

Binding: Smythe sewn

Paper: Cover on 17-pt. linen finish
Text on 70-lb White Matte

Ink: Cover—4-color process
Text—Black

Quantity: 1,000

CONTENTS OF POCKET

Plates 6–14 begin on page 253.