

MEMOIR 20

Biostratigraphy and Carbonate Facies
of the Mississippian Arroyo Peñasco
Formation, North—Central New Mexico

by AUGUSTUS K. ARMSTRONG

1967

STATE BUREAU OF MINES AND MINERAL RESOURCES NEW
MEXICO INSTITUTE OF MINING AND TECHNOLOGY
CAMPUS STATION

SOCORRO, NEW MEXICO

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2. Mississippian correlation chart B-B'	In pocket

Abstract

The Late Osage to Meramec Arroyo Peñasco Formation, 0 to 130 feet thick, rests on a peneplained surface of Precambrian rocks and is overlain unconformably by sediments of Pennsylvanian age. The Arroyo Peñasco Formation crops out in the San Pedro, Nacimiento, Jemez, Sandia, Manzanita, Manzano, and Sangre de Cristo mountains of north-central New Mexico.

The basal unit, 2 to 60 feet thick, is transgressive and is composed of quartz conglomerate, sandstone, and thin shale. Three incomplete carbonate depositional cycles were recognized. The lowest, Cycle 1, consists of dolomite, dedolomite, and coarse-grained poikilotopic calcite with corroded dolomite rhombs. These rocks contain gray nodular chert with a microfauna of Late Osage age: *Endothyra spinosa* Chernysheva, *E. skippeae* n. sp., and *Septabrunsiina parakrainica* Skipp, Holcomb, and Gutschick. The sediments of the earliest cycle show initial deposition as shallow-marine lime mudstone followed by stromatolitic intertidal to supratidal carbonate rocks.

Cycle 2 is shallow-marine to intertidal echinoderm wackestone to lime mudstone and dolomite containing a sparse

fauna of *Endothyra* aff. *E. spinosa* Chernysheva, *Endothyra* aff. *E. irregularis* (Zeller), *E. irregularis* (Zeller), and *Endothyra spiroides* Zeller of Early Meramec age.

Cycle 3 is shallow-marine to arenaceous oolitic to ooid-echinoderm packstone ending as subtidal lime mudstone to intertidal dolomite. The ooid facies contains a rich microfauna of Early to Middle Meramec age: *Endothyra prodigiosa* Armstrong, *E. macra* Zeller, *E. irregularis* (Zeller), *Endothyra* aff. *E. omphalota* Rauser—Cernousova and Reitlinger, and *Tournayella* sp.

Late Mississippian and Early Pennsylvanian uplift and erosion resulted in extensive erosion and removal of the Arroyo Peñasco Formation. A solution limestone collapse breccia, 5 to 30 feet thick, rests on a smooth surface of stromatolite dedolomite in the Sangre de Cristo Mountains. The breccia resulted from movement of meteoric ground waters in Late Mississippian or Early Pennsylvanian time. These dissolved a 5- to 30-foot-thick gypsum bed and caused subsequent collapse of adjacent overlying Lower Meramec carbonate rocks. Solution activity was extensive, and sinkholes developed.

Introduction

This study, hopefully, will provide a regional understanding of the biostratigraphic and facies relationship of the Mississippian strata in north-central New Mexico with the Leadville Limestone of the San Juan Basin and the San Juan Mountains of Colorado and the Mississippian carbonate rocks of south-central and southern New Mexico.

The known outcrops of Mississippian strata in north-central New Mexico (fig. 1) were examined and measured, and lithologic and micropaleontologic samples were collected at five-foot intervals (table 1).

The Mississippian and Devonian rocks of the San Juan Mountains of southwestern Colorado were examined and two sections carefully measured and studied: the classical section at Rockwood Quarry above Durango and the section at Davis' Creek in the Piedra River Canyon. The Kelly and Caloso Formations in the southern Ladron Mountains were also sampled and studied in thinsections.

All shale samples were treated with sodium bicarbonate, washed and screened, and then 'picked' under a binocular microscope for microfossils. A number of carbonate-rock suites were dissolved in formic acid, screened, and separated in heavy liquids for conodonts. The lithologic samples were cut for petrographic thinsections that were made for carbonate and foraminifera studies.

Both thinsections and polished slabs were used in chemical

staining techniques; the stains were those described by Friedman (1959). Alizarin Red S was employed for calcite, potassium ferrocyanide for iron-rich dolomite, and ammonium sulfide and copper sulfate for ankerite.

The thinsections made for this study are deposited with the New Mexico Bureau of Mines and Mineral Resources at Socorro, New Mexico. The thinsection suites for Peñasco Canyon, Nacimiento Mountains, and southern Ladron Mountains were made by Shell Oil Company and are in its paleontologic collection at the district office in Farmington, New Mexico.

The classification of carbonate rocks used is Dunham's (1962). Table 2 gives a brief outline of his classification.

The initial phase in the study of the Mississippian strata of north-central New Mexico was to develop regional biostratigraphic relationships. The most abundant group of time-significant fossils within these carbonate rocks is the foraminifera.

When biostratigraphic relationships were apparent, a detailed examination of the carbonate rocks was begun, including field studies of depositional structures and microscopic investigation of rock types, textures, and diagenetic changes. This was in conjunction with micropaleontologic studies and resulted in the construction of a carbonate depositional model for the Mississippian System of north-central New

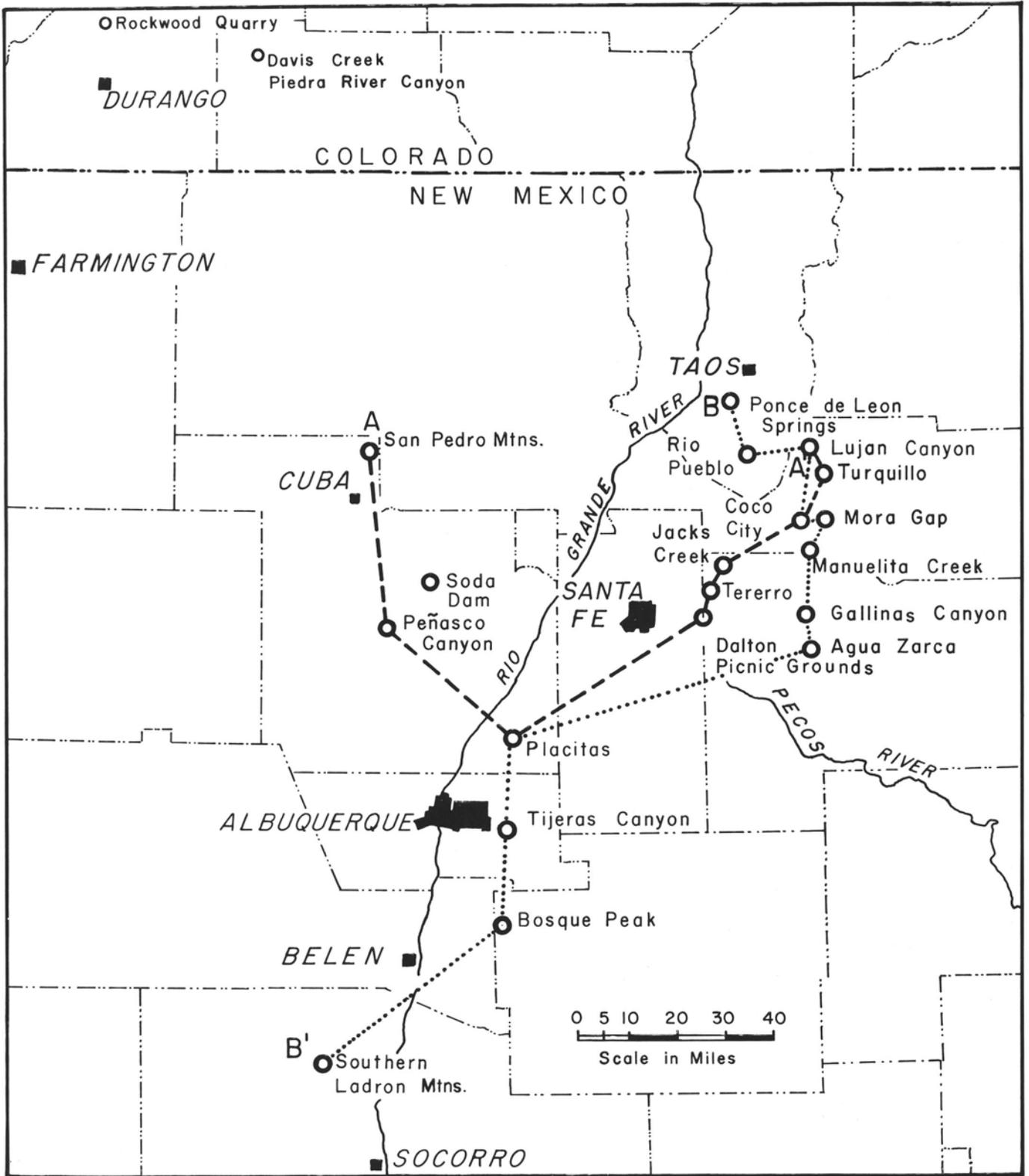


Figure 1

INDEX MAP OF NORTHERN NEW MEXICO AND LOCATION OF MEASURED SECTIONS

TABLE 1. CODE NUMBER OF MEASURED SECTIONS AND THE SAMPLES COLLECTED FROM WHICH THINSECTIONS HAVE BEEN MADE

LOCATION	N. MEX. BUR. MINES & MIN. RES. NOS.	SHELL OIL CO. FARMINGTON N. MEX. DIST. PALEO COLLECTIONS
Nacimiento Mountains		
Peñasco & Piños canyons	NM 66A-2	SO-PC-1 to 35
San Pedro Mountains	NM 65A-11	
Jemez Mountains		
Soda Dam	NM 65A-20	
Sangre de Cristo Mountains		
Ponce de Leon Springs	NM 65A-2	
Rio Pueblo	NM 65A-4	
Lujan Canyon	NM 65A-5	
Turquillo	NM 65A-16	
Coco City	NM 65A-17	
Mora Gap	NM 65A-6	
Manuelitas Creek Gap	NM 65A-7	
Gallinas Canyon	NM 65A-8	
Agua Zarca	NM 65A-9	
Jacks Creek	NM 65A-14	
Tererro	NM 65A-15	
Dalton Picnic Grounds	NM 65A-13	
Sandia Mountains		
Placitas	NM 65A-1	
Manzanita Mountains		
Tijeras Canyon	NM 66A-1	
Manzano Mountains		
Bosque Peak	NM 66A-3	
Southern Ladron Mountains	NM 63A-1	SO-K & C

Mexico as well as showing relationship of these strata to the Mississippian strata of southwestern Colorado and southern New Mexico.

ACKNOWLEDGMENTS

The New Mexico Bureau of Mines and Mineral Resources helped defray field expenses and paid for making the thinsections. It is a special pleasure to acknowledge the stimulation received from Dr. Frank E. Kottlowski, Bureau staff, who followed this study with much interest. Discussions with Dr. James Lee Wilson, Rice University, about recent and ancient carbonate sedimentation and techniques of carbonate studies have been of great value and strengthened my faith in the ecologic interpretations presented in this report. Dr. Robert Walpole and Jerry Lucia, Shell Development Corporation, gave much needed help in the

unraveling of the "dedolomite and gypsum" problems. Lee Holcomb, senior paleontologist, Shell Oil Company, spent many hours discussing and sharing with me his extensive knowledge of Mississippian foraminifera; he examined the foraminifera material. Drs. Kottlowski and Wilson critically reviewed the manuscript.

I also wish to express to my wife, Shirley, gratitude for initial typings of the manuscript and to Mrs. Lois Devlin and Mrs. Cheryl LePlatt, of the Bureau staff, appreciation for the final typings.

PREVIOUS STUDIES

Read et al. (1944) recognized the distinctness of these rocks in north-central New Mexico and mapped them as the lower limestone member of the Sandia Formation, Magdalen Group, Pennsylvanian age. They suggested a pre-

TABLE 2. CLASSIFICATION OF CARBONATE ROCKS ACCORDING TO DEPOSITIONAL TEXTURE

DEPOSITIONAL TEXTURE RECOGNIZABLE				Original components were bound together during deposition. . . as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices	DEPOSITIONAL TEXTURE NOT RECOGNIZABLE
Original Components Not Bound Together During Deposition			Lacks mud and is grain-supported		<i>Crystalline carbonate</i> (Subdivide according to classifications designed to bear on physical texture or diagenesis)
Contains mud (particles of clay and fine silt size)		Grain-supported			
Mud-supported	More than 10 per cent grains		Less than 10 per cent grains		
<i>Mudstone</i>	<i>Wackestone</i>	<i>Packstone</i>	<i>Grainstone</i>		

Pennsylvanian age for this member. The lower gray limestone member was described by Wood and Northrop (1946) in the Nacimiento and San Pedro mountains and by Northrop et al. (1946) in the southeastern foothills of the Sangre de Cristo Mountains.

Armstrong (1955) reported a Meramec endothyrid fauna in outcrops of the lower gray limestone and proposed the name *Arroyo Peñasco Formation* (type section Peñasco and Pinos canyons, Nacimiento Mountains; see fig. 24). Fitzsimmons, Armstrong, and Gordon (1956) listed a fauna of mega-fossils from the exposure of the Arroyo Peñasco Formation on the northwestern side of the San Pedro Mountains and the type section in the Nacimiento Mountains. Armstrong (1958a) published a systematic description of the major elements of the Meramec endothyrid fauna of the Arroyo Peñasco Formation. He demonstrated that the Meramec endothyrid fauna at the type section in the Nacimiento Mountains and the fauna in the Sangre de Cristo Mountains contained the same species and were of the same age.

Armstrong (1955) showed that the basal carbonate rocks at Lujan Canyon, Sangre de Cristo Mountains, have a rich Meramec endothyrid fauna and later (1958a) showed that the basal part of these carbonate rocks in the southeastern Sangre de Cristo Mountains was also of probable Mississippian and possible Meramec age. Armstrong restated this view in 1962 (p. 14). Because of the discovery by Lee Holcomb (Shell Oil Company) of the *E. spinosa* Chernysheva microfauna in cherts of the lower carbonate rocks, Armstrong (1963, p. 1965, p. 133) determined the age of the Arroyo Peñasco Formation as Late Osage and Meramec.

Baltz, Wanek, and Read (1956), Baltz and Bachman (1956), and Baltz and Read (1959) rejected the concept of the Arroyo Peñasco Formation for the Sangre de Cristo Mountains as defined in the Nacimiento and San Pedro mountains. They believed these pre-Pennsylvanian, Paleozoic rocks to be Devonian(?) to Mississippian in age.

Baltz and Read (1960) formally rejected the name *Arroyo Peñasco Formation* for the Sangre de Cristo Mountains and restricted it to the Nacimiento and San Pedro mountains. They considered the pre-Pennsylvanian sandstones and carbonate rocks of the Sangre de Cristo Mountains as representing a thin but highly complex sequence of sandstones and limestones of Devonian(?) and Mississippian ages. They divided these strata into two new formations and three members (figs. 2, 3, 4, and 5). Their oldest formation, the Espiritu Santo Formation, consisting of thin sandstones and dolomitic limestones, they considered Devonian in age on the basis of stratigraphic position and lithologic similarity to rocks of Devonian age in Colorado, and they discounted (p. 1758) the endothyrids Armstrong (1955, 1958a) found in this zone by stating that "the stratigraphic range and significance of this new form (*Endothyra*) are yet to be demonstrated." They added (p. 1767) that "species of *Endothyra* are known from rocks of Late Devonian as well as Mississippian age."

Overlying their Espiritu Santo Formation, Baltz and Read believed there exists a widespread erosional unconformity followed by deposition of their Tererro Formation. The latter was divided into three members, in ascending order, Macho, Manuelitas, and Cowles (figs. 3 and 4).

Baltz and Read considered their Macho Member derived mostly from solution and collapse of the cavernous parts of the upper beds of their Devonian(?) Espiritu Santo Formation and, to a lesser degree, from collapsed breccia derived from the overlying Manuelitas Member. They assigned (p. 1766) the Macho Member a Kinderhook age. The Manuelitas Member, they believed, rested unconformably on the Macho Member, and at many places these beds were involved in collapse into large sinkholes in the Macho Member and the Espiritu Santo Formation during deposition of the Manuelitas Member. They considered the Manuelitas Member as Kinderhook to Late Osage in age. Their youngest lithologic unit, the arenaceous, Meramec, Cowles Member,

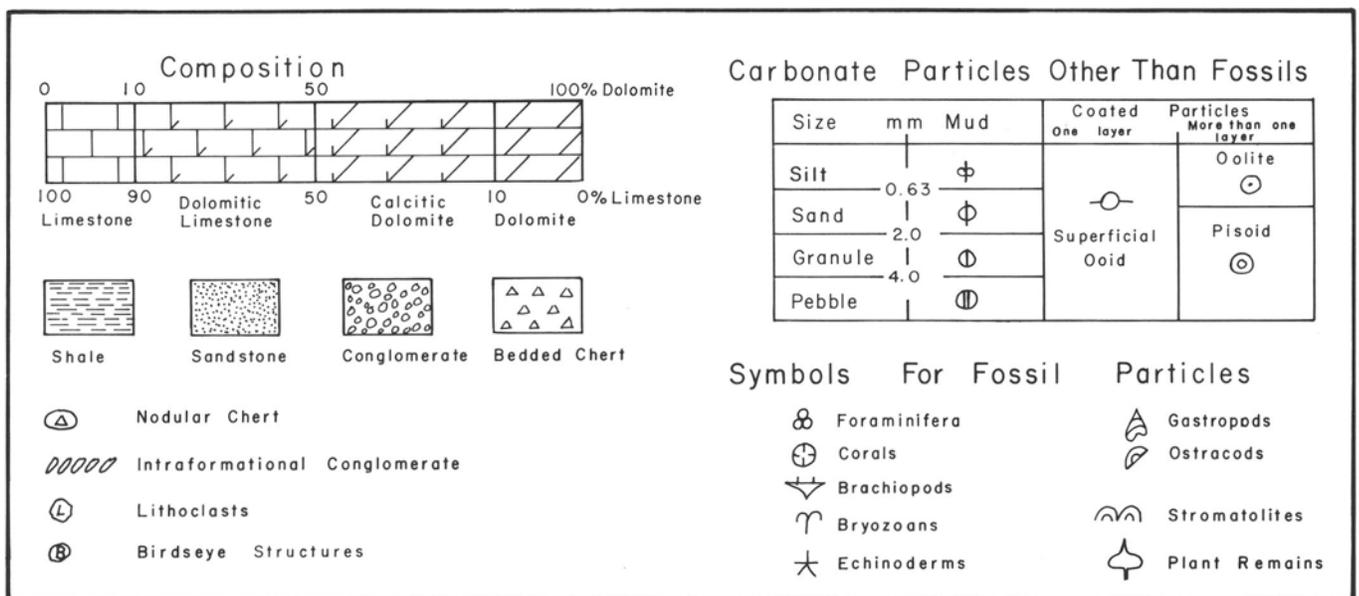


Figure 2

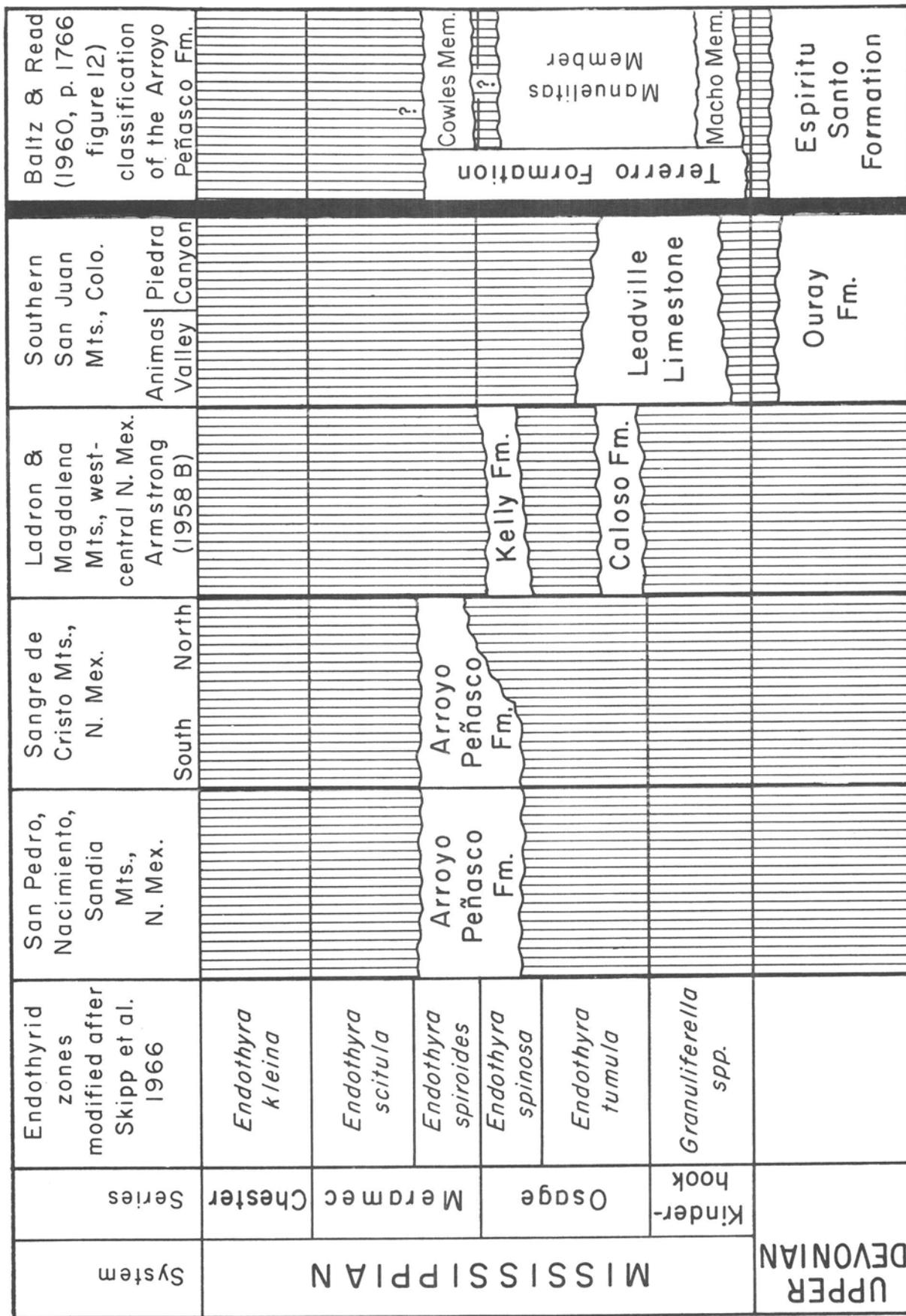


Figure 3

CORRELATION CHART OF MISSISSIPPIAN ROCKS OF NORTH-CENTRAL NEW MEXICO AND SOUTHWESTERN COLORADO

The column at the far right is Baltz and Read's (1960) classification and nomenclature of the Arroyo Peñasco Formation in the Sangre de Cristo Mountains.

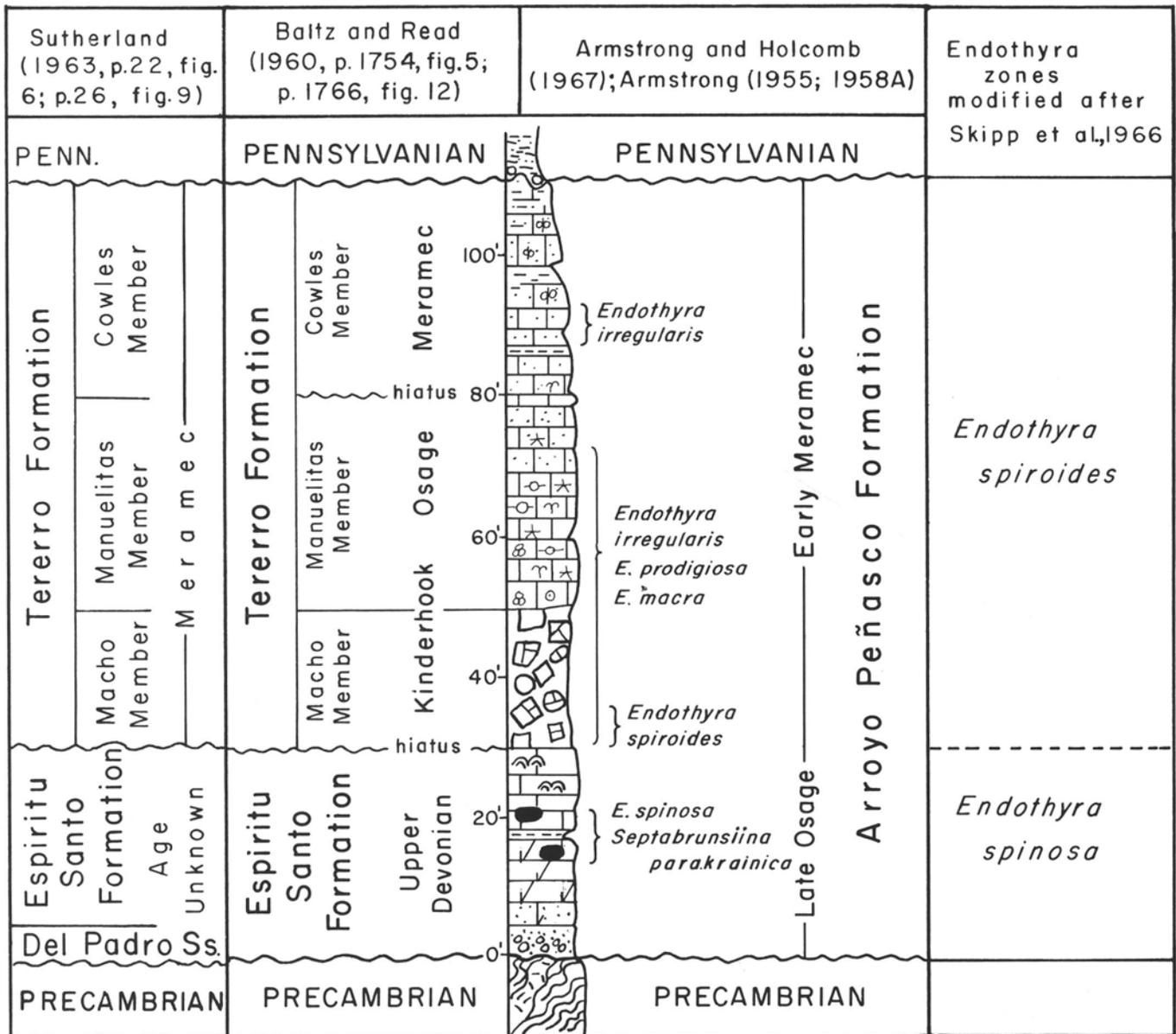


Figure 4

NOMENCLATURE, TERERRO SECTION, PECOS RIVER CANYON, SANGRE DE CRISTO MOUNTAINS

Type section for Baltz and Read's (1960) "Espirito Santo" and "Tererro Formations."

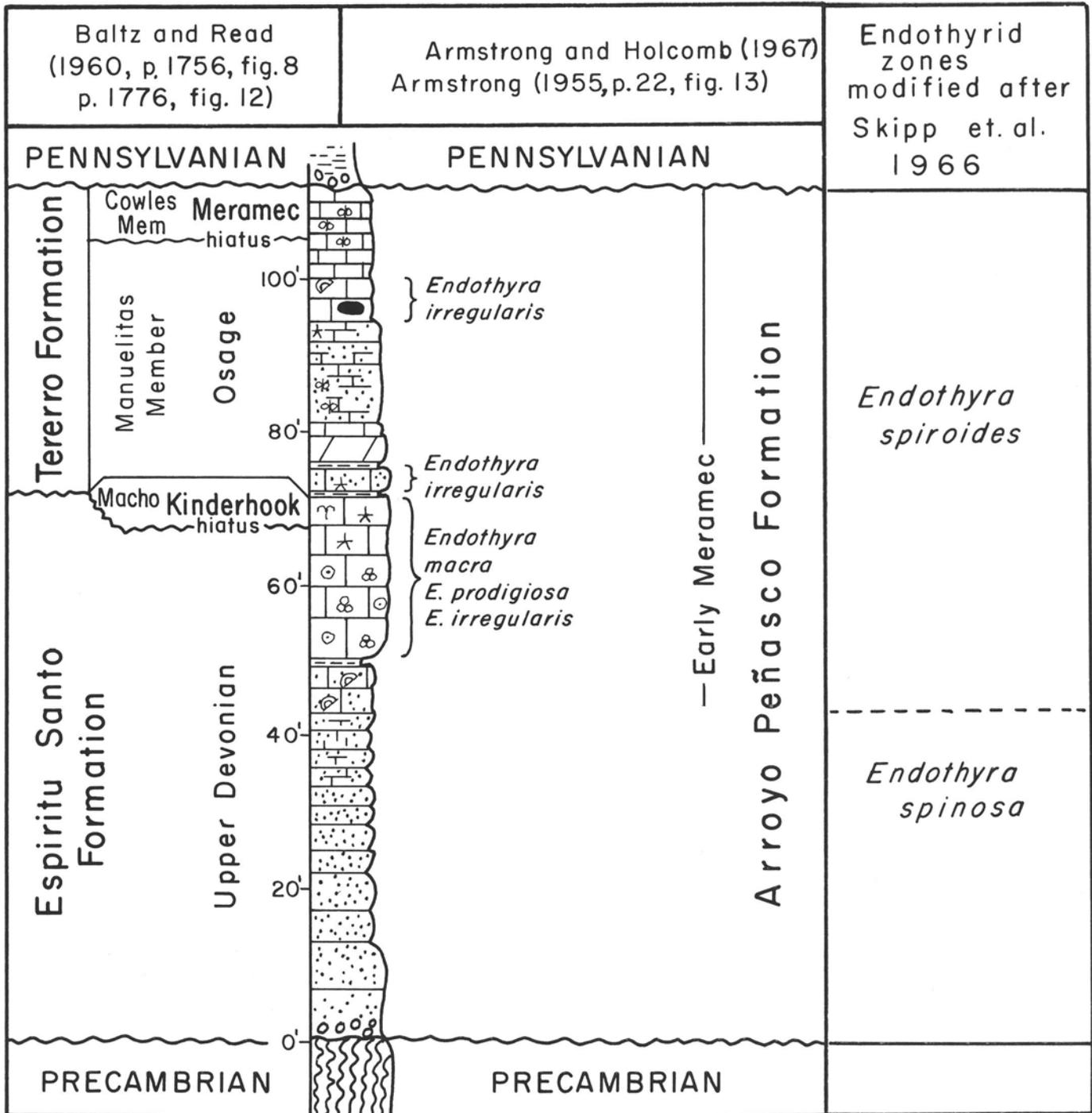


Figure 5

NOMENCLATURE, LUJAN CANYON SECTION, RINCON RANGE, SANGRE DE CRISTO MOUNTAINS

Solution breccias were not found. The zone between 50 and 70 feet is a foraminiferal oolitic packstone.

they described as resting unconformably on the Manuelitas Member (fig. 3).

This interpretation of Baltz and Read (1960) of the pre-Pennsylvanian Paleozoic elastic and carbonate rocks of the Sangre de Cristo Mountains has been widely accepted in recent geologic publications. In central Colorado, Rold (1961) compared the Devonian Dyer Dolomite pebbles in the basal sandstones of the Leadville Limestone to supposed Devonian pebbles in Baltz and Read's Macho. In their regional studies of the Devonian and Mississippian of the central part of the Colorado Plateau, Parker and Roberts (1963, p. 36, fig. 4; p. 45; fig. xi; 1966, fig. 1) accepted the existence of Devonian rocks in the Sangre de Cristo Mountains of New Mexico. Kelley (1963) on his geologic map extended a Devonian(?)—Early Mississippian age to the pre-Pennsylvanian carbonate rocks of the Sandia Mountains.

Sutherland (1963) studied pre-Pennsylvanian rocks of the Pecos River Canyon and Rio Pueblo region of the Sangre de Cristo Mountains. He recognized in general Baltz and Read's 1960 nomenclature for these rocks but added major revisions (fig. 4). He removed the basal sandstone of the pre-Pennsylvanian carbonate rocks in the Pecos River Canyon from Baltz and Read's Espiritu Santo Formation and classified it as Del Padre Sandstone. He included in this Del Padre Sandstone 754 feet of conglomeratic sandstone at his Rio Chiquito section (p. 25-26), north of Truchas Peak. He considered his unfossiliferous Del Padre Sandstone as any age from Late Precambrian (postmetamorphic) to Early Mississippian, although probably interfingering laterally with the Espiritu Santo Formation, which he restricted to the carbonate rocks below the breccia zone. These rocks, too, he considered as any age from Late Precambrian to Early Mississippian. The Tererro Formation, which Baltz and Read considered Early Kinderhook to Meramec, Sutherland noted for its endothyrid fauna, stating (p. 29), "The entire Tererro Formation is therefore best considered to be Meramec in age."

However, Baltz (1965) restated the Devonian(?)—early Mississippian ages for these strata. Dane and Bachman (1965a), in their chart of the principal formations of northeastern New Mexico, show *without a query* the age of the Espiritu Santo Formation as Devonian. Dane and Bachman (1965b), the editors for the new 1 : 500,000 geologic map of New Mexico published by the U.S. Geological Survey, listed and showed in the Sangre de Cristo Mountains the Devonian (?) Espiritu Santo Formation and the Mississippian Tererro Formation. The map symbol is MD. Schleh (1966, p. 275), in his discussion of the sub-Tamaroa unconformity in the Cordilleran region, cited Baltz and Read (1960): "The Lower Mississippian Tererro Formation everywhere rests upon the Upper Devonian Espiritu Santo Formation with a pronounced unconformity."

Armstrong and Holcomb (1967) published a short paper that discussed the nomenclatural and time-stratigraphic confusion now surrounding the Mississippian strata of north-central New Mexico. They described the occurrence of nodular chert in the basal dedolomites of the Arroyo Peñasco Formation in the Nacimiento and Sandia mountains that contains a fauna of *Endothyra spinosa* of Late Osage age. They also pointed out that Baltz and Read's (1960) type section of the Upper Devonian(?) at Tererro in the Sangre de Cristo Mountains was primarily a "dedolomite" with an *E. spinosa* fauna preserved in the chert nodules. Furthermore, they demonstrated that Baltz and Read's Devonian(?) Espiritu Santo Formation in the Lujan Canyon contains a rich fauna of *Endothyra prodigiosa* Armstrong, which is of Early Meramec age. The paper concluded with the suggestion that Baltz and Read's (1960) complex nomenclature for the Mississippian rocks of the Sangre de Cristos be discarded because it was based on a series of unconformities and age assignments that do not exist. Armstrong and Holcomb further suggested that Armstrong's (1955, 1958a) proposal of the name *Arroyo Peñasco Formation* for the Mississippian strata of the Sangre de Cristo Mountains be reinstated.

Arroyo Peñasco Formation Lithology

BASAL CLASTIC ROCKS

The basal sandstones of the Arroyo Peñasco Formation are from 1 to 50 feet thick. In the San Pedro, Jemez, Nacimiento, Sandia, Manzanita, and Manzano mountains, the unit is less than 10 feet thick, averaging 2 to 4 feet. It consists of reworked and sorted quartz pebbles and sand formed from a Precambrian regolith. In places, it grades into the basal carbonate rocks or has numerous shale partings. The sand size and percentage of quartz sand at most localities decrease rapidly 3 feet or more above the Precambrian contact. The cement is silica, calcite, dolomite, or argillaceous material.

In the Pecos River Canyon of the Sangre de Cristo Mountains, the basal sandstones range from 5 feet thick at Dalton Picnic Grounds to more than 15 feet at Jacks Creek section. In Lujan Canyon, Rincon Range, it is 50 feet thick and southeast of Taos, it is more than 25 feet thick. At localities where the basal sandstones are thick, individual beds more than 2 feet thick are generally cross-bedded. The basal elastics are composed of quartz in the fine- to medium-grained grain size with occasional pebbles. Minor amounts of feldspar and mica are present locally. The cement in most places is silica with some calcite. Thin sections show that many of the pore spaces are filled with clay.

The basal sandstones thicken to the north in the Sangre de Cristo Mountains. The field evidence suggests that in Late Osage time, a highland and source area existed north of a line drawn from Taos to Guadalupita. This concept is supported by the Turquillo section, where the Upper Osage part of the section is absent and Early Meramec-age rocks rest directly on the Precambrian.

Sutherland (p. 22) proposed the name *Del Padre Sandstone* for the unfossiliferous orthoquartzitic sandstones of undetermined age in the southern Sangre de Cristo Mountains (fig. 4). In the Pecos River Canyon, Rio Pueblo area, and the Ponce de Leon Springs section, his formation includes the basal sandstones of the Arroyo Peñasco Formation.

At Rio Chiquito, in the high country north of Truchas Peak, Sutherland included 754 feet of massive, quartzitic, cross-bedded sandstones in his Del Padre Sandstone. This section appears to be a high-energy, nearshore deposit. Its higher beds are gradational with fossiliferous Pennsylvanian marine shales and siltstones. The main body of the sandstones appears to be unfossiliferous. Samples were collected in a siltstone parting for spore studies that might conclusively resolve the sandstones' age. As yet, these studies have not been made.

I consider Sutherland's thick Del Padre Sandstone section at Rio Chiquito to be of Pennsylvanian age for the following reasons:

1. The surface upon which the Arroyo Peñasco Formation was deposited was a relatively flat peneplain with occasional low monadnocks. Even the highlands, such as the Zuni or possibly the Sierra Grande and Pederal, were very subdued, not having been rejuvenated since early Paleozoic. None of the high-

lands in Colorado or New Mexico, prior to Chester time, contributed appreciable quantities of elastic material to the Mississippian seas of southern Colorado or New Mexico.

2. The sedimentary record in southern Colorado and New Mexico indicates no tectonic activity in the Mississippian prior to Late Meramec or Chester time.
3. The Mississippian carbonate rocks of north-central New Mexico were probably never more than 175 to 200 feet thick and were deposited in less than 50 feet of water. A significant part was deposited in subtidal to intertidal environments. Thus, it seems improbable that conditions existed during this time for the deposition of 754 feet of high-energy, shallow-marine sandstones. In contrast, in Pennsylvanian time, the tectonic setting and marine conditions were conducive to this type of sedimentation.

CARBONATE DEPOSITIONAL CYCLES

Significant advances have been made in recent years in understanding the mechanisms and biology of carbonate sedimentation and of the various depositional environments and carbonate textural types associated with them. In unraveling the complex history of the Mississippian strata of north-central New Mexico, I have used extensively the concepts gained through detailed studies of modern shallow-water carbonate sediments.

Carbonate sedimentation on the inner margins of shallow shelves have been studied by modern analogs in the Bahama Islands and the Persian Gulf by Purdy (1963), Kinsman (1966b), Illing, Wells, and Taylor (1965), and Shinn, Ginsburg, and Lloyd (1965). The process may be summarized thusly: The shallow marine, inner continental shelf is and has been through geologic time an area of rapid sedimentation. The sediments of this environment may be of terrigenous or carbonate types, depending on rates of terrigenous influx and on climate. When carbonate production exceeds the rate of subsidence, lime muds in protected areas adjacent to the shore begin to infill to low-water, spring-tide level. The lime muds prograde over the shallow marine sediments and are followed by intertidal sedimentation that proceeds up to high-water, spring-tide level. The intertidal sediments develop on their surface a thick mat of stromatolitic algae that traps the lime muds brought in by suspension on flood tides (Ginsburg, 1966). The lime muds are transported from the shallow marine to the intertidal and supratidal environments by an intricate network of tidal channels. Thus is developed a carbonate "delta" somewhat analogous to a normal delta but in reverse: although it builds out from the land, its sediment source is the sea. Tidal channels fed from the sea form the distribution system of the sediments. The current flow directions change with every tide. Excellent photographs by Illing, Wells, and Taylor (their fig. 3) demonstrated carbonate progradation, tidal channels, intertidal algal mats, and supratidal algal mats.

Both Ginsburg and Kinsman (1966a,b) give a schematic

diagram of this type of carbonate sedimentation pattern which, with modification, is presented in Figure 6.

With the initial rapid sea-level rise and a period of sea-level stability, during which carbonate production exceeds subsidence, the supratidal and intertidal carbonate sediments fill in the marine environment. This is accomplished by the seaward advance of supratidal sediments prograding over the intertidal stromatolitic lime muds, which in turn prograde over the shallow-marine environment beds. The carbonate tidal flats continue to advance over the shallow-marine environment as long as the supply of lime mud is maintained. If the carbonate tidal flats encroach over a large enough area of the shallow-marine beds so that the production and supply of lime mud is reduced, the system may come into a sort of equilibrium, and tidal flats may not continue to prograde seaward. Frequently, before a carbonate cycle can reach this critical state of equilibrium, another period of rapid sea-level rise may interrupt it, and another carbonate cycle will begin above the older cycle; it will form the same as the older cycle if all conditions are the same. By varying rates of carbonate production, sea-level stability, distance from shore, water depths, and terrigenous influx, it is possible to stack a complex series of incomplete to complete carbonate cycles. They may be either highly varied or monotonous repetitions. Fischer (1964) described some 200 carbonate depositional cycles (Lofer cyclothems) of shallow-marine to intertidal sediments from the Triassic of the Austrian Alps. These Triassic cycles have many carbonate depositional structures analogous to those seen in the Arroyo Peñasco Formation of north-central New Mexico.

Figure 7 graphically represents a depositional model for the various shallow-water marine cratonic carbonate-rock facies of the Mississippian System in New Mexico and southern Colorado. This diagram is the basis for recognizing, in detail, carbonate depositional cycles within the Arroyo Peñasco Formation. The concept and format of the chart are those of Dr. James L. Wilson, Rice University.

Field studies in New Mexico and southern Colorado suggest that an idealized shallow, marine, cratonic Mississippian carbonate depositional cycle would consist of the following facies, in ascending order: (1) bioclastic, dark-gray wackestones, rich in echinoderms, brachiopods, and corals, fauna well preserved; (2) echinoderm-bryozoan packstones and grainstones, light-gray color; (3) oolitic grainstones and packstones, cross-bedded; (4) ooid packstones, fair sorting, abundant abraded bioclasts; (5) pelletoid packstones, well sorted, and in the Arroyo Peñasco Formation abundant 0.1 to 0.2 mm quartz sand; (6) pelletoid wackestones and lime mudstones; sediments either laminated or extensively burrowed; (7) intertidal lime mudstones, stromatolitic, abundant small lithoclasts and chips; (8) supratidal lime mudstones with cracks, chips, and interclasts.

Carbonate depositional cycles are seldom complete; this is particularly true of the cycles in the Arroyo Peñasco Formation. An example is Cycle 1, which began in facies 6 and ended in facies 8. Cycle 2 started in facies 7 and ended in facies 9. In the Nacimiento Mountains, Cycle 3 started in facies 4 and ended in facies 7 (fig. 7).

The carbonate sediments of the Arroyo Peñasco accumulated in a setting in which sedimentation exceeded sub-

sidence. The sedimentary record indicates that rises in relative sea level were rather rapid and were followed by periods of approximate, although not perfect, sea-level stability during which carbonate sediments built up to sea level and prograded over the marine environment.

CYCLE I

This cycle's initial phase was a transgression across the weathered Precambrian terrain and the deposition of a basal elastic unit. The basal carbonate sediments were apparently pelletoid, shallow-marine lime mudstones, and the end of the cycle was marked by intertidal to supratidal algal stromatolitic lime mudstones. This unit ranges from 10 to 60 feet in thickness and has been subjected to severe diagenetic alteration. The carbonate rocks are now dolomites, dedolomites (coarse crystalline poikilotopic calcite with corroded dolomite rhombs), and minor amounts of lime mudstone.

These altered carbonate rocks crop out in the San Pedro, Nacimiento, Jemez, Manzanitas, Manzano, Sandia, and Sangre de Cristo mountains of northern New Mexico. On a weathered surface, the dedolomites and coarse crystalline calcite limestones are cinnamon brown. On a fresh break, these carbonates have a steel-gray to pearly gray luster and are characterized by large crystals. In thinsection (pl. 1, figs. 1-2; pl. 2, figs. 3-4; pl. 3, fig. 4; pl. 5, figs. 4-8; pl. 6, figs. 6-8), the carbonates are typically interlocking crystals of calcite that give the limestone a pseudometamorphic texture. Sutherland, unaware of the microfossils preserved in the chert or the phenomenon of "dedolomitization," believed that the extensive recrystallization of this unit in the Pecos River Canyon of the Sangre de Cristo Mountains was possibly the result of mild deformation before the deposition of the overlying Lower Meramec carbonate rocks.

The cherts associated with the recrystallized carbonates of Cycle 1 have preserved the original depositional fabric of the limestone. The chert thinsections reveal that the limestone was a calcisphere, ostracod, foraminifera, pelletoid, lime mudstone deposited possibly in a shallow, restricted marine environment (pl. 1, fig. 4; pl. 2, fig. 2; pl. 3, fig. 3; pl. 7, figs. 1-2) or a calcisphere, sponge spicule algal stromatolitic lime mudstone deposited in an intertidal environment. The dolomites with rhombs in the 10- to 100-micron range in this unit generally, but not always, occur beneath the coarse poikilotopic calcite with corroded dolomite rhombs.

In Cycle 1, lime mudstones that have not been dolomitized are rare, but they do occur in the lower part of the section and are generally separated from the overlying dolomites and dedolomites by thin shale beds. At the Coco City section, the carbonate rocks of this cycle are relatively unaltered, burrowed, ostracodal, arenaceous lime mudstone (pl. 3, fig. 1). At the Rio Pueblo section, a significant amount of the lower part of Cycle 1 consists of ostracodal, pelletoid, arenaceous, dolomitic lime mudstones, above which are dolomites.

The thickest known exposure of carbonate rocks of Cycle 1 is at the Ponce de Leon section, Sangre de Cristo Mountains. Excellent exposures occur along the crest of a ridge south of the village of Talpa where field studies revealed many sedimentary features of shallow subtidal and intertidal origin. The rocks are dolomites and calcite replacement

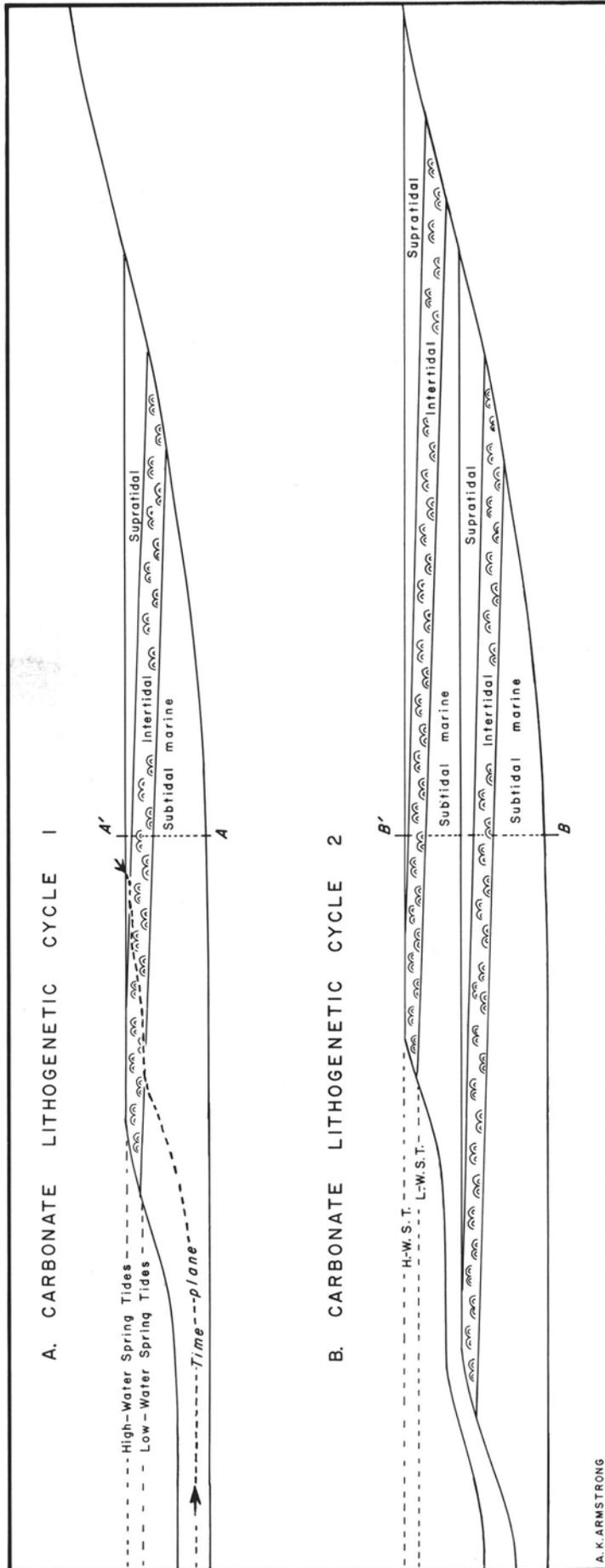


Figure 6
GENERALIZED CARBONATE DEPOSITIONAL CYCLE MODEL

Modified in part from Ginsburg (1964) and Kinsman (1966a,b). A. Initial requisite is a rapid pulse of subsidence of basin and a period of stability for the development of the regressive carbonate offlap. The seaward advance of the environmental belts results in the supratidal facies overlying the stromatolitic algal intertidal facies, this in turn overlying the subtidal marine facies. A core taken at point A-A' would show three carbonate types and facies and is considered one cycle in this report. B. During the development of carbonate lithogenetic Cycle 1, a rapid rise in sea level occurs and deposition of Cycle 2 begins. A core taken at points B-B' would show two cycles, each with three facies. These two illustrations show only the simplest of conditions. The thickness of any cycle or of the facies within a cycle would be the result of a complex interplay of the rates of sea-level rise, if steady or in pulsations, and possible sea-level fall and erosion, the rate of carbonate production, the tidal range, and the velocity of coastwise currents.

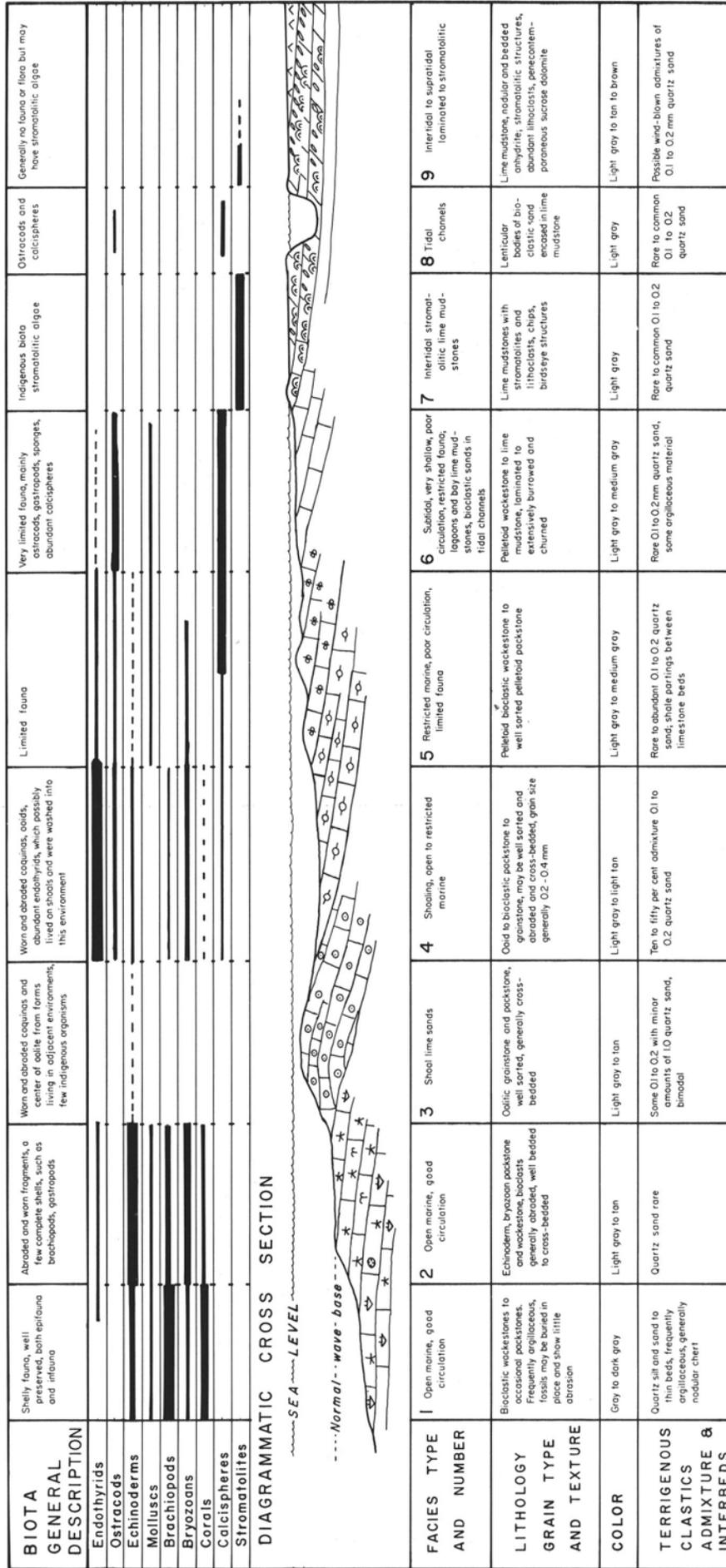


Figure 7 DEPOSITIONAL MODEL FOR THE VARIOUS SHALLOW-WATER CRATONIC MISSISSIPPIAN CARBONATE FACIES OF NORTH- AND WEST-CENTRAL NEW MEXICO

"pseudomorphs" of gypsum with numerous algal stromatolites, chips, lamination, and intraformation conglomerates (fig. 8).

CYCLE 2

Carbonate rocks of Cycle 2 are 45 feet thick in the San Pedro and Nacimiento mountains and 30 feet thick in the

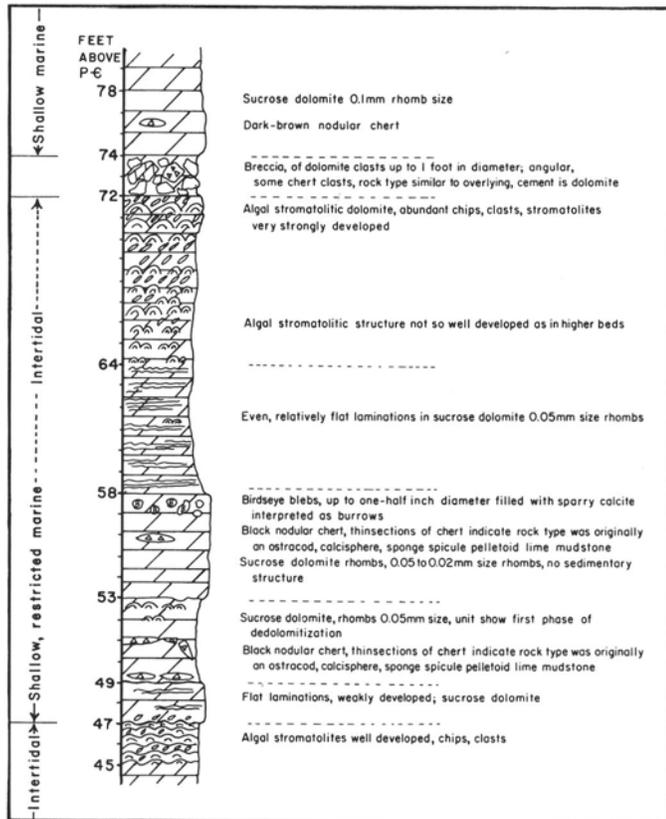


Figure 8

PART OF THE PONCE DE LEON (TALPA) SECTION, ILLUSTRATING IN GRAPHIC DETAIL THE ABUNDANT CARBONATE SEDIMENTARY FEATURES

(See fig. 28 for complete section.)

Sandia Mountains. The rocks are subtidal echinoderm wackestones and pelletoid lime mudstones capped by possibly intertidal penecontemporaneous dolomites. At Peñasco Canyon (fig. 9), a zone of algal stromatolites (fig. 24) developed in the lower third of the section. Beds of coarse poikilotopic calcite with corroded dolomite rhombs occur in the lower part of this cycle at Peñasco Canyon and at Placitas in the Sandia Mountains. These strata may represent a western shallow-marine to intertidal carbonate facies of Cycle in the San Pedro (fig. 16), Nacimiento, and Sandia mountains. The time equivalents to this facies in the Sangre de Cristo Mountains may have been the intertidal to supratidal interbedded gypsum and dolomites that marked the final phase of Cycle 1.

The foraminifera collected from this unit in the San Pedro and Nacimiento mountains suggest that these carbon

ate rocks are transitional from the underlying Upper Osagian beds with *E. spinosa* Chernysheva to the overlying Lower Meramecian beds with *Endothyra prodigiosa* Armstrong. The fauna of Cycle z is characterized by the lower Meramec index fossil *Endothyra spiroides* Zeller of Meramecian age and *Endothyra aff. E. spinosa* Chernysheva of Upper Osagian affinities. In the Sangre de Cristo Mountains at Ponce de Leon Springs section, 12 feet of dolomites are believed to represent this cycle, whereas to the east at Rio Pueblo and Lujan Canyon sections, 8 to 10 feet of ostracod and pelletoid lime mudstones are believed to represent this cycle. In the Sangre de Cristo Mountains, carbonate rocks of Cycle z in the exposures from Coco City south to Agua Zarca and in the Pecos River Canyon are believed to be involved in the collapse breccia lens and are almost impossible to study stratigraphically. It is significant to note that a number of clasts from the lower part of the collapse breccia lens have yielded *E. spiroides* Zeller (pl. 3, fig. 5; pl. 8, fig. 18).

CYCLE 3

Cycle 3 in the San Pedro, Nacimiento, and Sandia mountains overlies the lime mudstones and dolomites of Cycle z. In the Sangre de Cristo Mountains at Ponce de Leon Springs, it overlies dolomites and at Rio Pueblo and Lujan Canyon, ostracod, pelletoid lime mudstones. In the exposures from Coco City and Mora Gap southward to Agua Zarca and in the Pecos River Canyon, Cycle 3 is involved in and overlies the collapse breccia lens. Carbonate rocks of Cycle 3 represent the most open marine conditions found within the Arroyo Peñasco Formation. The cycle records within it two minor sea-level fluctuations. The higher beds of the cycle have been extensively and differentially removed by Early Pennsylvanian erosion; consequently, the original thickness and total composition of this cycle are impossible to ascertain.

Beneath the Pennsylvanian erosion surface at Peñasco and Los Pinos canyons in the Nacimiento Mountains, 57 feet of Cycle 3 are preserved. At Tererro in the Pecos River Canyon, in the Sangre de Cristo Mountains, about 55 feet occur below the Pennsylvanian erosion surface and above the collapse breccia lens. At Placitas, in the Sandia Mountains, less than 10 feet are preserved.

In general, the lower part of the cycle is an ooid to oolitic, echinoderm, bryozoan packstone that grades vertically into a finer grained ooid to pelletoid, bioclastic, arenaceous (bimodal quartz sand) packstone and wackestone.

A rise in sea level during the deposition of Cycle 3 is reflected in the middle of the cycle by arenaceous, oolitic, and ooid packstones that rest on lime mudstone and dolomites at Peñasco Canyon, in the Nacimiento and San Pedro mountains. A second rise in sea level within this cycle is suggested in the Sangre de Cristo Mountains region at Lujan Canyon by pelletoid, ooid sandstones that overlie dolomites and at Coco City by arenaceous, oolitic to ooid packstones overlying ostracod wackestones.

At Dalton Picnic Grounds, Tererro, and Jacks Creek sections, an ostracod, pelletoid limestone is overlain by an ooid packstone and/or pelletoid, bioclastic, arenaceous packstone that grades upward into progressively more arenaceous and argillaceous, fine-grained, pelletoid, and bioclastic packstones. Outcrops of the upper part of Cycle 3 in the east-



Figure 9

TYPE SECTION OF THE ARROYO PEÑASCO FORMATION AS VIEWED FROM STATE HIGHWAY 44

(Looking east) just north of Warm Springs, New Mexico. Arrow 1 points to excellent outcrop of dedolomites with chert that contains an excellent microfauna and arrow 2 points to outcrop and base of measured section. Section is measured down the slope due north along the fence line. (See fig. 20.)

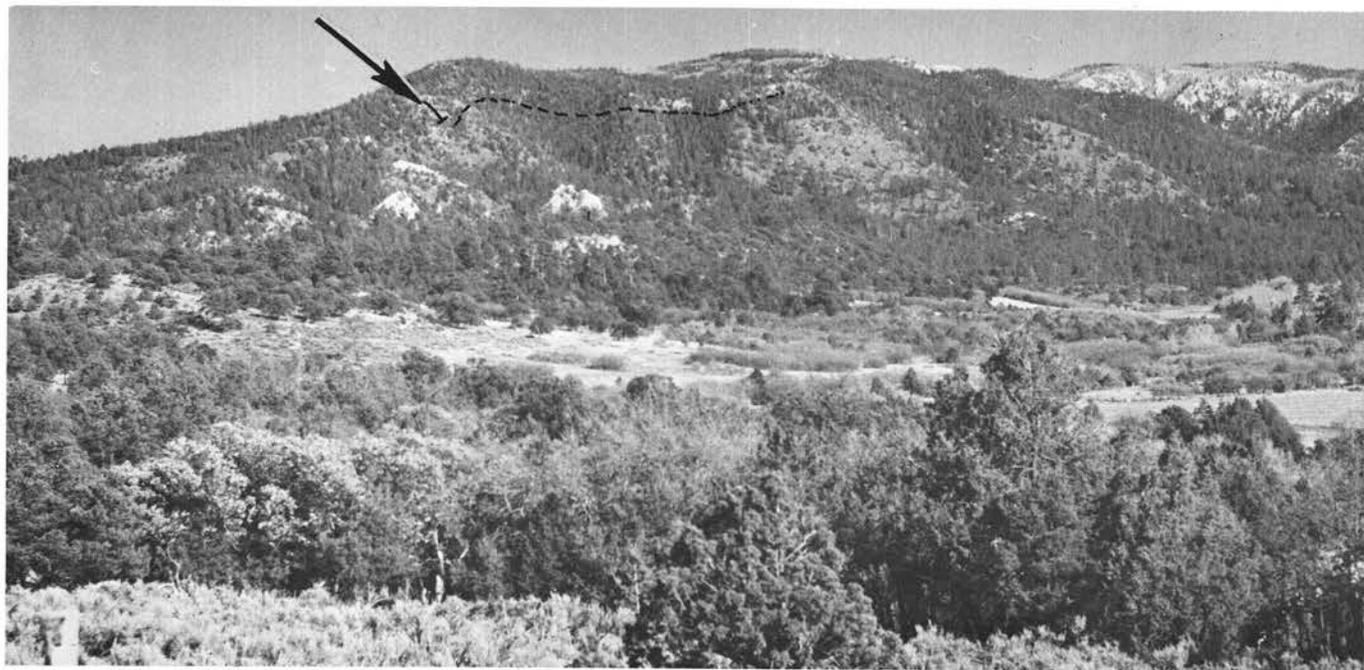


Figure 10

SAN PEDRO MOUNTAINS SECTION AS VIEWED FROM NORTH OF REGINA, NEW MEXICO

(On State Highway 96) The line marks outcrop of Arroyo Peñasco Formation. Arrow points to location of measured section. Dotted line marks approximate outcrop of the formation.

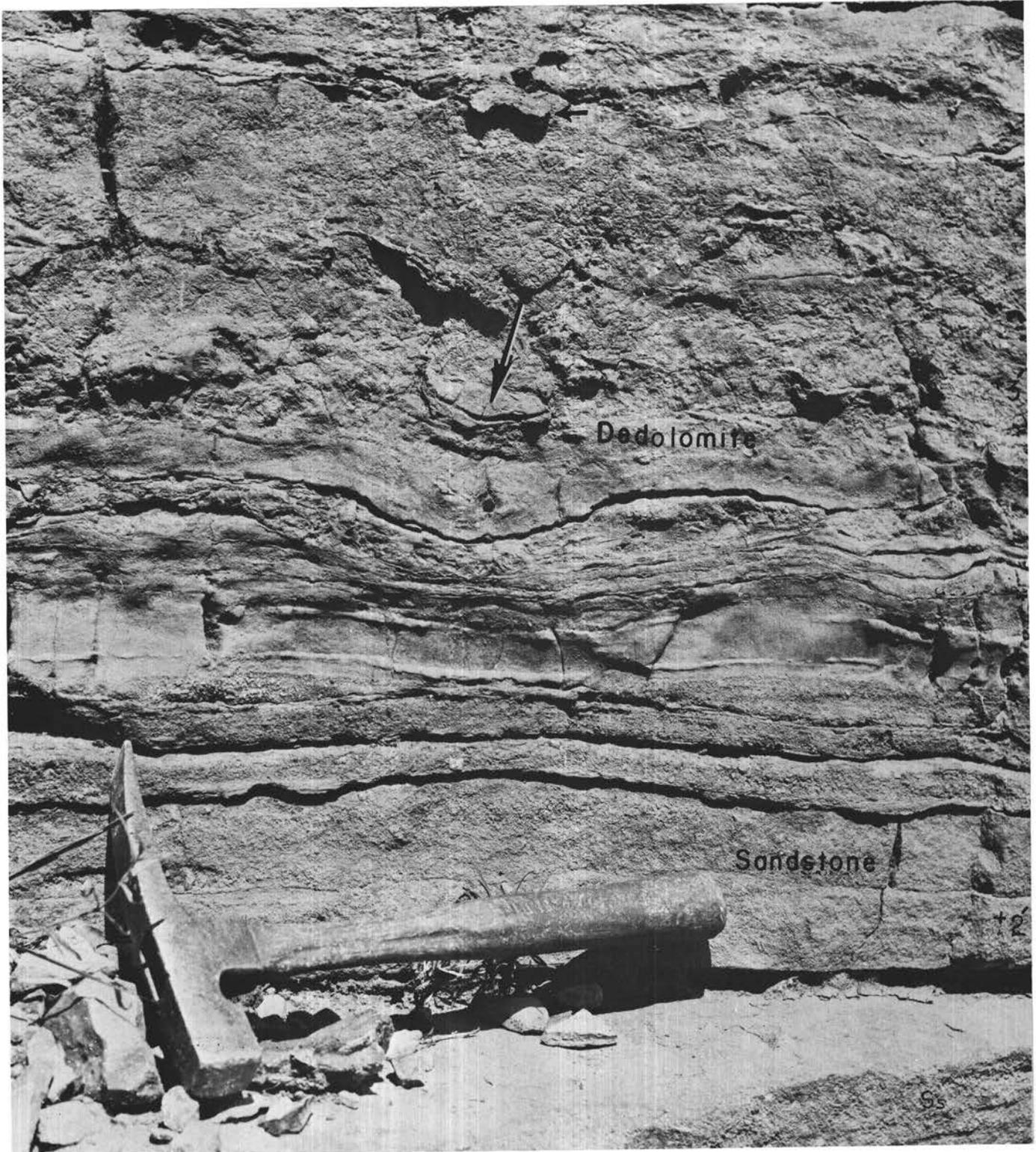


Figure 11

ALGAL STROMATOLITES, CHIPS, AND LAMINATIONS AS SEEN IN OUTCROP ON STATE HIGHWAY 65 IN GALLINAS CANYON, SANGRE DE CRISTO MOUNTAINS

Algal stromatolites rest directly on basal sandstones. The dedolomites of Cycle 1 have on a fresh surface a crystalline pearly gray luster. Above the pronounced algal stromatolitic structure, an arrow points to a prominent clast. These sedimentary features indicate an intertidal deposition environment.

ern and northern Sangre de Cristo Mountains contain 30 to 65 per cent 0.1 to 0.2 mm quartz sand with abraded and rounded carbonate fossil fragments and lime-mud pellets in the 0.1 to 0.2 mm size (pl. 4, figs. 1, 2, 7). In outcrops, these beds are generally massive and cross-bedded. At Manuelitas Creek and Lujan Canyon sections, the arenaceous packstones are overlain with a sharp contact by 10 to 20 feet of medium-bedded, medium- to light-gray, ostracod- and occasionally gastropod-rich lime mudstone (pl. 6, fig. 1). These, in turn, are locally overlain by argillaceous, burrowed, unfossiliferous lime mudstones. All these lime mudstones have a low content of quartz sand in contrast to the adjacent underlying packstones.

Within Cycle 3, the ooid packstone generally contains a rich fauna of microfossils. The fauna has been found in the Nacimiento, San Pedro, and Sangre de Cristo mountains and is characterized by the presence of the following species: *Endothyra macra* Zeller, *E. prodigiosa* Armstrong, *E. irregularis* (Zeller) and *Tourmayella* sp. The fauna is Meramec in age and is believed to represent an Early Meramec Warsaw—Salem assemblage, although beds as young as St. Louis age may be present in the upper part of the cycle.

Cycle 3 in north-central New Mexico is characterized by elastic quartz sand, which in the lower part of the cycle may be bimodal. The bimodal sizes are a small amount of 0.6 to mm subrounded quartz sand, with the majority of the grains in the 0.1 to 0.2 mm size. In the upper half of the cycle, the 0.1 to 0.2 mm quartz sand comprises a significant part of the rock (pl. 3, fig. 8; pl. 4, figs. 1, 2, 3, 6, 7; pl. 7, figs. 3-4).

In the Sangre de Cristo Mountains, Cycle 3 contains the same general lithostratigraphic succession and variety of carbonate types as found in the Nacimiento and San Pedro mountains. The major difference is that the percentage of quartz-sand content is somewhat higher.

CARBONATE DIAGENETIC PROCESS

The early limestone diagenesis of the Arroyo Peñasco Formation is not described. These early events include the changes between deposition as probable aragonite and high magnesium calcite and their subsequent mineralogical and textural changes leading to calcite limestone. The limestones in the Arroyo Peñasco Formation appear to have followed the normal sequence of events described in detail by Friedman (1964, 1965), Bathurst (1958, 1959), and Folk (1965).

The diagenetic events discussed in this report are dolomitization, dedolomitization, calcite replacement of gypsum, calcite-grain growth, and vadose zone alteration during the Early Pennsylvanian.

DEDOLOMITIZATION AND CALCIFICATION OF GYPSUM—ANHYDRITE

Von Morlot (1848, fide Shearman, Khouri, and Taha, 1961) believed that the replacement of dolomite by calcite was a possible process in limestones and coined the term *dedolomitization*. J. J. H. Teall (1903) established the term to describe the metamorphic transformation of the mineral dolomite. This paper follows Shearman, Khouri, and Taha on the definition of dedolomite based on priority as origi-

nally defined by Von Morlot. Lucia (1961, p. 1107) pointed out that the term has extensive use in Russian literature, and he introduced the term *dedolomite* into the American literature. However, Lucia's definition of *dedolomite* involved the concept of replacement of dolomite by gypsum and/or anhydrite and then the replacement of gypsum and/or anhydrite by calcite. Friedman (1964, p. 651) and Schmidt (1965, p. 149-150) also discussed and described occurrences of dedolomite. In this study, dedolomitization is restricted to the replacement of dolomite by calcite, forming a rock termed *dedolomite*. In this paper, *calcification* describes both dolomitization and calcite replacement of gypsum and/or anhydrite (see figs. 24 through 43).

The carbonate rocks (fig. 12) within the *Endothyra spinosa* zone of Cycle I have undergone a complex diagenetic history. In north-central New Mexico, these rocks are generally 0 to 40 feet thick and are dolomites, dedolomites, and coarse-grained, pseudometamorphic limestones that contain varying amounts of 10- to 30-micron corroded dolomite rhombs. Within this unit are nodules and stringers of brown to gray cherts. Thinsections of the chert reveal that it is an early phase of diagenetic replacement by silica of an original ostracod, foraminifera lime mudstone, and stromatolitic lime mudstone. Sedimentary features and thinsection studies of the chert indicate that the rocks in this unit were deposited in a shallow, subtidal, marine, lime mud environment and that the higher beds were deposited in an intertidal stromatolitic environment.

Carbonate rocks of this cycle at Peñasco Canyon are coarse-grained, crystalline, pseudometamorphic, poikilotopic calcite containing relics of 10- to 100-micron dolomite rhombs. Poikilotopic calcite with corroded dolomite rhombs occurs at the sections in the San Pedro Mountains; Placitas, Sandia Mountains; Tijeras Canyon, Manzanita Mountains; and Bosque Peak, Manzano Mountains (pl. 5, figs. 4-8; pl. 6, figs. 6-8).

In the Pecos River Canyon and on the eastern flank of the Sangre de Cristo Mountains where there is an overlying collapse breccia (particularly where it is thickest), the underlying rocks are coarsely crystalline and have a pseudo-metamorphic texture. At these localities, dolomite relic rhombs are not apparent in low-powered magnification of thinsections, but at 100 power and above, the large, calcite crystals are poikilotopic and display corroded dolomite rhombs (pl. 5, figs. 7-8).

The 0.5 to 2.0 mm interlocking crystals of calcite (pl. 1, fig. 2; pl. 6, figs. 7-8) with their inclusions of corroded dolomite are considered to have been formed by replacement. The dolomite inclusions are too scattered to have formed a supported framework. Lucia (p. 1108) gave the following reasons for a replacement origin for similar rock types in the Permian Tansill Formation of West Texas and New Mexico. His thesis is applicable to the carbonates in the Arroyo Peñasco Formation. Dolomite has not replaced calcite because (1) finely crystalline dolomite frequently surrounds the pseudometamorphic calcite (pl. 5, fig. 5; pl. 6, fig. 6), (2) dolomite is concentrated in the center of many of the calcite crystals and, (3) the dolomite rhombs are generally corroded and not euhedral as commonly seen when dolomite replaces calcite.

The material replaced by the calcite was probably dolomite or gypsum-anhydrite or both. The former presence of

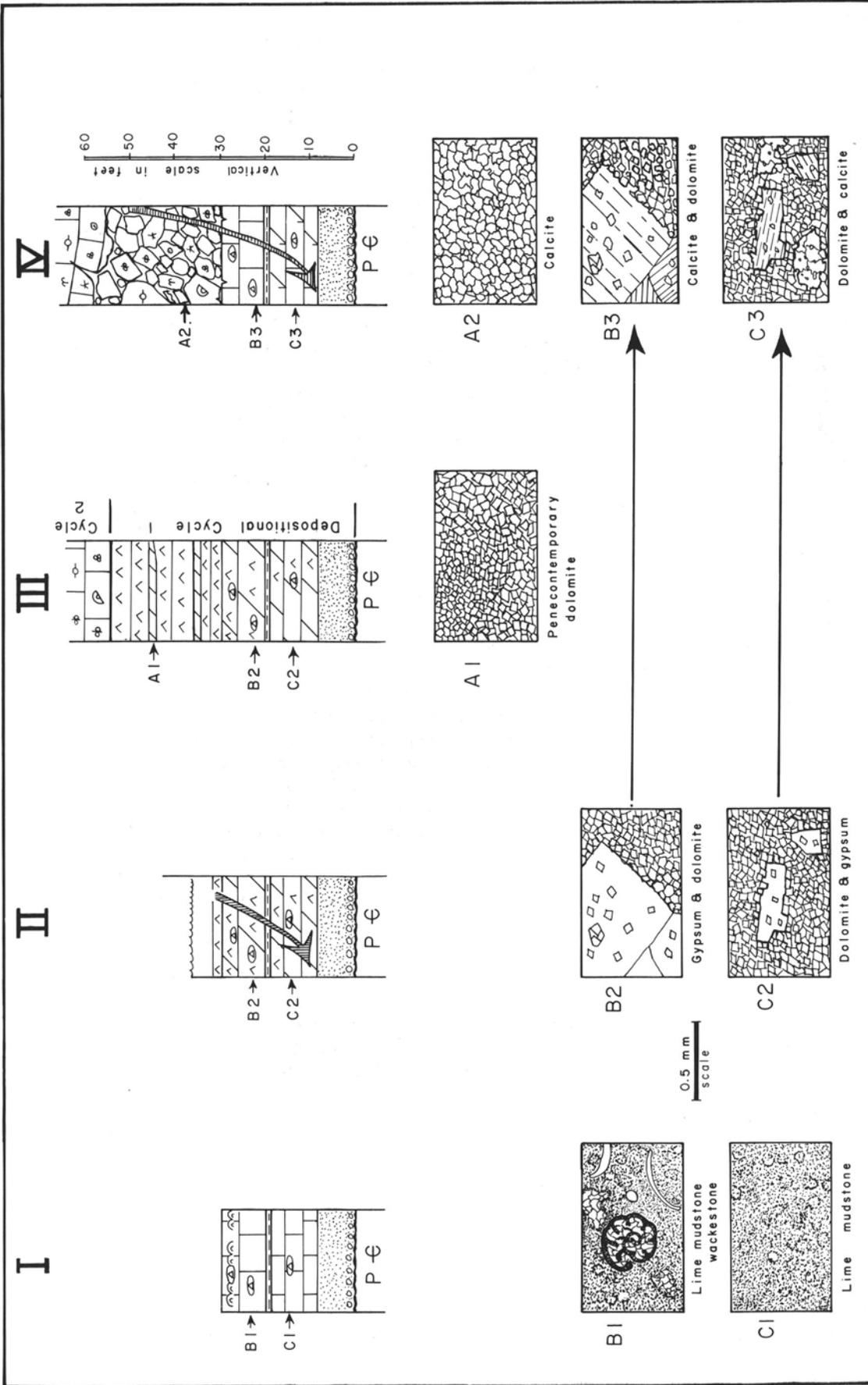


Figure 12

DIAGRAMMATIC REPRESENTATION OF THE DIAGENETIC HISTORY OF THE CARBONATES OF CYCLE I (EXEMPLIFIED AT TERERRO, SANGRE DE CRISTO MOUNTAINS)

Column I, deposition of shallow marine lime mudstones and wackestones grading upward to intertidal, stromatolitic, lime mudstones. Chert nodules formed, replacing the calcite and preserving within them the carbonate microtexture and microfossils. B1 and C1 are the original carbonate textures as seen in thinsections of the chert. Column II illustrates the Late Osage hypersaline fluids above the stromatolite and the deposition of gypsum. The hypersaline fluids, which migrate downward into the limestones, replaced the calcium with dolomite and gypsum. The large replacement gypsum crystals contained abundant enclosed rhombs of dolomite. The replacement gypsum was progressively more abundant adjacent to the bedded gypsum. B2 illustrates the large gypsum crystals with enclosed rhombs of dolomite and adjacent patches of dolomite. C2 is dolomite rhombs that surround a small replacement gypsum crystal. Column III, Early Meramec, the end of Cycle I, which was characterized by bedded gypsum and thin-bedded penecontemporary dolomite. The overlying carbonate depositional cycles were fossiliferous wackestones and ooid packstones. A1 is the interpretative dolomite that existed interbedded with the bedded gypsum. Column IV, the Arroyo Peñasco Formation in Late Mississippian and/or Early Pennsylvanian time was elevated, and solution by meteoric ground waters resulted in the removal of the bedded gypsum, causing the collapse and brecciation of the interbedded dolomites and the overlying carbonates of the *Endothyra spiroides*, *E. macra* zone. The downward migration of these meteoric waters rich in Ca and SO₄ ions caused the replacement gypsum and, in part, the dolomite to be leached and replaced by calcite. The calcification is most intense in the underlying *Endothyra spinosa* zone adjacent to the breccia zone. The replacement gypsum was completely removed and replaced by calcite. Within this zone, the dolomite rhombs and dolomites have been extensively corroded and replaced by calcite. A2, the dolomite interbedded within the bedded gypsum was brecciated and dedolomitized into fine 2.5- to 35-micron crystalline calcite.

gypsum-anhydrite is suggested by relic forms (pl. 5, fig. 5; pl. 6, fig. 3) outlined by the included dolomite. The relic forms show rectangular re-entrance and straight sides.

Associated with and generally beneath these coarse crystalline limestones are fine-grained dolomites and dolomitic lime mudstones. The dolomites are generally equigranular, and the rhomb sizes range from 10 to 100 microns (pl. 5, fig. 1). The dolomitic lime mudstones are rare and may be pelletoid, calcisphere, ostrocod-bearing. The majority of the dolomitic lime mudstones appears to result from a form of dedolomitization—in the initial stages of calcite replacing 10- to 50-micron dolomite rhombs. These dolomitic limestones may have been fine-grained dolomites in which dedolomitization occurred, the calcite replacement mosaic regenerating the predolomitization texture (Shearman, Khouri, and Taha, Type 3; pl. 5, fig. 3).

The development of the coarse, poikilotopic calcite with enclosed dolomite is believed to be related to two inferred factors:

(1) The existence of 5- to 30-foot-thick gypsum and gypsiferous dolomite beds deposited in a supratidal environment above the intertidal stromatolitic beds. Hypersaline fluids, accompanying deposition of the bedded gypsum, had a higher specific gravity and moved downward, replacing the interstitial sea water in the porous lime mudstones. The reflux fluids dolomitized the lime mudstones into dolomite, forming 10- to 100-micron rhombs. The reflux fluids continued to react with the underlying carbonates, particularly the higher beds. In *situ* replacement crystals of gypsum and/or anhydrite formed containing numerous inclusions of dolomite rhombs (fig. 12).

(2) The removal of the bedded gypsum in solution by meteoric ground water during Late Mississippian and/or Early Pennsylvanian time resulted in development of the collapse breccia and its partial cementation by calcite. The underlying replacement dolomite and gypsum reacted to the ground waters bearing Ca^{++} and SO_4^{--} . Shearman, Khouri, and Taha (p. 11) and Lucia discussed the possible role of magnesium sulphate solution in the formation of dolomite and cited the equation, $2\text{CaCO}_3 + \text{MgSO}_4 = \text{CaCO}_3 + \text{MgCO}_3 + \text{CaSO}_4$. They also observed that this is a reversible reaction and suggested that a gypsiferous solution could bring about dedolomitization. The 'calcified' gypsum was replaced with calcium carbonate, which frequently formed pseudomorphs of calcite after gypsum. The dolomite within the former gypsum crystals corroded and the adjacent dolomite masses underwent various degrees of dedolomitization.

In the Pecos River Canyon and on the eastern flank of the Sangre de Cristo Mountains, where the limestone collapse breccia is thickest, the underlying carbonate rocks have undergone the most extensive alteration. At the Rio Pueblo section, where the breccia is absent, the dolomites do not show the extensive effects of "dedolomitization."

Abundant evidence does exist for the former presence of gypsum and/or anhydrite in the carbonate rocks of Cycle 1. Relic forms of anhydrite, surrounded by partly dedolomitized dolomite, are particularly abundant. The basal carbonate rocks of the Arroyo Peñasco Formation in the San Pedro, Nacimiento, Jemez, Sandia, Manzanita, and Manzano mountains are megascopically and microscopically of the same

lithology as those found in the Sangre de Cristo Mountains. These are composed of the pseudometamorphic poikilotopic calcite with enclosed corroded dolomite rhombs in association with dedolomitized beds of calcareous dolomite. These latter are in the 10- to 100-micron corroded dolomite rhombs (pl. 1; figs. 1, 2; pl. 2, figs. 3, 4; pl. 5, figs. 4, 6).

COLLAPSE BRECCIA LENS

A limestone breccia lens, 5 to 40 feet thick, occurs at the top of bedded carbonates of Cycle 1 in the Sangre de Cristo Mountains. The breccia zone is weakly developed at the Ponce de Leon section southeast of Taos; it is absent at Turquillo, Lujan Canyon, and Rio Pueblo sections.

The limestone breccia is composed of rounded to angular fragments of limestone ranging in size from silt to blocks thirty feet across. The lithology of the majority of the clasts is the same as that of the overlying beds, which contain the same foraminifera fauna. The contact of the breccia with the underlying carbonates is an even, almost flat, surface. Clasts of dolomites or the coarsely crystalline poikilotopic calcite with corroded dolomite rhombs are very rarely found above the basal contact and are not found at all within the main mass of the breccia. The relationship with the overlying beds is an irregular contact, marked by large blocks that have fallen down into the breccia zone. "Pipes" or "stopes" of breccia extend up into and cut through the overlying beds. These features are well displayed at the exposures west of Tererro (fig. 13) and at Jacks Creek (fig. 14). At Manuelitas Creek section, a sinkhole extends from the Pennsylvanian erosion surface down through the Meramec section and connects with the breccia zone. This feature was studied in considerable detail and is graphically shown in Figure I 5.

In thinsections, the lithology of the clasts generally ranges from ostracod, foraminifera lime mudstones to oolitic pack-stones. No clasts were found containing microfaunas older or younger than Meramec. A significant number of clasts, in particular those under one inch in diameter, are composed of equal granular calcite crystals in the 25- to 50-micron size. This lithology has only been observed within the breccia lens. Filling the space between the larger clasts is a series of small limestone fragments. The void or cavities between the various-sized clasts are frequently floored with a layer of silt-sized quartz sand (pl. 3, fig. 6). The quartz sand grains were probably derived by solution from the surrounding limestone clasts. The voids are filled with drusy calcite which increase in crystal size toward the void center (Bathurst's (1958) rule).

The formation of the limestone breccia lens in the Arroyo Peñasco Formation in the Sangre de Cristo Mountains has been ascribed to several methods. Baltz and Read (1960, p. 1768) believed a shallow Kinderhookian sea transgressed into northern New Mexico across a karst topography developed on their Devonian(?) Espiritu Santo Formation (*Endothyra spinosa* zone dolomites, dedolomites, and coarse crystalline pseudometamorphic limestones of this report). They stated that preceding and during this Kinderhookian marine incursion of the sea, extensive collapse of cavernous parts of the Espiritu Santo Formation formed much of the breccia. Advance of the sea was accompanied by erosion and

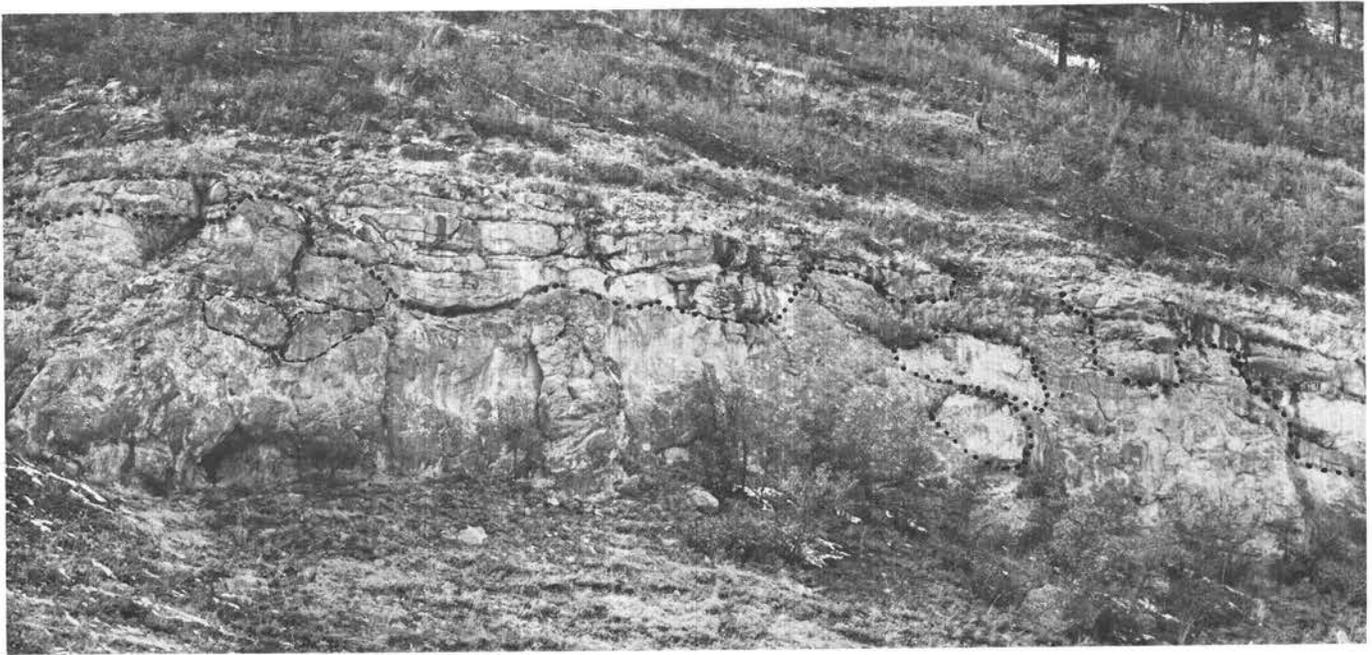


Figure 13

BRECCIA LENS OUTCROP WEST OF TERERRO, PECOS RIVER CANYON, SANGRE DE CRISTO MOUNTAINS

This is an excellent exposure of the breccia zone, illustrating the very irregular upper surface with "pipes" of breccia penetrating into higher beds; also, the large blocks of limestone within the breccia are clearly shown.

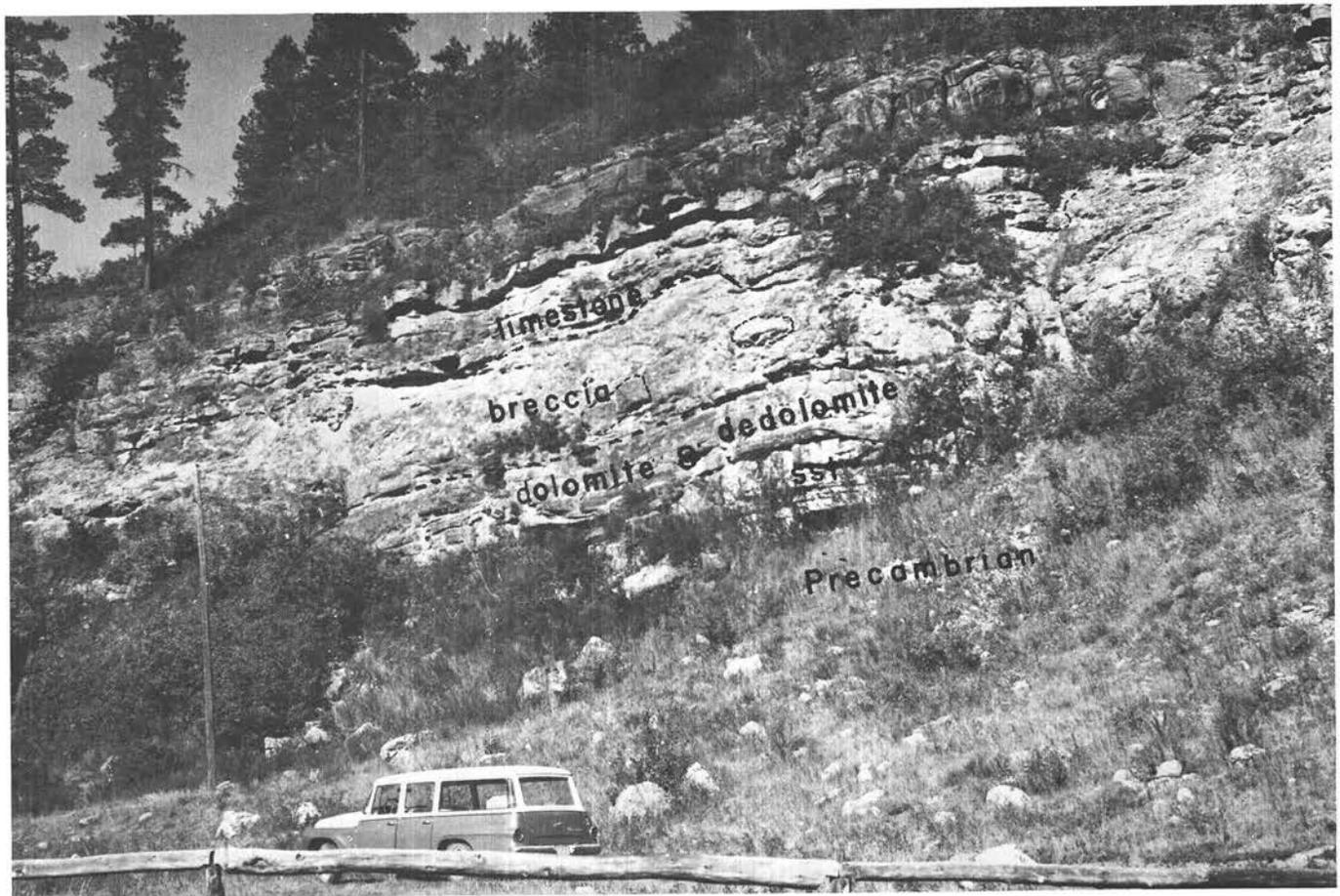


Figure 14

SECTION AT JACKS CREEK, SANGRE DE CRISTO MOUNTAINS

Photograph taken from same location as Sutherland (1963, pl. 11, fig. A). Irregular upper surface of breccia and lower smooth contact on dedolomite and dolomites is illustrated.

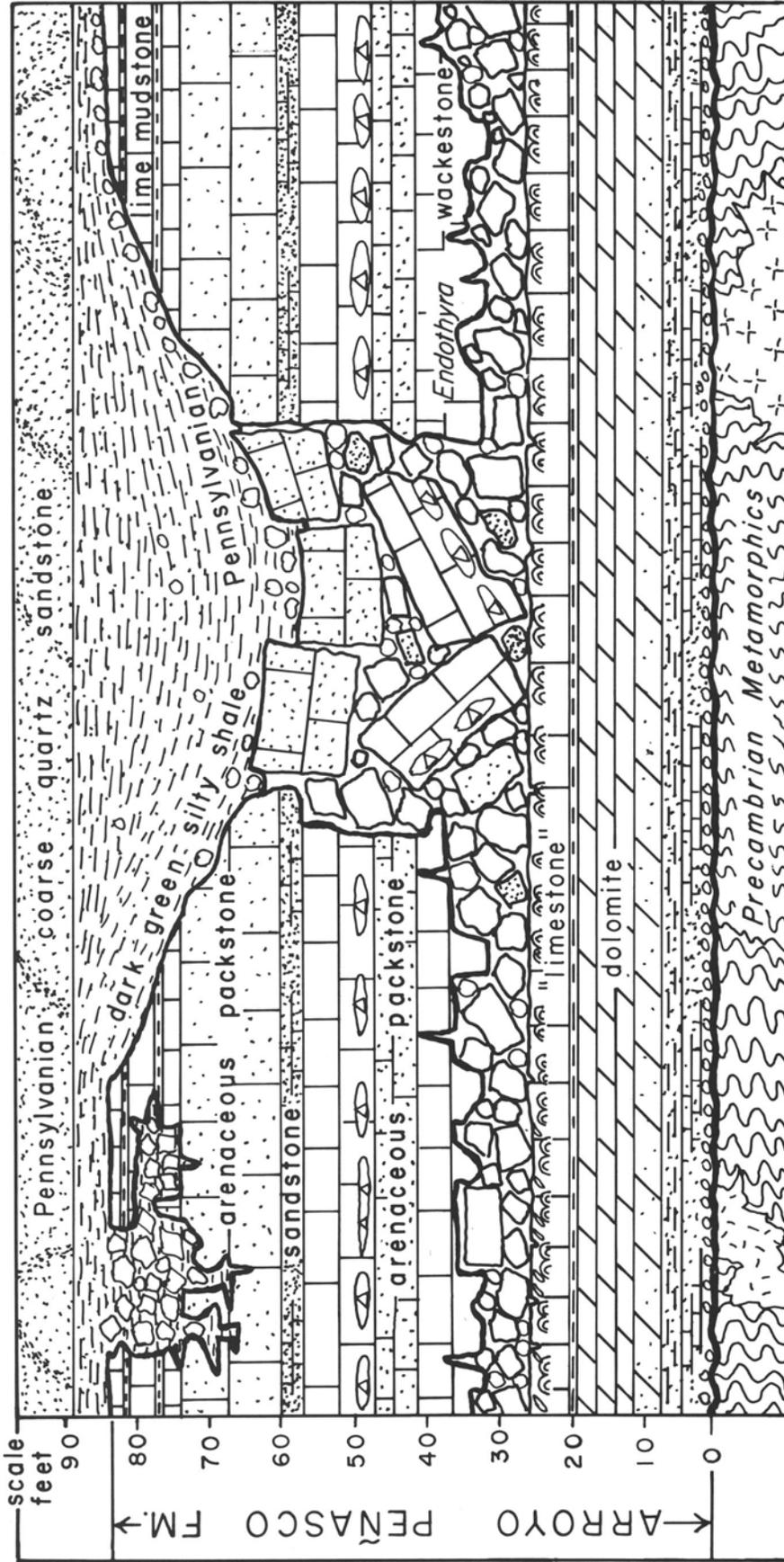


Figure 15

GRAPHIC ILLUSTRATION OF THE SINKHOLE IN THE ARROYO PEÑASCO FORMATION, MANUELITAS CREEK GAP, SANGRE DE CRISTO MOUNTAINS

The sinkhole connects with the breccia lens. The outcrop shows that the brecciation is a post-Arroyo Peñasco depositional phenomenon. The exposure is 200 yards north of Manuelitas Creek Gap. Vertical and horizontal scales are the same.

reworking of the debris, which was then deposited as limestone conglomerates, calcarenite, and fine-grained calcareous mud.

Sutherland and Land (1959) and Sutherland repudiated the concept of solution activity and karsting in the formation of the breccia and believed it the result of a transgressive sea that eroded a limestone cliff. They interpreted the breccia as a basal limestone conglomerate. Sutherland (p. 39) did note that the rock type of the clasts within the limestone conglomerate was markedly different from that of the underlying carbonate rocks. Although he did not know the age of the latter, he did observe the Meramec endothyrids in the breccia clasts. He further commented on the origin of the breccia conglomerate (p. 39), "The mechanics of deposition are not clear. Deposition and partial or complete lithification of the Meramecian limestone sequence from which the boulders were primarily derived would appear to have been followed by elevation of the area above sea level. With the sea advance which followed, the unit was subjected, possibly as a limestone cliff, to high-energy wave action which fragmented the layers, partly rounded the fragments, and deposited them more or less *in situ* as the sea advanced."

I interpret the limestone breccia as resulting from removal by solution in meteoric ground waters of bedded and nodular gypsum and subsequent collapse of the interbedded dolomites and overlying limestones (*see* fig. 12, discussion under de-dolomites, and Stanton (1966)). During the formation of the breccia, channels were opened to the Pennsylvanian erosion surface via sinkholes and fractures (fig. 15). The breccia zone became a channel for increased movement of ground water. A study of the breccia fragments and the calcite matrix between the clasts supports the view of active solutions that dedolomitized the fine-grained sucrose dolomite interbedded with the gypsum and also dissolved and redeposited calcite in this zone. Some of the smaller clasts are composed of equal granular calcite crystals in the 25- to 50-micron size. These are interpreted as fragments of former fine-grained dolomites interbedded with the gypsum but dedolomitized into calcite during the removal of gypsum by solution (fig. 12). Many of the former void spaces between clast fragments are floored with a fine-grained quartz sand. The sand was undoubtedly freed from the adjacent limestone by solution and was "washed" into the voids.

Other parts of the voids were in turn filled with drusy calcite that began by growing on the walls of the clasts. The crystals of drusy calcite follow Bathurst's (1958) rule of void filling by increasing in crystal size from the walls to the interior of the void. The writer is aware that some of the void filling may well be a recent weathering phenomenon. Baltz (p. 2045) reported that the Continental No. 1 Mares—Duran well on the Ocate anticline (sec. 14, T. 23 N., R. 17 E.), 10 miles east of Mora and the Sangre de Cristo Mountains, lost circulation when it penetrated the breccia zone in the subsurface. Apparently in the subsurface, the voids between the clasts are not completely filled or cemented.

CALCITE NEOMORPHISM AND DOLOMITE BEDS

Diagenetic alteration in the carbonate rocks of Cycle 2 and Cycle 3 is not so dramatic as that observed in the collapse breccia lens or the carbonates of Cycle 1.

In the upper beds of Cycle 2 in the San Pedro, Nacimiento, and Sandia mountains is a 9- to 16-foot-thick bed of calcareous dolomites to dolomites with dolomite rhombs in the 20- to 100-micron size; also associated is coarse crystalline poikilotopic calcite. The middle part of Cycle 3 at Lujan Canyon in the Sangre de Cristo Mountains is a 4-foot-thick bed of dolomites with 40- to 60-micron dolomite rhombs. A similar rock type is exposed at Peñasco Canyon in the Nacimiento Mountains, where a 2- to 3-foot-thick bed of calcareous dolomite is composed of 40- to 60-micron dolomite rhombs. These dolomites are believed to have derived from carbonate muds in which the dolomite was of the very early replacement type. The dolomitization probably occurred soon after deposition and under surface conditions (Shinn, Ginsburg, and Lloyd; Illing, Wells, and Taylor).

Neomorphism of calcite to microspar, as defined by Folk (1965), is common in the lime mudstones and wackestones of Cycle 2 in the San Pedro, Nacimiento, and Sandia mountains (pl. 2, fig. 7).

Crystals of 50- to 250-micron replacement celestite are abundant in the lower 10 to 20 feet of dolomites at Placitas in the Sandia Mountains and near Tererro in the Pecos River Canyon section (pl. 2, fig. 1).

Biostratigraphy of the Arroyo Peñasco Formation

Megafossils are rare in the Arroyo Peñasco Formation. The largest and most significant faunas collected to date came from Peñasco Canyon in the Nacimiento Mountains. The majority of the megafossils were collected between 110 and 130 feet above the Precambrian. Smaller collections were found at the section at the northwestern side of the San Pedro Mountains. These are believed to have collected in a zone some 95 to 110 feet above the Precambrian. Fitzsimmons, Armstrong, and Gordon published the identification of these fossils by Drs. Mackenzie Gordon, Jr., and Helen Duncan, who believed that the megafauna suggested a Meramec and, in particular, a St. Louis age for this part of the Arroyo Peñasco Formation. Table 3 gives the brachiopod part of their faunal list.

Baltz and Read (1960), Sutherland, and the writer have carefully searched the other Mississippian outcrops of north-central New Mexico for megafossils; in particular, we all scrutinized the sections in the Sangre de Cristo Mountains with essentially no results.

Details studies of the carbonate rocks clearly indicate that the environment of deposition was not a brachiopod or coral facies. This may have been due to the shallow water and possibly the poor circulation, with resulting alternating seasonal high and low salinities. Figure 7 shows the distribution of fossil fragments associated with the various rock types in the Arroyo Peñasco Formation.

In contrast to the poorly represented megafossils, foraminifera are abundant in certain facies and can be used with confidence to zone the Arroyo Peñasco Formation over north-central New Mexico (fig. 16).

The oldest foraminifera microfauna recognized in the Arroyo Peñasco Formation consists of *Endothyra spinosa* Chernysheva, *Endothyra skippeae* (n. sp.), *Septabrunsiina parakrainica* Skipp, Holcomb, and Gutschick (1966), *Palaeotextularia* sp., and *Hyperamina* sp. *E. spinosa* is characteristic of Late Osage and *E. skippeae* is Osage. *Septabrunsiina parakrainica* is Osage and is found in the Mooney Falls Member of the Redwall limestone of Arizona.

This microfauna of Late Osage age occurs in the chert nodules in the carbonate rocks of Cycle I, which have been subjected to extensive diagenetic changes (fig. 17). Most of these carbonate rocks were dolomitized and, to some degree, were replaced by gypsum; at a later time, they underwent calcification to form coarse crystalline limestone (fig. 12). Except in the chert nodules, the original fauna in these rocks has long been obliterated. The chert formed prior to dolomitization and was a silica replacement that preserved the original depositional fabric and microfauna of the lime mudstones. Late Osage microfaunas have been found in the chert nodules in the basal carbonate rocks of the Arroyo Peñasco Formation at the type section at Peñasco Canyon in the Nacimiento Mountains, at the same stratigraphic level in the San Pedro

TABLE 3. MERAMEC BRACHIOPODS FROM NACIMIENTO AND SAN PEDRO MOUNTAINS

BRACHIOPODA	NACIMIENTO MOUNTAINS								SAN PEDRO MOUNTAINS	
	* 12812	12813	12814	12815	12816	12817	12818	12821	12819	12820
	†1	2	3	4	5	6	7	10	8	9
Strophomenoid, genus and species indeterminate		X					X			
<i>Productus tenuicostus</i> Hall						X	X			
<i>Productus</i> aff. <i>P. parvus</i> Meek and Worthen	X		X			X				
<i>Productus</i> (<i>Scitigerites</i>) <i>scitulus</i> Meek and Worthen									X	
<i>Productus</i> (<i>Linoproductus</i>) <i>pileiformis</i> McChesney						X	?		X	
<i>Productus</i> (<i>Pustula</i> ?) cf. <i>P. indianensis</i> Hall	X								X	
<i>Pugnoides</i> cf. <i>P. ottumwa</i> (White)						X		X		
<i>Dielasma</i> cf. <i>D. sinualum</i> Weller	X									
<i>Girtyella</i> sp.			X						X	
<i>Punctospirifer</i> sp.		X						X		
<i>Spirifer</i> cf. <i>S. pellaensis</i> Weller	?			X		X	X			
<i>Spirifer</i> cf. <i>S. subaequalis</i> Hall							X			
<i>Brachythyris</i> aff. <i>B. altonensis</i> Weller					X					
<i>Brachythyris</i> sp.										X
<i>Eumetria</i> cf. <i>E. verncuiliana</i> (Hall)	X		X	X			X			
<i>Composita</i> sp.									X	
<i>Composita</i> ? sp. indeterminate			X			X	X			

* U.S. Geological Survey collection numbers

† Lot numbers

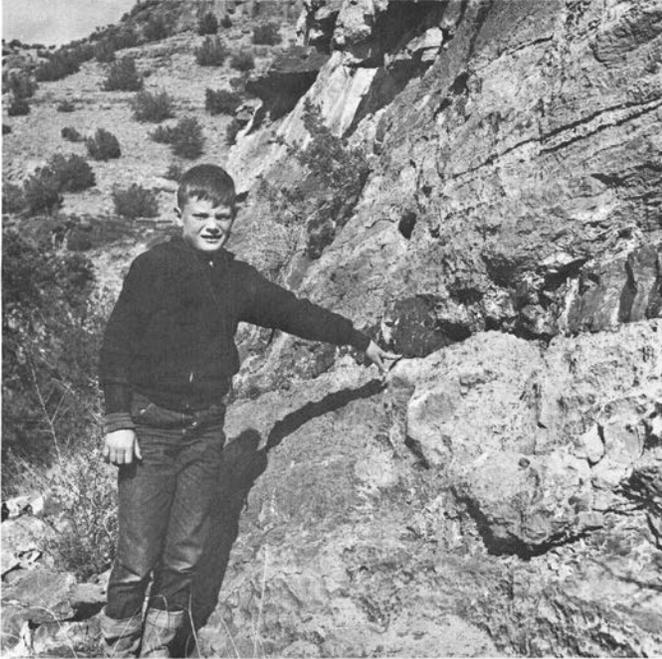


Figure 17

FOSSILIFEROUS CHERT BED SURROUNDED BY DEDOLOMITES,
SANDIA MOUNTAINS

Bed has yielded Upper Osage silicified microfauna of *E. skipper* and *Septabrunsiina parakrainica*

Mountains, and at Placitas in the Sandia Mountains. This microfauna also occurs at Tererro in the Sangre de Cristo Mountains, at Agua Zarca, and above the basal sandstone at Ponce de Leon Springs southeast of Taos.

Late Osage foraminifera faunas are most abundant in sediments containing a large amount of 0.2 to 0.4 mm abraded bioclastic material and are rich in calcispheres. It appears that foraminifera and other bioclastic material with which they are associated have been somewhat winnowed. The chert nodules that portray pelletoid lime mudstone generally do not contain microfaunas. Only small parts of the basal carbonate beds were deposited in an environment marginally favorable for the existence of foraminifera. It is necessary to collect a large number of chert samples, both vertically and horizontally, from this unit and to make numerous thinsections.

At the type section in the Nacimiento Mountains, at a stratigraphic level 40 to 50 feet above the Precambrian, a very Early Meramec microfauna is preserved in chert (fig. 19). The Early Meramec species, *Endothyra spiroides* Zeller occur with *Endothyra* aff. *E. irregularis* (Zeller) and *Endothyra* aff. *E. spinosa* Chernysheva. This latter form differs from *E. spinosa* Chernysheva s.s. in having less pronounced hook-shaped secondary deposits on its chamber floors. It appears to be a more advanced form than *E. spinosa* s.s. *E. spiroides* has been found in clasts from the lower part of the breccia zone at Tererro and Manuelitas Creek.

In the collapse breccia lens (fig. 16) and the ooid packstones of Cycle 3, there is a rich fauna of Early to possibly Middle Meramec foraminifera of *Endothyra macra* Zeller, *E. prodigiosa* Armstrong, *E. irregularis* (Zeller), *Tournayella*

sp., *Ammodiscus* sp., and *Turbertina* sp. This fauna is present in the Arroyo Peñasco Formation in the San Pedro, Nacimiento, Sandia, and Sangre de Cristo mountains. The higher beds of Cycle 3 are lower energy sediments with a high percentage of quartz sand and lime mud and are generally devoid of an endothyrid fauna.

The sensitivity of the Early Meramec endothyrids to their environment is very apparent in the Arroyo Peñasco Formation. They are most abundant in the ooid facies, are less common in the oolitic facies, and become extremely rare in the lime mud and arenaceous facies. Figure 7 graphically portrays this. Observations in the Mission Canyon formation of Montana (J. L. Wilson, personal communication) agree with those of the writer. Presumably, endothyrids lived on or near shoal areas and were often buried in lime sands deposited in water of moderate energy.

REGIONAL BIOSTRATIGRAPHIC RELATIONSHIPS

UPPER OSAGE

The Upper Osage *Endothyra spinosa* zone of the Arroyo Peñasco Formation is believed to be a northward pelletoid lime mudstone facies of the open marine encrinite packstones and grainstones of the Upper Osage Kelly Formation of the Ladron, Lemitar, and Magdalena mountains (fig. 21) of



Figure 18

CLOSE-UP VIEW OF BRECCIA BED

The breccia results from Early Pennsylvanian solution activity; void space between the limestone fragments is filled with dark-green shales and siltstones from the overlying Pennsylvanian clastics.

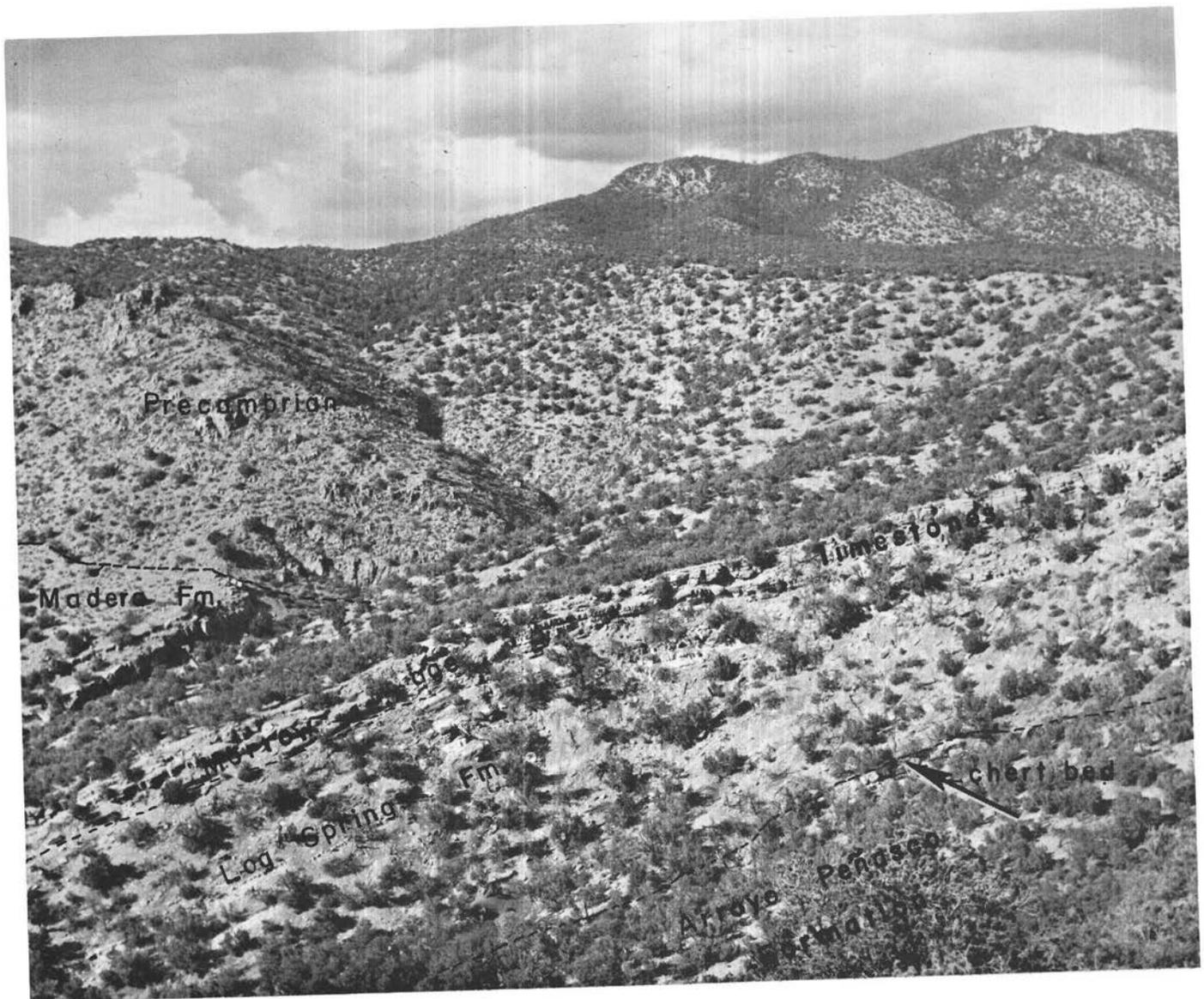


Figure 19

FOSSILIFEROUS MERAMEC CHERT BED AND LOG SPRINGS FORMATION

View looking north in Pinos Canyon, Nacimiento Mountains. Smalluesta formed by the arenaceous, bioclastic, Morrow-age limestone unconformably overlies the red-bed clastics of Log Springs Formation. The red beds, in turn, rest on a karsted and undulating surface of the Meramec Arroyo Peñasco limestone and replacement fossiliferous chert. Arrow points to chert bed that produced a large number of megafossils listed by Fitzsimmons et al. (1956).

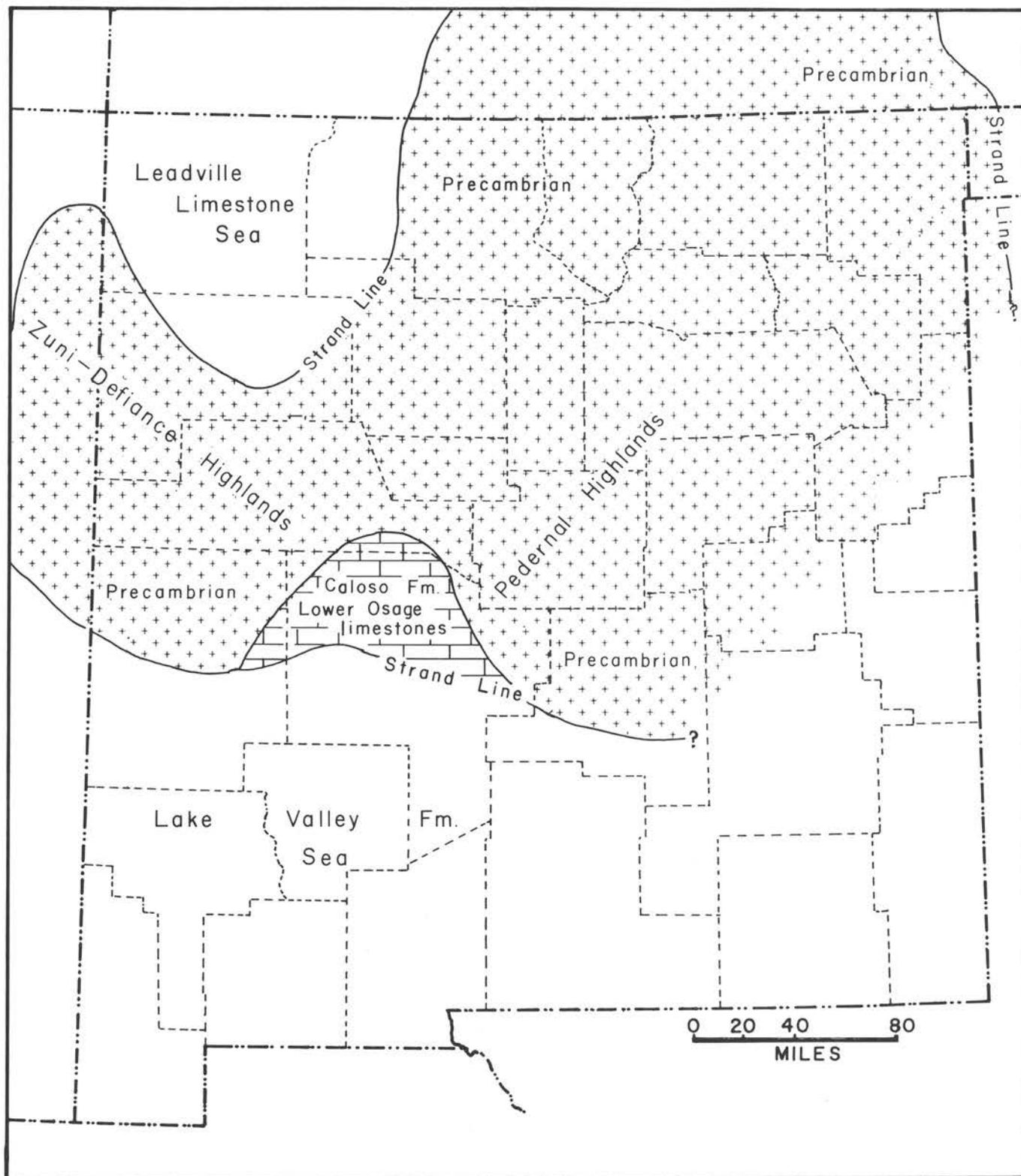


Figure 20

PALEOGEOGRAPHY OF NEW MEXICO AT THE END OF *ENDOTHYRA TUMULA* (ZELLER) ZONE AND BEFORE THE BEGINNING OF UPPER OSAGE TIME, *ENDOTHYRA SPINOSA* CHERNYSHEVA ZONE

In west-central New Mexico, the upper Osage sediments transgressed over the Lower Osage Caloso Formation (Armstrong, 1958b, 1963). The Zuni-Defiance and Pederal Highlands were of subdued relief and contributed little or no detrital material to the surrounding seas.

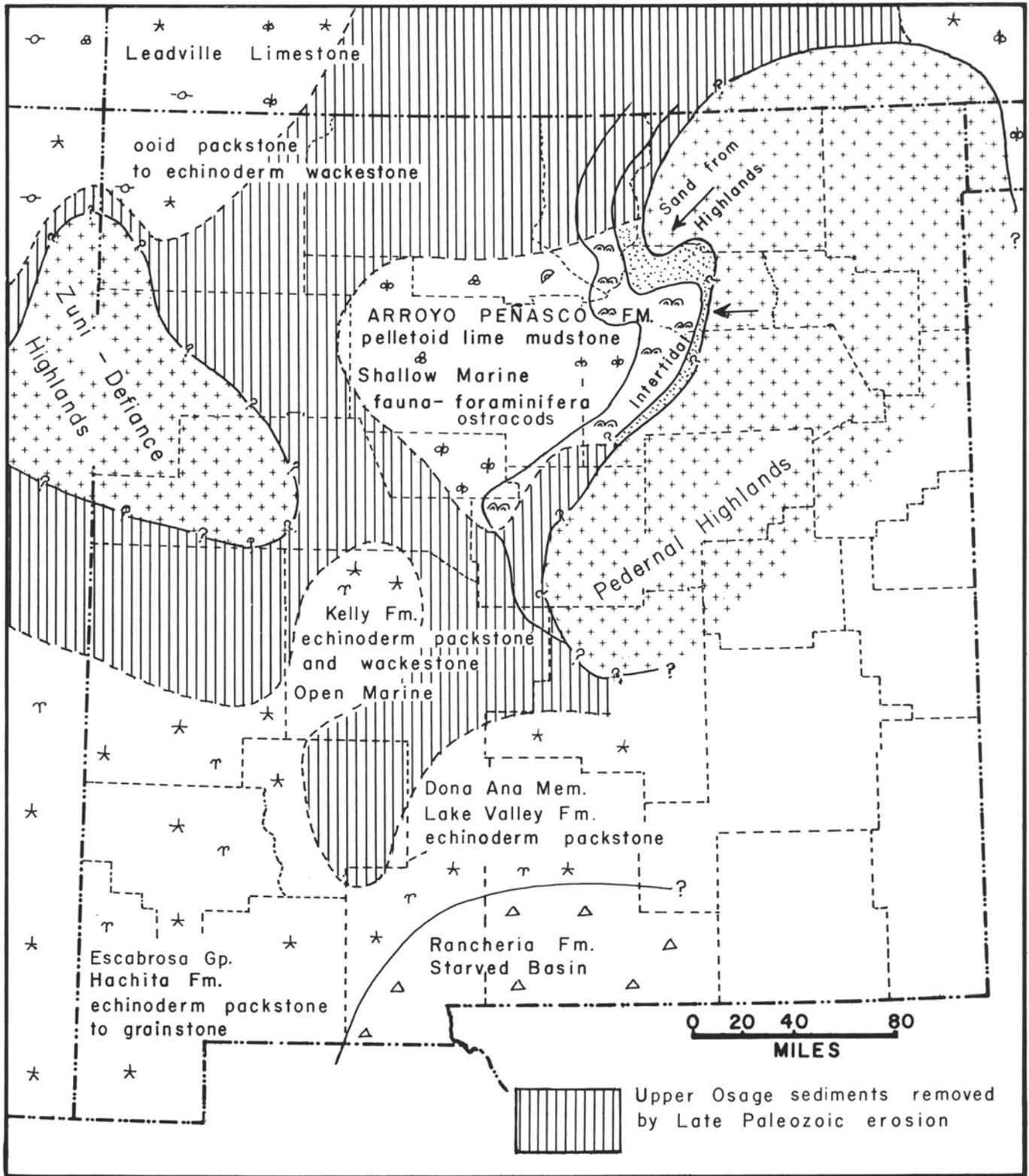


Figure 21

SUGGESTED RESTORED DIAGRAMMATIC REPRESENTATION OF CARBONATE FACIES AND DEPOSITIONAL PATTERNS IN NEW MEXICO AT THE INITIAL STAGE OF ARROYO PEÑASCO CARBONATE SEDIMENTATION
 This is within the *Endothyra spinosa* Chernysheva zone, Keokuk stage, Upper Osage.

west-central New Mexico. The fauna of the Kelly Formation is large and composed of brachiopods, blastoids, and corals. It was described and illustrated by Armstrong (1958a) and consists of the diagnostic species shown in Table 4.

TABLE 4. FAUNA OF THE KELLY FORMATION OF THE MAGDALENA, LEMITAR, AND LADRON MOUNTAINS, NEW MEXICO
(After Armstrong (1958b))

FAUNA	MAGDALENA Mts.	LEMITAR Mts.	LADRON Mts.
Brachiopoda			
<i>Linoproductus</i> sp.	X	X	X
<i>Echinoconchus</i> ? sp.	X	—	—
<i>Chonetes</i> cf. <i>illinoisensis</i> Worthen	—	—	X
<i>Tetracamera</i> cf. <i>T. subtrigona</i> (Meek and Worthen)	X	X	X
<i>Tetracamera subcuneata</i> (Hall)	X	X	X
<i>Rhynchopora persinuata</i> (Winchell)	—	—	X
<i>Spirifer tenuicostatus</i> Hall	X	X	X
<i>Spirifer grimesi</i> Hall	X	X	X
<i>Brachythyris suborbicularis</i> (Hall)	X	X	X
<i>Athyris</i> aff. <i>A. lamellosa</i> (Leveille)	X	X	X
<i>Cleiothyridina hirsuta</i> (Hall)	X	X	X
<i>Cleiothyridina?</i> <i>parvirostris</i> (Meek and Worthen)	X	—	—
<i>Cleiothyridina obmaxim</i> (McChesney)	X	X	X
<i>Dimegelasma neglectum</i> (Hall)	—	X	X
Blastoidea			
<i>Pentremites conoideus</i> Hall	X	X	X
<i>Orbitremites floweri</i> , Armstrong	X	X	X
Coelenterata			
<i>Zaphriphyllum casteri</i> , Armstrong	X	X	X

The fauna of the crinoid packstones and wackestones of the Upper Osage Doña Ana Member of the Lake Valley Limestone in the San Andres and Sacramento mountains of south-central New Mexico has not been studied in detail or illustrated and documented, but the Doña Ana Member is believed to be a biostratigraphic equivalent to the Upper Osage part of the Arroyo Peñasco Formation.

At Davis' Creek in the Piedra River Canyon of the San Juan Mountains (fig. 20), beds younger than Late Osage in the Leadville Limestone have been removed by Pennsylvanian erosion. At Rockwood Quarry, north of Durango, Colorado, beds as young as the base of the *Endothyra spinosa* zone are present in the Leadville. In the subsurface of the San Juan Basin, the E. *spinosa* zone has been stripped off by Early Pennsylvanian erosion except in the extreme Four Corners region and on the northeastern flank of the Zuni—Defiance uplift. *E. spinosa* and *Septabrunsiina parakrainica* are present to the west in the Mooney Falls Member of the Redwall Limestone of the Grand Canyon region (Skipp, Holcomb, and Gutschick).

MERAMEC

The Meramec regional equivalents (fig. 22) to the upper part of the Arroyo Peñasco Formation were extensively removed by erosion during Late Mississippian and Early Pennsylvanian time (fig. 23). The nearest known biostratigraphic equivalents to the southwest are the encrinite packstones of the Hachita Formation, Escabrosa Group, in the Klondike Hills southwest of Deming, New Mexico. Starved basin equivalents may be present to the south in the Rancheria

Formation of the southern San Andres (Kottlowski et al., 1956), Sacramento, Franklin, and Hueco mountains (Kottlowski, 1963).

Lower Meramec rocks are believed to have been stripped off before deposition of Pennsylvanian sediments in the central and western parts of the San Juan Basin. They are present in the subsurface of the Black Mesa Basin, Arizona, in the Redwall Limestone, and in the subsurface of the Paradox Basin in the Leadville Limestone. Maher and Collins (1949) reported Upper Osage and Meramec carbonate strata in the subsurface of western Oklahoma and northwest Texas that may be the biostratigraphic time equivalents to the Arroyo Peñasco Formation.

LATE MISSISSIPPIAN AND EARLY PENNSYLVANIAN SOLUTION ACTIVITY AND EROSION

The extensive removal of Arroyo Peñasco Formation strata by Late Paleozoic erosion obscures the exact time that carbonate sedimentation ceased (fig. 23). The nearest preserved outcrops of Late Meramec and Chester sedimentary rocks are in southern and southwestern New Mexico. The lower part of the Meramec *Endothyra scitula* Toomey zone, in the Big Hatchet Mountains and Klondike Hills of southwestern New Mexico, consists of massive, terrigenous-free carbonate rocks of oolitic to bioclastic packstones and wackestones. The upper part of this zone is characterized by an influx of sand and shales, suggesting the beginning of tectonic unrest in central and northern New Mexico. Thus, in southwestern New Mexico, the oldest record in the Escabrosa Group of a significant influx of terrigenous material is slightly younger than the youngest known Mississippian marine sediments of north-central New Mexico. The evidence suggests that carbonate sedimentation in north-central New Mexico ceased by mid- or late Meramec time.

Mississippian strata in west-central and northern New Mexico were folded and faulted and subjected to extensive removal and truncation before Pennsylvanian deposition (Armstrong, 1955, 1958a, 1962). The Arroyo Peñasco Formation in outcrop in many places consists of discontinuous erosional remnants beneath the Pennsylvanian clastic rocks. It thins out in Tijeras Canyon of the Manzanita Mountains from about 18 feet thick to 0 in less than a sixth of a mile. It is discontinuous north of Bosque Peak in the Manzano Mountains. Kelley's map shows the 80-foot-thick Mississippian section at Placitas in the Sandia Mountains thinning to 0 in a few miles to the south and west. The Mississippian section on the northwest side of the San Pedro Mountains thins out rapidly to the east and southeast where Pennsylvanian and Permian sediments rest on the Precambrian.

The most continuous exposure of the Arroyo Peñasco Formation is in the Sangre de Cristo Mountains (Dane and Bachman; Sutherland). Here, late Mississippian and Early Pennsylvanian vadose weathering and solution activity has had a pronounced effect on the Arroyo Peñasco Formation, resulting in the development of collapse breccia lens and sinkholes. An excellent exposure of a sinkhole is zoo yards north of Manuelitas Creek Gap in the Sangre de Cristo

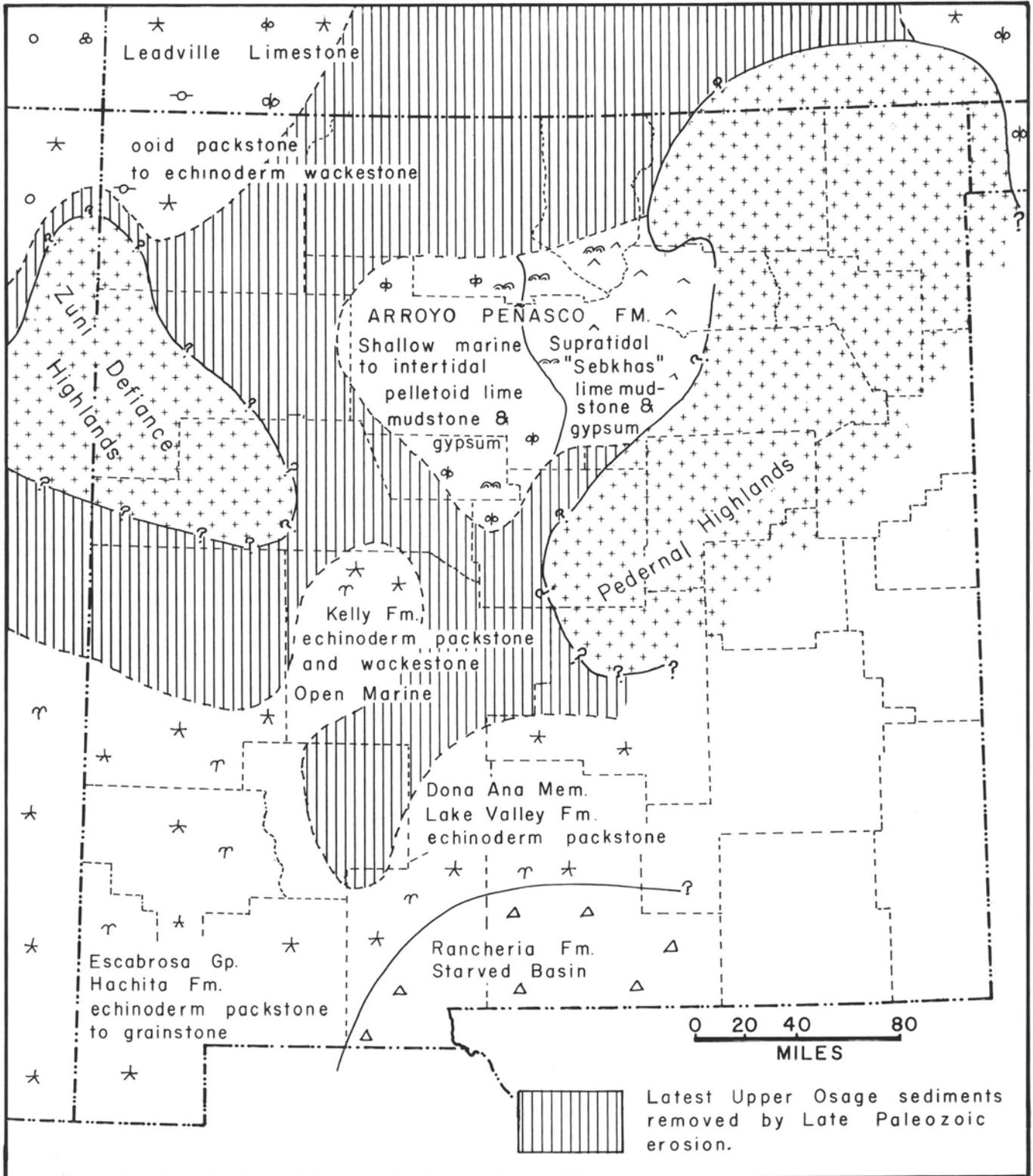


Figure 22

SUGGESTED RESTORED DIAGRAMMATIC REPRESENTATION OF CARBONATE FACIES AND DEPOSITIONAL PATTERNS IN NEW MEXICO AT THE END OF THE ENDOTHYRA SPINOSA CHERNYSHEVA ZONE, KEOKUK, OSAGE

Comparison of this map with Figure 21 shows the development of the first carbonate depositional cycle within the Arroyo Peñasco Formation as a progradation of intertidal and supratidal carbonates westward over marine carbonate muds.

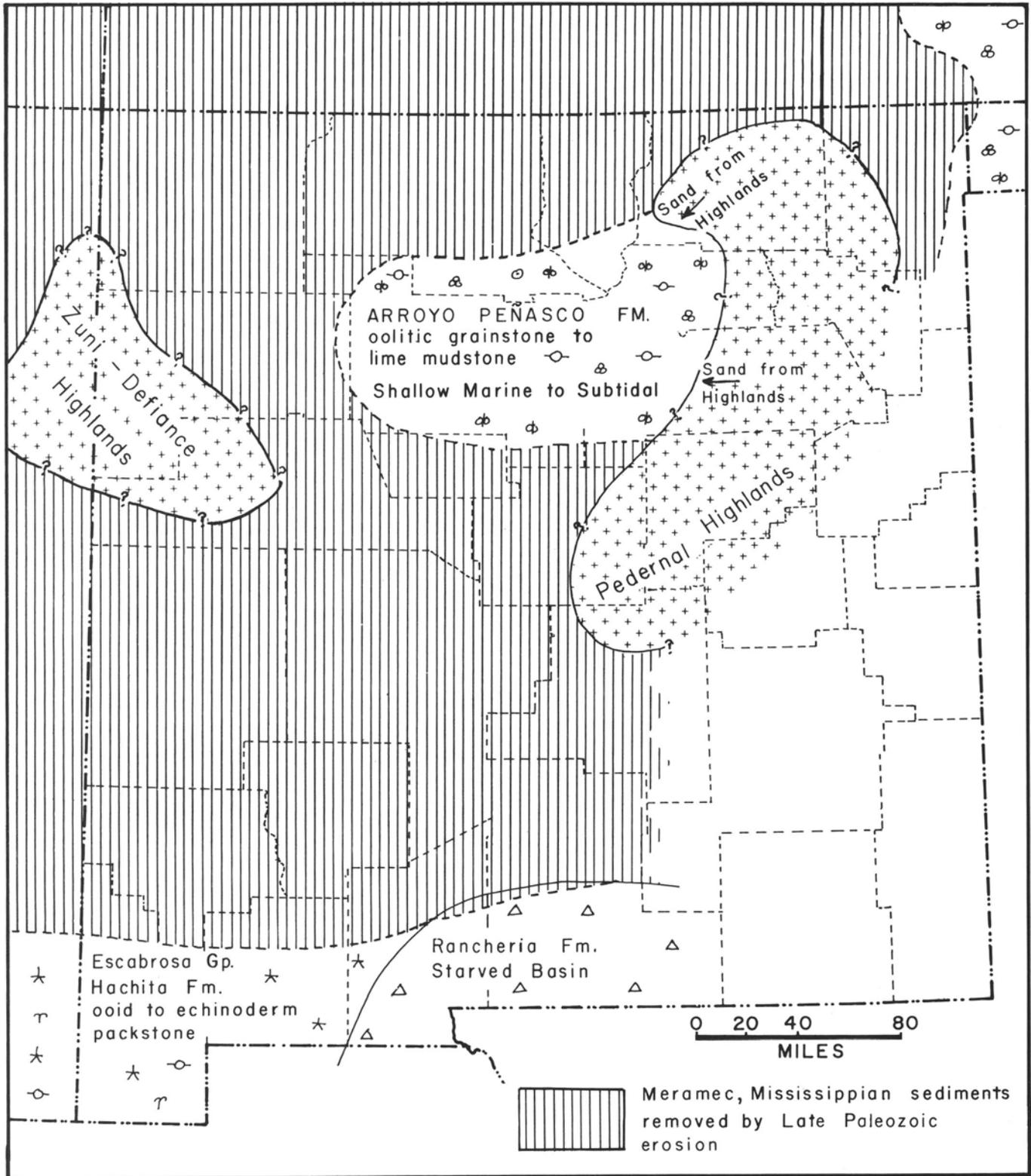


Figure 23

SUGGESTED RESTORED DEPOSITIONAL PATTERN FOR NEW MEXICO DURING *ENDOTHYRA SPIROIDES* ZELLER AND THE BASAL PART OF THE *E. SCITULA* TOOMEY ZONES

Sediments of this age have been extensively removed by Late Paleozoic erosion.

Mountains; it connects with the breccia lens, penetrating the Meramec carbonate rocks from the Early Pennsylvanian erosion surface (fig. 15).

Within the Arroyo Peñasco Formation at the Manuelitas Creek section, a thin sandstone bed 58 to 60 feet above the Precambrian is brecciated in the sinkhole, and cobbles of it have fallen into the zone of the breccia lens.

In the Pecos River Canyon, Sutherland and Land (p. 1683) and Sutherland (p. 27-28) noted a significant, but small, percentage of boulders and cobbles of sandstone within the breccia lens. They believed the sandstone cobbles supported the theory that the breccia formed as the result of the erosion of a limestone cliff by a transgressive sea and the formation of a basal limestone conglomerate on which the overlying Meramec carbonate rocks were deposited.

Other solution activity beneath the Pennsylvanian—Mississippian contact is well exposed at the Manuelitas Creek section. Prior to the deposition of the Pennsylvanian sediments, pockets of limestone breccia formed at the top and in the upper third of the Arroyo Peñasco Formation. The spaces between the clasts and the enlarged joints were subsequently filled by the olive-green and dusky yellowish-green shales and siltstone of the basal Pennsylvanian sediments (fig. 18). Excellent exposures of the breccia, enlarged joints, and green shale infillings can be studied along the north side of Manuelitas Creek Gap.

The highest 3 to 6 feet of the Arroyo Peñasco Formation at Placitas in the Sandia Mountains contain a zone of well-developed pisolites (pl. 2, fig. 8), interpreted as the result of Late Mississippian—Early Pennsylvanian percolating vadose water below the soil zone (Dunham, 1965, p. 338).

The section at Peñasco and Pinos canyons in the Nacimiento Mountains has undergone extensive solution activity, the effects of which can be seen from about 35 feet above the Precambrian and, with increasing intensity upward, to the Pennsylvanian contact. Solution activity resulted in the development of numerous cavities, vugs, greatly enlarged joints and bedding planes, and associated "solution recrystallization" of some of the limestones. Most of the voids formed by vadose waters have been filled with red shales and siltstones from the overlying Pennsylvanian elastics.

A vitreous to chalky, very light-gray to pinkish-gray chert occupies the highest 10 feet of the Arroyo Peñasco Formation at Peñasco Canyon. This chert (fig. 19) has yielded a large fauna of brachiopods (Fitzsimmons, Armstrong, Gordon) and replaces an arenaceous packstone and wackestone. The chert is believed to be the result of Early Pennsylvanian silica-rich vadose water.

Pieces of a similar type of chert have been observed at the San Pedro Mountains outcrop as rubble and float on the forest floor along the boundary between the Pennsylvanian—Mississippian contact. At the measured section in the San Pedro Mountains, the chert was not found.

LOG SPRINGS FORMATION AND ASSOCIATED OVERLYING RED BEDS

A red-bed sequence of continental elastic sediments from 40 to 60 feet thick is unconformably overlain by fossiliferous, arenaceous limestones of Morrow (Early Pennsylvanian) age

at Peñasco and Pinos canyons in the Nacimiento Mountains (fig. 19). Armstrong (1955) proposed the name *Log Springs Formation* for this sequence of rocks. The lower 8 to 10 feet of this unit consist of red to dusky red, silty, hematitic shales. The contact with the underlying Arroyo Peñasco Formation is very irregular with abundant solution-rounded pebbles and cobbles of limestone and chert fragments. The red shale contains numerous 1 to 5 mm "oolites or pisolites" of dark-red hematite. This shale unit appears to be a terra rossa soil that has been slightly, if at all, reworked. Above the shale lie 30 to 40 feet of arkosic to conglomeratic, cross-bedded, argillaceous dusky red to mottled pale-orange sandstones. They occur in beds from a few inches to almost 10 feet thick and are cross-bedded, and both sandstones and shales are lenticular in shape. Within these elastic beds are numerous rounded pebbles to cobbles of Arroyo Peñasco chert and carbonate rocks plus an assorted mixture of Precambrian gneiss, greenstones, and quartz. Clastic material tends to become coarser in the higher beds of the Log Springs Formation. The formation is truncated by an angular unconformity and is overlain by argillaceous, arenaceous, bioclastic packstones of Morrow, Lower Pennsylvanian age. The unconformity is marked by abundant channels and conglomerate channel fill.

The Log Springs Formation resembles the Molas Formation of the San Juan Mountains of Colorado. Merrill and Winard (1958) believed that the Molas Formation was produced in part from residual soil and other materials being reworked and deposited, largely by streams in a terrestrial environment, the upper part of the Molas Formation being deposited in a marine environment.

The lower hematitic red shales of the Log Springs Formation are believed to be a residual soil, but the higher sandstones appear to be in part derived from reworked residual soil and coarse detrital material stripped from elevated uplands of Mississippian limestone and exposed metamorphic Precambrian terrain.

The Log Springs Formation differs from the Molas Formation in having coarser clastic material in the upper two thirds of the unit, the detritus being composed largely of Precambrian debris and the sandstone being cross-bedded and lenticular in shape. According to Merrill and Winard, the higher beds of the Molas Formation are marine, whereas the Log Springs Formation is apparently totally terrestrial in origin.

On the northwest side of the San Pedro Mountains in the zone where the Pennsylvanian—Mississippian contact occurs, red shales and arkosic sandstone similar to the Log Springs Formation are found as float on the forest floor. These do not occur at the measured section, where the basal Pennsylvanian consists of brown quartz conglomeratic sandstones.

A red to dusky red, hematitic, silty mudstone 1 to 8 feet thick lies on top of the Arroyo Peñasco Formation and below the massive sandstone of the Sandia Formation at Placitas section in the Sandia Mountains.

Red, terra rossa soils or regolithlike material has not been observed in the Sangre de Cristo Mountains. The basal Pennsylvanian elastic rocks are typically gray to brown and frequently grayish olive-green to grayish-green shales or siltstone and/or pale-brown to light-brown, massive, cross-bedded, quartz sandstone.

No recognizable fossils have been found in the Log Springs Formation, which rests on beds possibly as young as St. Louis, Meramec age, and is unconformably overlain and truncated by arenaceous carbonate rocks that contain a rich microfauna of *Millerella* spp. and megafossils of brachiopods, corals, and mollusca. The brachiopods are *Schizophoria oklabomae* Dunbar and Condra, *Composita subtilita* (Hall), *Spirifer* spp., and *Hustedia* sp. The fauna is Morrow, Early Pennsylvanian age. At the base of the Log Springs Formation, the basal regolith, terra rossa, as well as some of the sandstone, may have been formed in Late Mississippian time. Thus, the age of the Log Springs Formation may be Late Mississippian and/or Early Pennsylvanian.

GEOLOGIC HISTORY AND LITHOFACIES MAPS

Late Mississippian and Early Pennsylvanian erosion extensively removed Mississippian sediments from northern and central New Mexico (figs. 21, 22, 23). Reconstruction of the facies and distribution of Mississippian carbonate beds is fraught with difficulties, and with this consideration in mind, the following sequence of events is presented.

The Arroyo Peñasco Formation of north-central New Mexico represents the maximum advance of Mississippian seas in New Mexico. This advance, begun in the early part of the period, was a progressive flooding with only minor fluctuations and was accomplished by an eastward transgres-

sion from the Cordilleran miogeosyncline through the Paradox basin, around the north flank of the Zuni—Defiance highlands, and into areas of the present-day San Juan Basin. Another transgression came from southern New Mexico northward between the Pedernal highlands and the Zuni—Defiance uplift. By late Early Osage time, the seaways had advanced as shown in Figure 20. By Late Osage time, the seaways joined over north-central New Mexico, covering the weakly developed transcontinental arch. The Zuni—Defiance highlands were now an island. In Late Osage time, the Pedernal—Sierra Grande highlands are believed to have blocked connection with the Osage seaway of western Oklahoma and northwestern Texas. The Early Meramec sea, probably extending to the north in Colorado from the present-day Sangre de Cristo Mountains to western Kansas and Oklahoma, may have had direct access across this highland to connect with the Meramec sea of northwestern Texas and Oklahoma. Otherwise, the Early Meramec sea, which was a continuation of the Late Osage seaway, probably maintained the same sea-land relationship.

Meramec rocks were more extensively removed than were Osage strata by Late Mississippian and Early Pennsylvanian erosion (fig. 23).

Figures 24 through 43 show the various measured sections, while Figures 44 and 45 are index maps of the Lujan Canyon and Turquillo sections and the Coco City, Mora Gap, and Manuelitas Creek Gap sections, respectively.

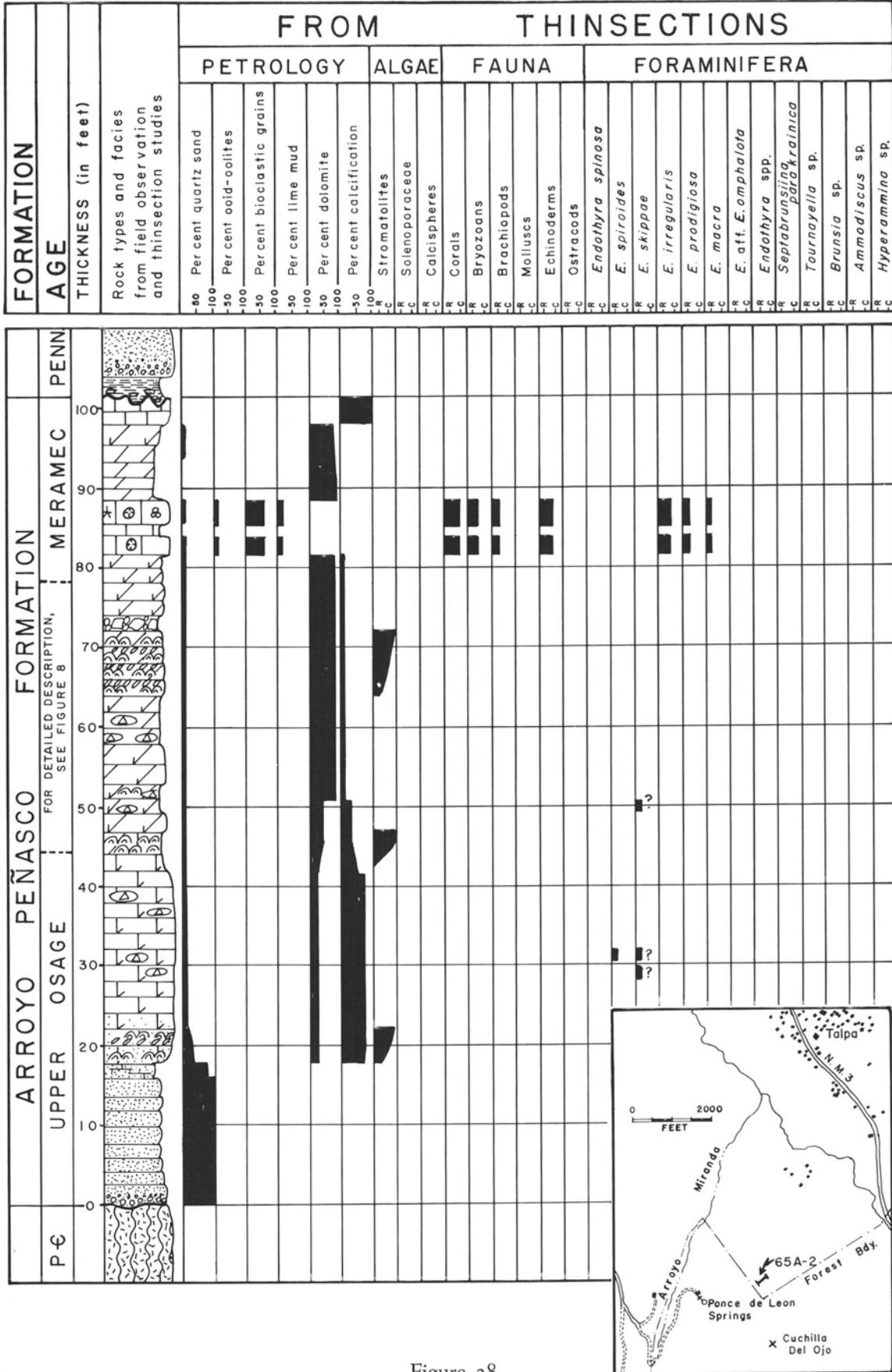


Figure 28

PONCE DE LEON SPRINGS (TALPA) SECTION, SANGRE DE CRISTO MOUNTAINS (65A-2)

Index map, 1:24,000, from Ranchos de Taos quadrangle (1964 edition).

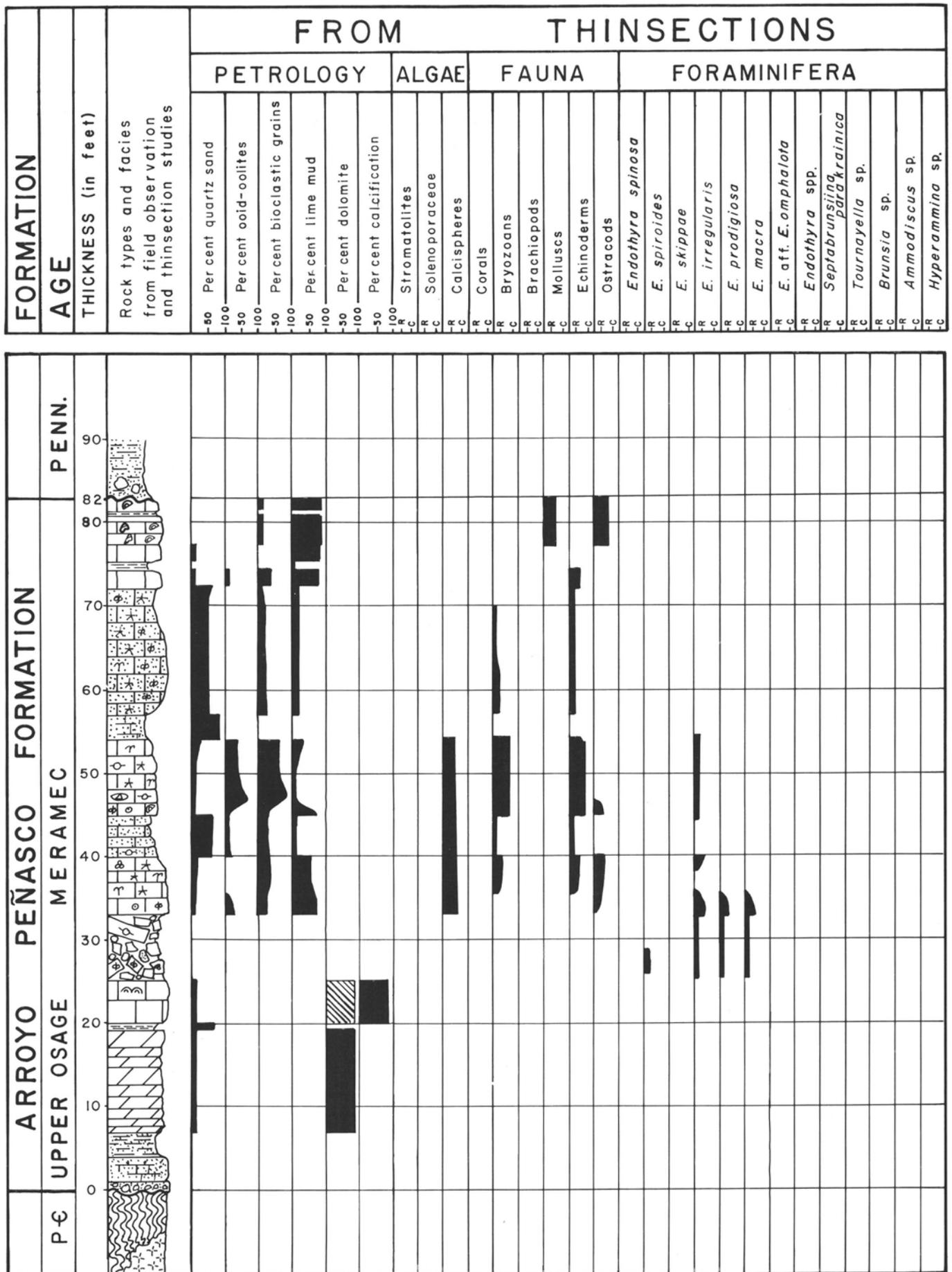


Figure 34
 MANUELITAS CREEK GAP SECTION, SANGRE DE CRISTO MOUNTAINS (65A-7)
 Figure 45 gives location of measured section.

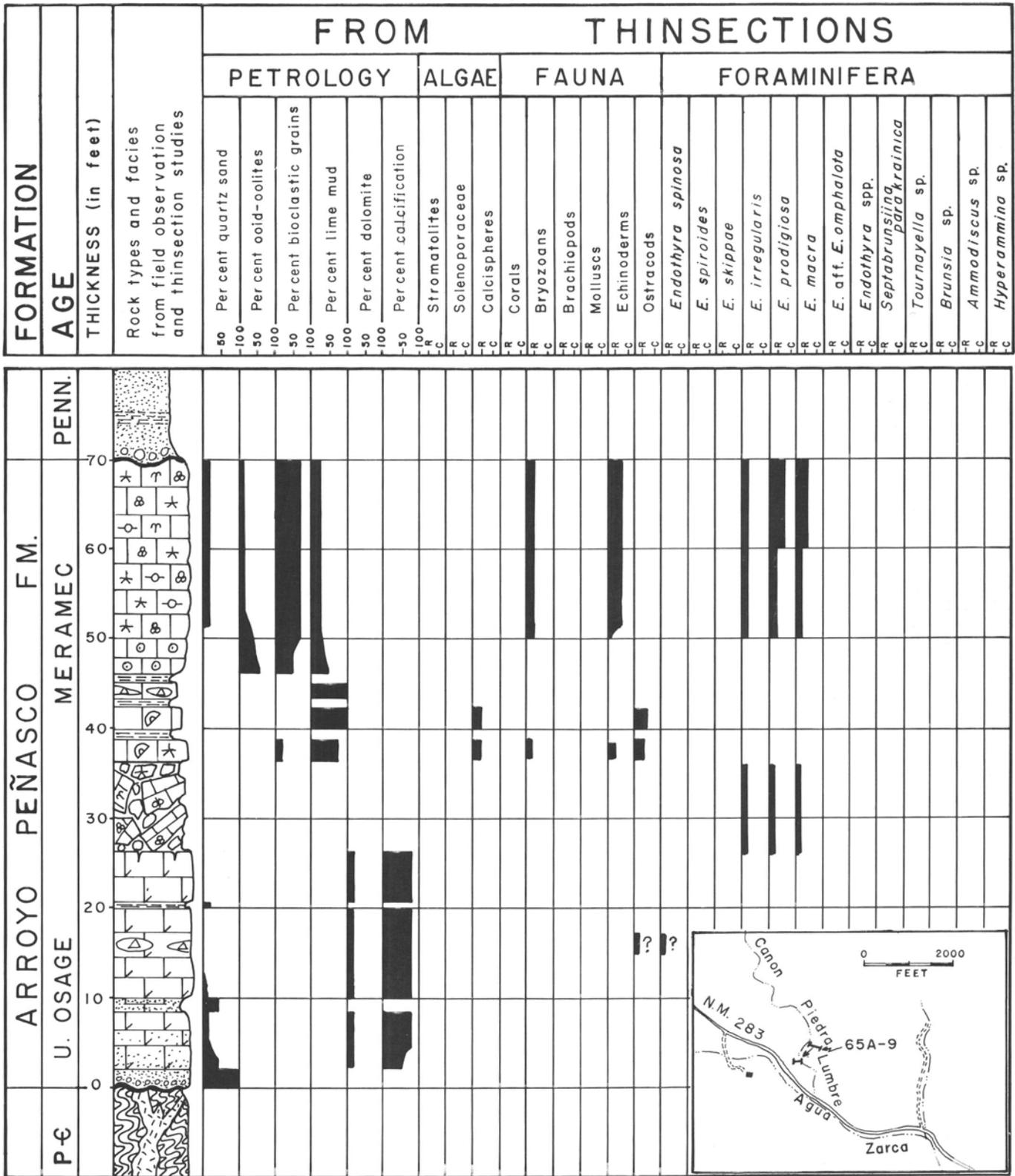


Figure 36

AGUA ZARCA SECTION, SANGRE DE CRISTO MOUNTAINS (65A-9)

Section is 4.6 miles west of U.S. Highway 85. Index map, 1:24,000, from Ojitos Frios quadrangle (1961 edition).

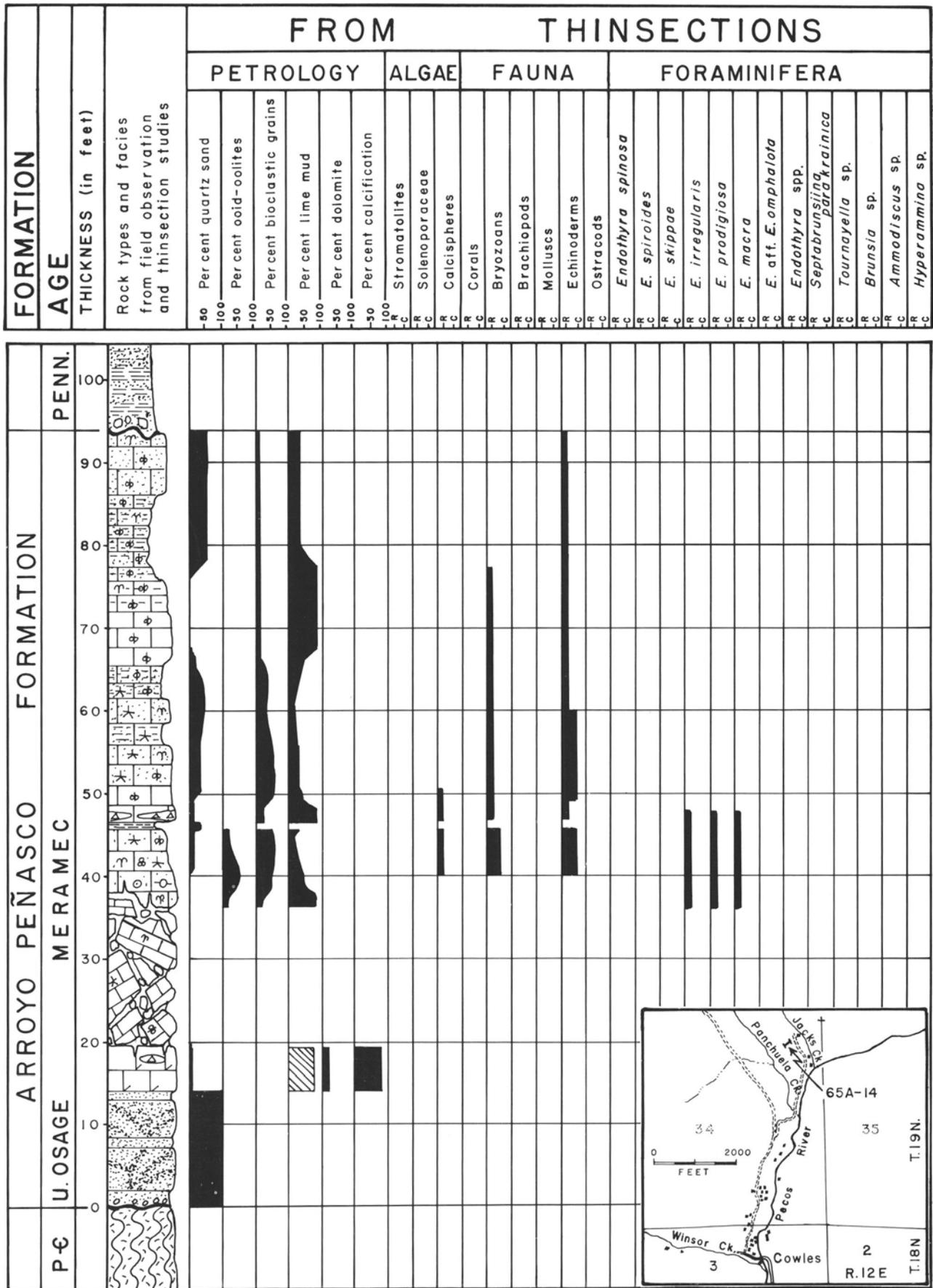


Figure 37

JACKS CREEK SECTION, SANGRE DE CRISTO MOUNTAINS (65A-14)

Section measured 1000 feet north of confluence of Jacks Creek and Pecos River on the west canyon wall; Figure 14 is a photograph of the outcrop. Index map, 1:24,000, from Cowles quadrangle (1961 edition).

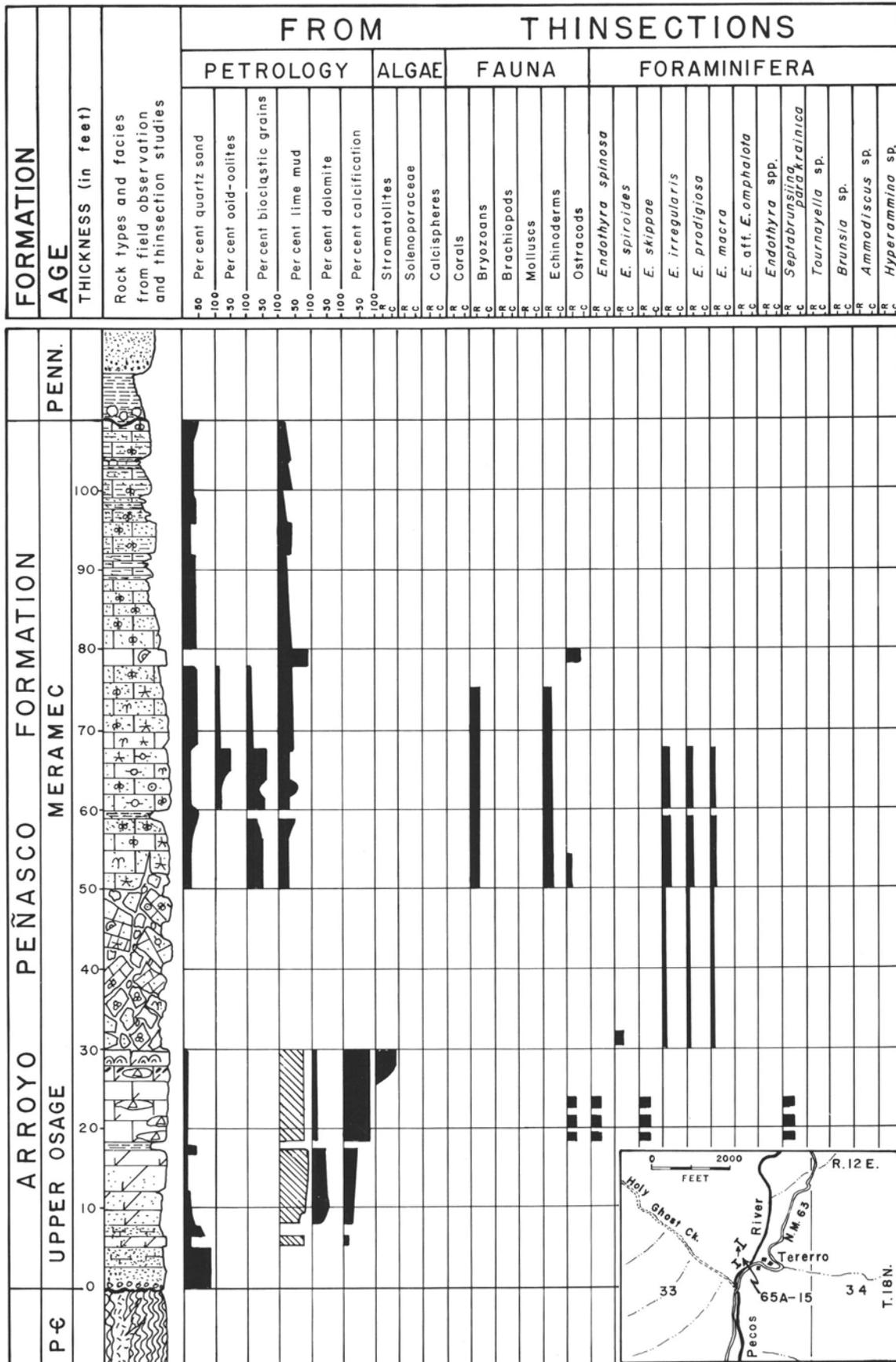


Figure 38

TERERRO SECTION, PECOS RIVER CANYON, SANGRE DE CRISTO MOUNTAINS (65A-15)

Index map, 1:24,000, from Rosilla Peak quadrangle (1961 edition).

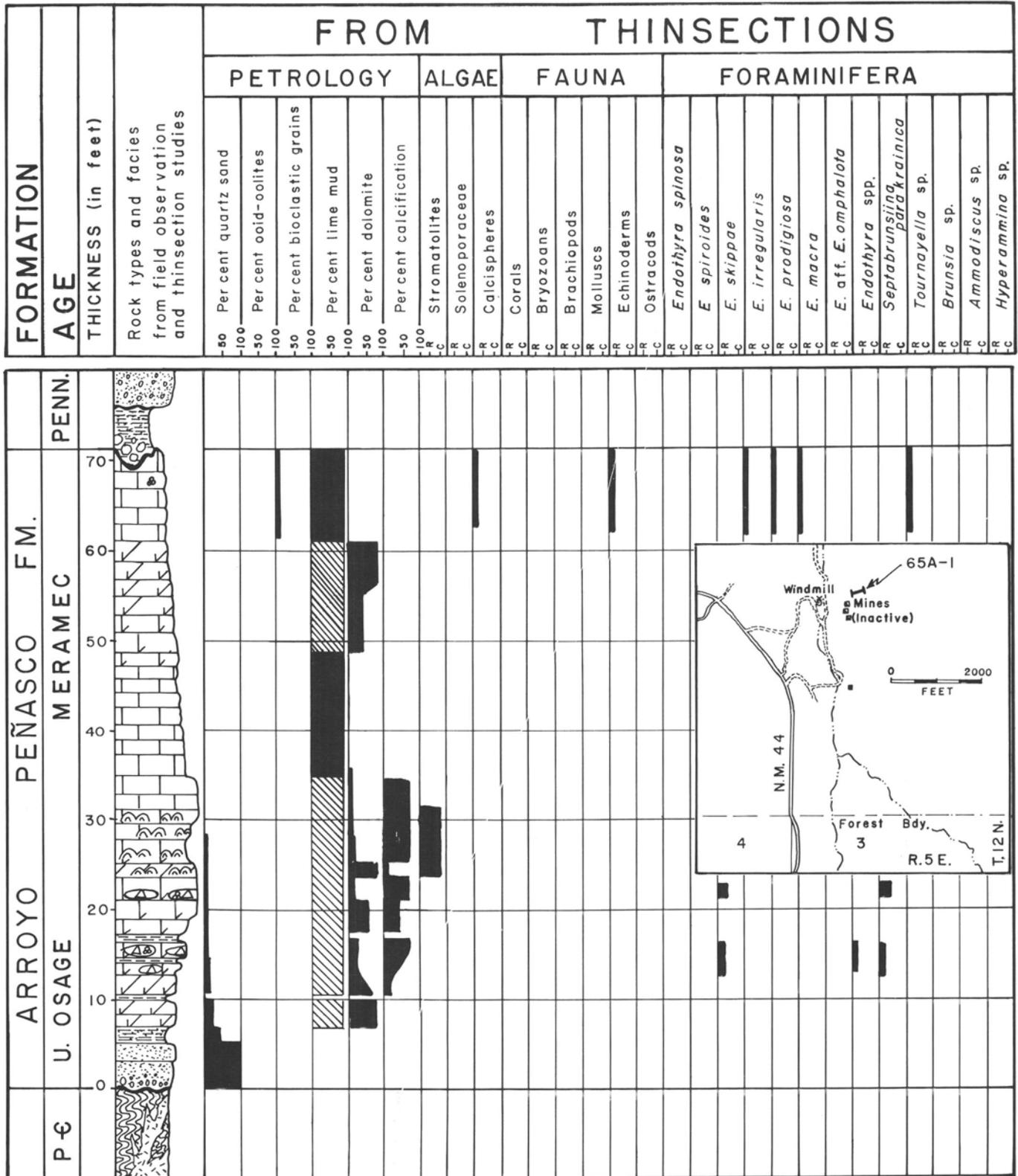


Figure 40

PLACITAS SECTION, SANDIA MOUNTAINS (65A-1)

Index map, 1:24,000, from Rosilla Peak quadrangle (1961 edition).

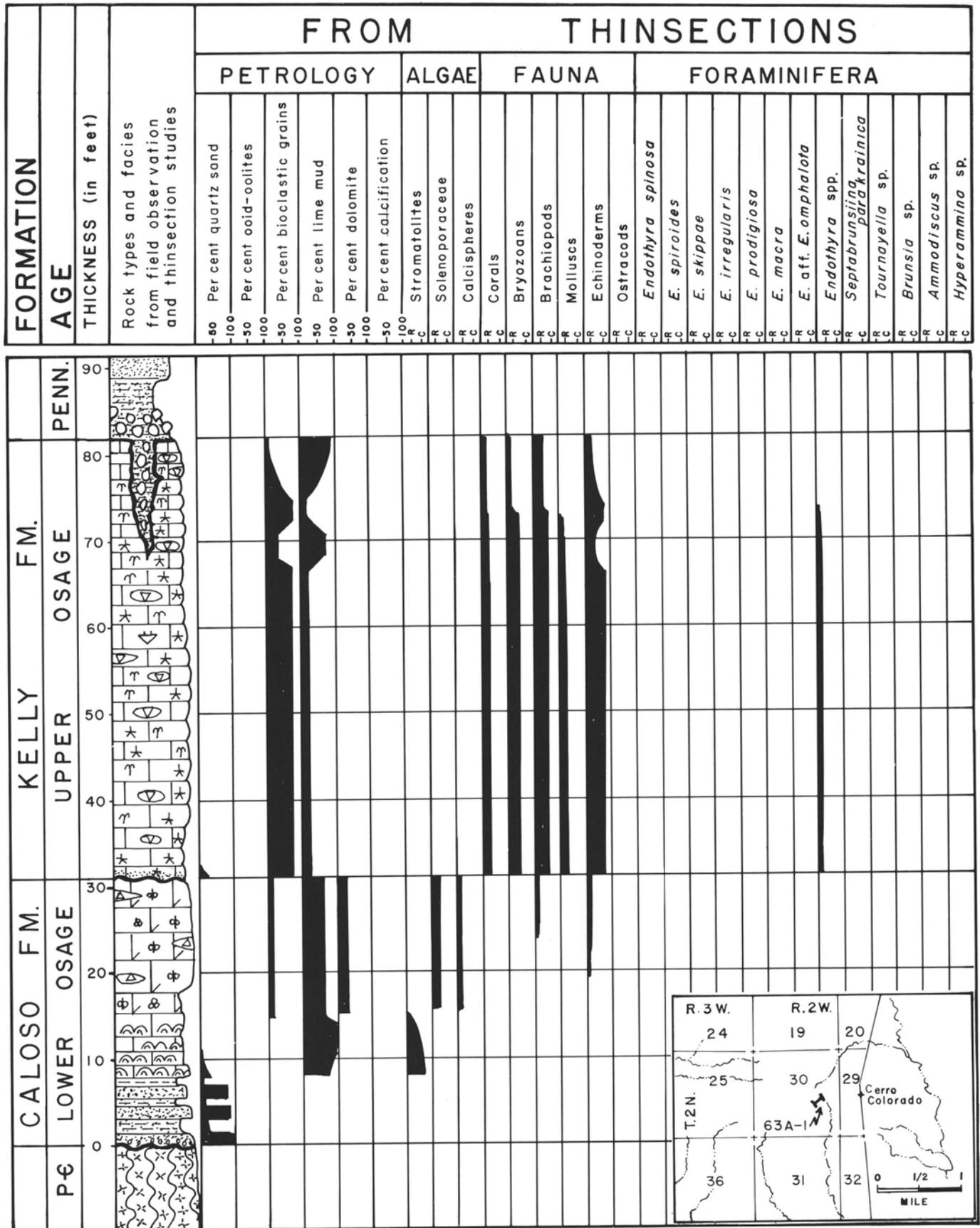


Figure 43

SOUTHERN LADRON MOUNTAINS SECTION OF THE KELLY AND CALOSO FORMATIONS (63A-1)

Index map, 1:62,500, from Riley quadrangle (1959 edition).

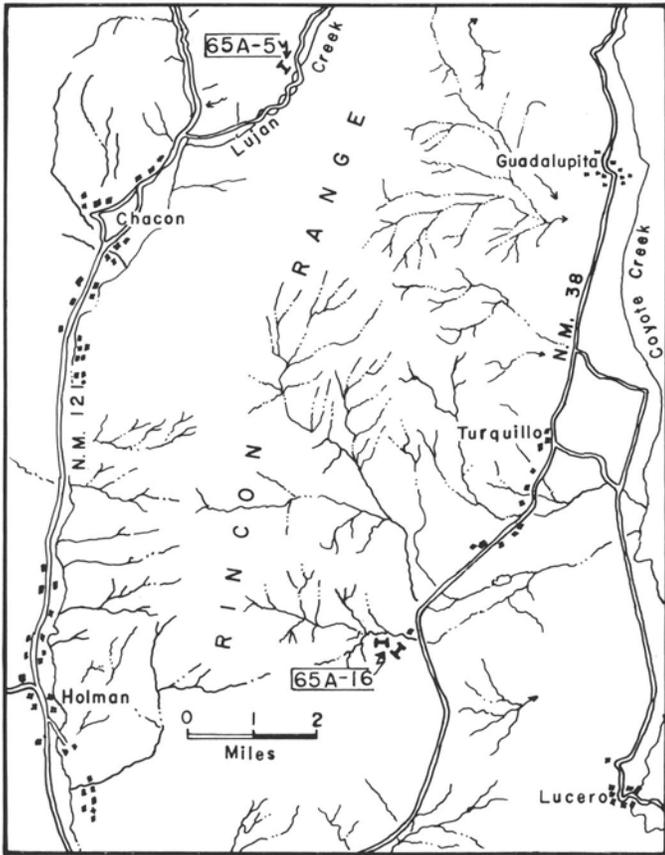


Figure 44

LUJAN CANYON (65A-5) AND TURQUILLO (65A-16) SECTIONS, RINCON RANGE, SANGRE DE CRISTO MOUNTAINS

Lujan Canyon section 3.9 miles northeast of Chacon Presbyterian Day School. Turquillo section 4 miles south of Turquillo village on N. Mex. Highway 38, then east to small ranch and up canyon on old logging road 0.5 mile. Mississippian outcrop is along south side of the canyon wall. Index map from N. Mex. State Highway Commission, Black Lake quadrangle (1952 edition).

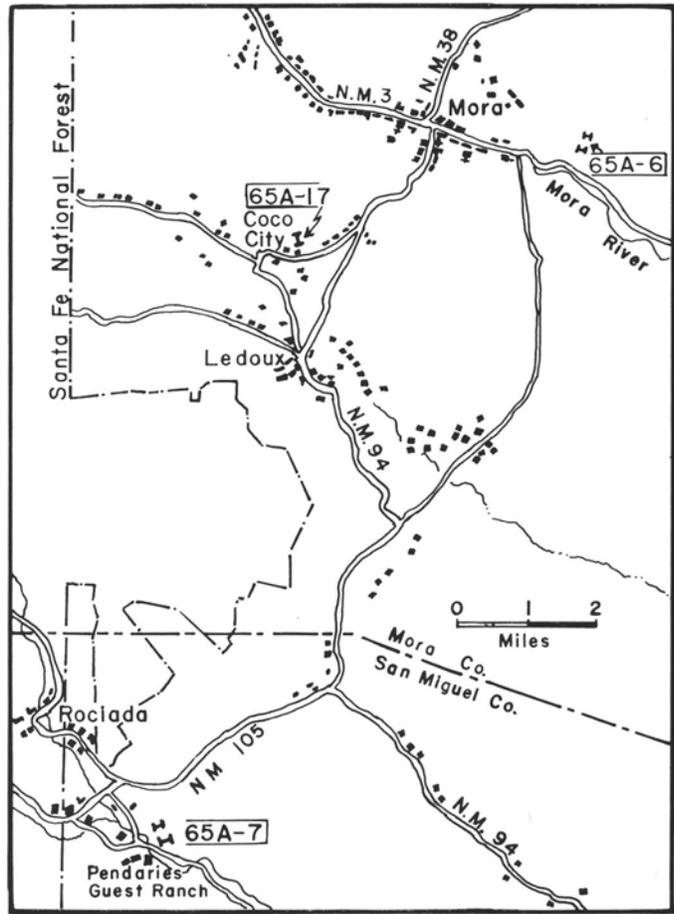


Figure 45

COCO CITY (65A-17), MORA GAP (65A-6), AND MANUELITAS CREEK GAP (65A-7) SECTIONS, SANGRE DE CRISTO MOUNTAINS

Coco City section was measured on the north side of the dirt road east of Coco City village. Mora Gap section, on the north side of Mora River 1.9 miles east of Mora town limits, was measured at two locations; basal part well exposed 100 yards north of main outcrop. Manuelitas Creek Gap section was measured across creek from Pendaries Guest Ranch; base exposed in first gully or dry creek bed in the hogback, north of Manuelitas Creek. Index map from N. Mex. State Highway Commission, Las Vegas quadrangle (1951 edition).

Systematic Paleontology

The generic classification used for the foraminifera in this report is that proposed by Loeblich and Tappan (1964) in *The Treatise on Invertebrate Paleontology*.

CALCISPHERES, POSITION UNKNOWN

Plate 10, Figures 1, 2, 3

The origin of calcispheres has been problematical since the genus was established by Williamson (1880). Calcispheres are defined in this report as hollow spheres with calcite walls; they range from 0.1 to 0.5 mm in diameter. They are frequently encountered in abundance in lime mudstones to grainstones. For a detailed discussion of the taxonomic history of calcispheres the reader is referred to Teichert (1965, p. 99-105).

Rupp (1966) pointed out the similarities between certain calcispheres from the Middle Devonian of the northwest territories of Canada to the calcified apanospores found in the modern shallow-water dasycladacean algae, *Chalmasia* from Florida Bay. The thin-walled calcispheres from the Arroyo Peñasco Formation are strongly reminiscent of dasycladacean apanospores.

If detailed studies can establish that many of the forms from the Upper Paleozoic now classified as calcispheres by various workers are related to the modern dasycladacean algae, then a significant paleoecological tool is available to the biostratigrapher. Living dasycladacean algae are restricted to water depths of less than 30 feet; they are most abundant in waters of less than 6 feet.

Family *Endothyra* Brady, 1884

Subfamily Endothyrinae Brady, 1884

Genus *Endothyra* Phillips, 1846

ENDOTHYRA SPINOSA Chernysheva

Plate 8, Figures 5, 22

Endothyra spinosa Chernysheva, 1940, Soc. Nat. Moscow, Bull., tome 48, n. 5-6, p. 126, pl. 2, fig. 12

Endothyra spinosa, McKay and Green, 1963, Res. Council Alberta, Bull. to, p. 38, pl. 2, figs. 3, 4

Plectogyra spinosa, Conil and Lys, 1964, Memoir Inst. Geol., Univ. Louvain, p. 219-220, pl. 37, fig. 749

Diagnosis. Chambers are swollen between the sutures. The septa are long and anteriorly directed; coiling is plectogyral with various degrees of rotation in the plane of coiling. Average diameter of test varies from 0.35 to 0.55 mm. From 6 to 7 chambers in the final volution. Species is characterized by large anteriorly directed hooks on the last 3 to 4 chambers. Wall structure consists of a thin, dark, outer tectum layer and a thicker, inner, diaphanotheca layer.

Remarks. All the specimens of *Endothyra spinosa* from the Arroyo Peñasco have been preserved in chert nodules found in highly altered carbonates of Cycle I (figs. 12 and 17).

Horizon. *E. spinosa* Chernysheva has been found pre-

served in chert in the lower I o to 40 feet of the Arroyo Peñasco Formation at Peñasco Canyon in the Nacimiento Mountains, Soda Dam in the Jemez Mountains, and Tererro, Agua Zarca, and Ponce de Leon Springs in the Sangre de Cristo Mountains.

Skipp, Holcomb, and Gutschick, in their endothyrid zonation chart of the Mississippian System of North America, show *E. spinosa* as the index fossil for the late Osage (fig. 3).

McKay and Green (1963) found the species in the Shunda Formation at Morro Creek, Alberta. Conil and Lys (1964, p. 220) reported the species from the Middle and Upper Tournaian of Russia and Lower Viséan of Belgium.

ENDOTHYRA SKIPPÆ n. sp.

Plate 8, Figures 6 and 9

Plectogyra inflata Zeller, 1957, Jour. Paleont., v. 31, n. 4, p. 699700, pl. 79, fig. 18

Plectogyra inflata Zeller 1957 (Mississippian endothyroid foraminifera from the Cordilleran geosyncline) is preoccupied by *Endothyra inflata* Lipina 1955 (Trans. 163, ser. geol. n. 70, p. 54-56, pl. 6, figs. 2, 4-6, 7-10), which also has plectogyral coiling. The genus *Plectogyra* Zeller is considered a junior synonym of the genus *Endothyra* Phillips. I propose to rename *Plectogyra inflata* Zeller, *Endothyra skippæ*, retaining Zeller's holotype as the type.

Diagnosis. Test is discoidal, involute, and umbilicate on one side, with plectogyral coiling. Chambers are strongly swollen between sutures, and the septa are short, anteriorly directed. The proloculus is small, 20 to 30 microns. Three to three and a half volutions are present, the final volution possibly having 5 to 6 chambers. The specimens are preserved in chert and indicate that the shell wall was calcareous with two layers, a thin outer tectum and a thicker diaphanotheca.

Remarks. The foraminifera from the Arroyo Peñasco Formation assigned to the species *Endothyra skippæ* n. sp. differ from the holotype in several respects. The Arroyo Peñasco specimens are slightly larger—0.4 to as much as 0.6 mm—compared to the description of the type specimen given by Zeller, which is 0.35 mm in diameter and has shorter septa. The *E. skippæ* n. sp. from cherts in Cycle 1 of the Arroyo Peñasco Formation are intermediate in general contour and size between *E. skippæ* n. sp. from the Madison Limestone and *E. irregularis* (Zeller).

Horizon. Foraminifera assigned to *E. skippæ* n. sp. are from the Arroyo Peñasco Formation chert nodules preserved within carbonates of Cycle 1. They have been found in this zone at San Pedro Mountains, Peñasco Canyon in the Nacimiento Mountains, Placitas in the Sandia Mountains, Soda Dam in the Jemez Mountains, and at Tererro, Pecos River Canyon in the Sangre de Cristo Mountains. The holotype (Zeller, p. 699) came from approximately 320 feet above the base of the Madison Limestone in Blacksmith Fork Canyon, Wasatch Mountains, Cache County, Utah.

ENDOTHYRA IRREGULARIS (Zeller)

Plate 8, Figures 21, 25, 26, 28, 29, 30; Plate I 1, Figure 11

Plectogryra irregularis Zeller, 1957, Jour. Paleont., v. 31, n. 4, p. 699, pl. 78, figs. 6, 12, 13, 14, 15

Diagnosis. Shell is discoidal, involute, strongly umbilicate on one side. The chambers are moderately to strongly swollen between sutures. Septa short, coiling plectogyrid, three volutions are present, with 7 to 8 chambers in the final volution. Walls are thin and consist of a thin, dark, outer tectum layer and a thicker, fibrous, inner diaphanotheca layer. Secondary deposits consist of low-lying humps on the final 3 or 4 chamber floors and thin deposits on posterior sides of the septa. Proloculus is thin-15 to 25 microns-and tests are 0.28 to 0.6 mm in diameter.

Remarks. Zeller (p. 699) stated that mature specimens of *E. irregularis* are about 0.25 mm in diameter, but the specimens in his illustrations (pl. 78, figs. 13, 14, 15) are between 0.34 and 0.38 mm in diameter. The Arroyo Peñasco Formation endothyrids referred to this species are somewhat larger, ranging in size from 0.25 mm to 0.55 mm, with the average about 0.35 mm. They also display weaker developed secondary deposits on the floors of the chamber, particularly in the final chamber.

Zeller's *E. rugosa* differs from the Arroyo Peñasco Formation *E. irregularis* in being somewhat larger, having thicker walls, longer septa, and much thicker secondary deposits on the floor of the chambers.

Range. The Arroyo Peñasco Formation endothyrids, considered *Endothyra* aff. *E. irregularis* (Zeller) (pl. 8, figs. 11, 12), are found associated with *Endothyra spiroides* Zeller and *Endothyra* aff. *E. spinosa* Chernysheva 54 feet above the Precambrian at Peñasco Canyon in the Nacimiento Mountains. *E. irregularis* is common in the clasts of the collapse breccia lens in the Sangre de Cristo Mountains. The species is common in the ooid and oolitic facies of the Arroyo Peñasco Formation and is generally associated with *E. macra* Zeller and *E. prodigiosa* Armstrong.

Zeller (p. 689, 699) reported the holotype as occurring in the Meramec *Endothyra scitula* Toomey zone of the Brazer Limestone at the Lakeside section, Lakeside Mountains, Box Elder County, Utah.

ENDOTHYRA aff. E. OMPHALOTA

Rausser-Cernousova and Reitlinger

Plate 9, Figure 15; Plate I 0, Figure 7

Endothyra omphalota Rausser-Cernousova and Reitlinger, 1936, Akad. Nauk. SSSR, Polionaia Komsissia, Trudy Fasc., p. 211*Plectogryra omphalota*, Conil and Lys, 1964, Memoir Inst. Geol., Univ. Louvain, tome 28, p. 198; pl. 32, figs. 635-642; pl. 33, figs. 643-645.

Diagnosis. Only one well-preserved specimen was found, an oblique section. The test is about 1.2 mm in diameter and is involute with plectogyral coiling. The septa are thick. There are some 8 to 9, weakly inflated, chambers in the outer whorl. The shell structure consists of a thin, dark, outer tectum layer and a thicker, dark, inner diaphanotheca layer (pl. 10, fig. 7).

Remarks. The Arroyo Peñasco specimen resembles in general size, shape, and number of volutions and septa the *E.*

omphalota shown by Conil and Lys (their pl. 32, figs. 636, 642). The New Mexico form differs from the European examples in having septa thick at their base and more strongly pointed anteriorly. The European forms have a more blunted-point septa with apparent well-developed secondary deposits.

Horizon. The Arroyo Peñasco Formation specimens came from 52 feet above the Precambrian at Mora Gap in the Sangre de Cristo Mountains. Conil and Lys (p. 198) reported that *E. omphalota* occurs in Europe in the Middle and Upper Viséan and the Upper Viséan of Russia.

McKay and Green (their pl. x 1, fig. 3, p. 36) described an *Endothyra* aff. *E. omphalota* from the Mount Head Formation, Tunnel Mountain, Alberta. Forms similar to this are also abundant in the Meramec part of the Lisburne Limestone in Arctic Alaska.

ENDOTHYRA SPIROIDES Zeller

Plate 8, Figures 13 and 18

Endothyra spiroides Zeller, 1957, Jour. Paleont., v. 31, n. 4, p. 702, pl. 75, fig. 25; pl. 76, figs. 6, 7, 8; pl. 80, figs. 18, 19, 28

Diagnosis. Shell is discoidal, involute. Chambers are weakly or not swollen between sutures and have planispiral coiling. Septa are of medium length and anteriorly directed; proloculus is 15 to 25 microns in diameter. Secondary deposits are a pronounced hamulus in the final chamber; a small node may be present in the next-to-last chamber. Coiling is planispiral and shows a slow rate of expansion; five volutions are present.

Horizons. *E. spiroides* Zeller has been recognized only below the *E. macra* Zeller and *E. prodigiosa* zone and above the *E. spinosa* Chernysheva and *E. skippeae* zone in the Arroyo Peñasco Formation. It is preserved in chert at Peñasco Canyon, 45 to 55 feet above the Precambrian in association with *Endothyra* aff. *E. spinosa* Chernysheva. It has also been found within clasts of the collapse breccia near Tererro, Pecos River Canyon, Manuelitas Creek, and Coco City sections in the Sangre de Cristo Mountains.

Zeller (p. 702) considered the species as apparently confined to rocks of Early Meramec age. Skipp, Holcomb, and Gutschick used the species as an endothyril zone marker for the Lower Meramec (fig. 3).

ENDOTHYRA MACRA Zeller

Plate 8, Figure 7; Plate 9, Figures 4, I 0, 12, 13

Endothyra macra Zeller, 1957, Jour. Paleont., v. 31, n. 4, p. 702, pl. 80, figs. 8, 14*Endothyra macra*, Armstrong, 1958, Jour. Paleont., v. 32, n. 5, p. 975, pl. 127, fig. 4*Endothyra macra*, McKay and Green, 1963, Res. Council Alberta, Bull. 10, p. 34, 35; pl. 9, fig. 8; pl. 12, fig. 6

Diagnosis. Chambers are slightly swollen between sutures. Septa are long and anteriorly directed with planispiral coiling. Proloculus is 20 to 30 microns in diameter. Hamulus is present in final chamber. Septal counts from the first to fourth volutions are 6, 8, 9, 11. First two volutions are tightly coiled; the third shows more rapid expansion; final volution rapidly expands. Wall structure consists of a thin, dark, outer tectum layer and a thicker inner, diaphanotheca layer. Shells average 0.5 to 0.6 mm in diameter.

Remarks. The Arroyo Peñasco Formation's *E. macra* differs from Zeller's types (pl. 80, figs. 7, 14) in that the third volution does not expand so rapidly. The examples of *E. macra* shown by McKay and Green (pl. 9, fig. 8, and pl. 12, fig. 6) also differ from the New Mexico forms in that they have a greater degree of expansion in the final volution.

Horizon. *E. macra* is common in the ooid, oolitic, and wackestone facies of Cycle 3 of the Arroyo Peñasco Formation. The species is common in the Cordilleran region of North America, in the Arroyo Peñasco Formation in New Mexico, in the Brazer Limestone of Utah (Zeller), and in the Mount Head Formation of western Canada (McKay and Green).

ENDOTHYRA PRODIGIOSA Armstrong

Plate 9, Figures 14, 16, 17, 18, 19, 20; Plate 10, Figure 6

Endothyra prodigiosa, Armstrong, 1958, Jour. Paleont., v. 32, n. 5, p. 973-974, pl. 127, figs. 1-3, 5-8

Diagnosis. Shell is discoidal and involute, and the cham-

bers are slightly swollen between sutures; coiling is planispiral. Septa are directly toward anterior. Proloculus is 40 to 50 microns in diameter. Hamulus is present on the floor of the final chamber, being partly reabsorbed in the preceding chamber. Septal counts from the first to fourth volutions are 8, 9, 11, 12. Wall structure consists of a thin, dark, outer tectum layer and a thicker, inner, diaphanotheca layer (pl.

10, fig. 6). Adult shells average between 0.8 and 1.2 mm in diameter.

Remarks. *Endothyra prodigiosa* differs from *Endothyra scitula* Toomey by its much larger size. It differs from *E. macra* Zeller also by its much larger size and more regular rate of expansion.

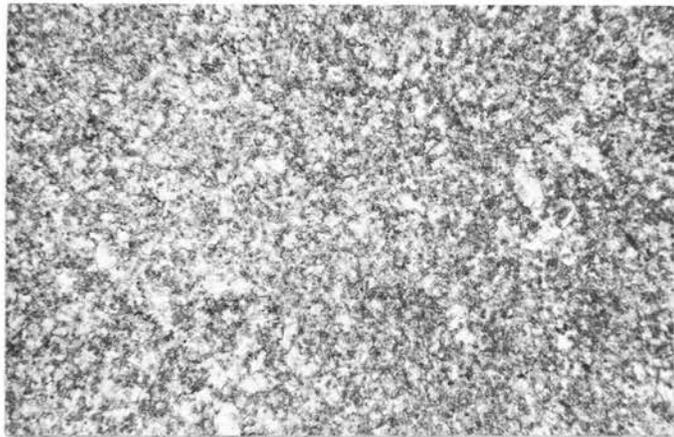
Endothyra robusta McKay and Green is similar to *E. prodigiosa* Armstrong, but McKay and Green (p. 37-38) declared their form to be more globular in outline with a thicker wall.

Horizon. *E. prodigiosa* is present in the ooid and oolitic facies of Cycle 3 of the Arroyo Peñasco Formation throughout its area of outcrop in north-central New Mexico.

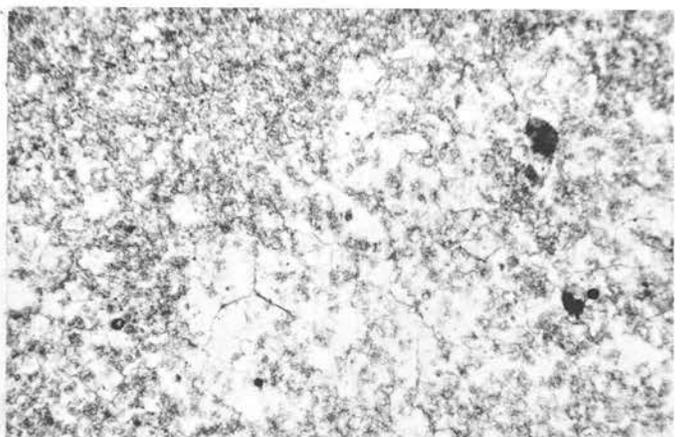
TEXT PLATES 1-10

WITH EXPLANATIONS

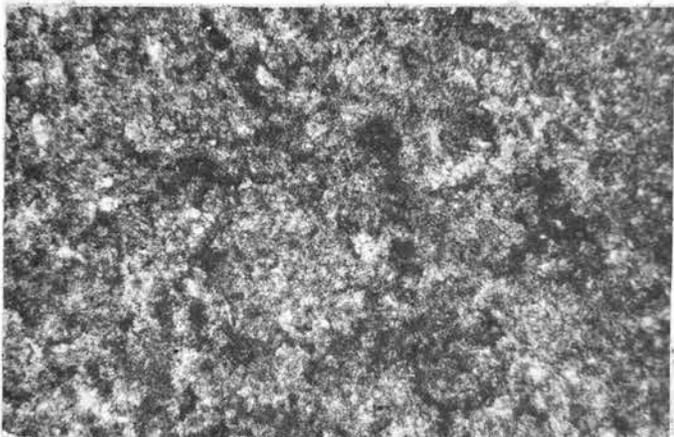
(Specimen numbers which begin with NM refer to the collection of the New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. Those beginning with SO refer to Shell Oil Company collections, Farmington, New Mexico.)



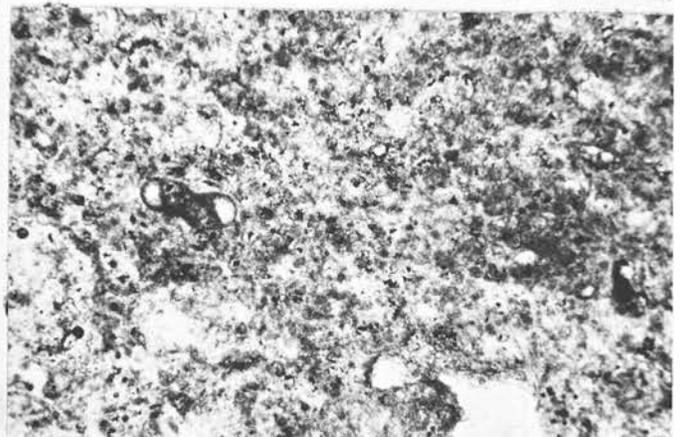
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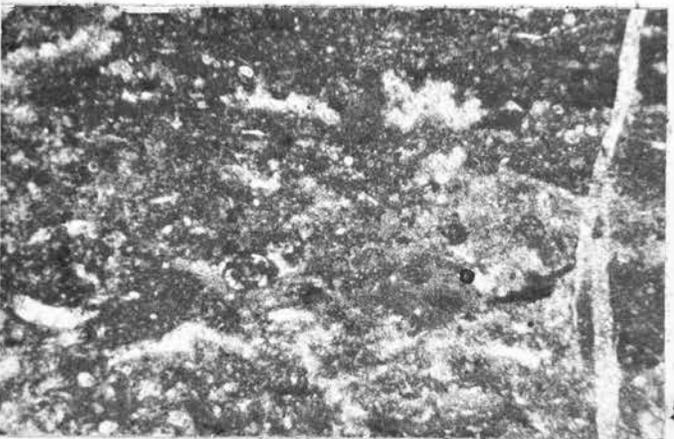
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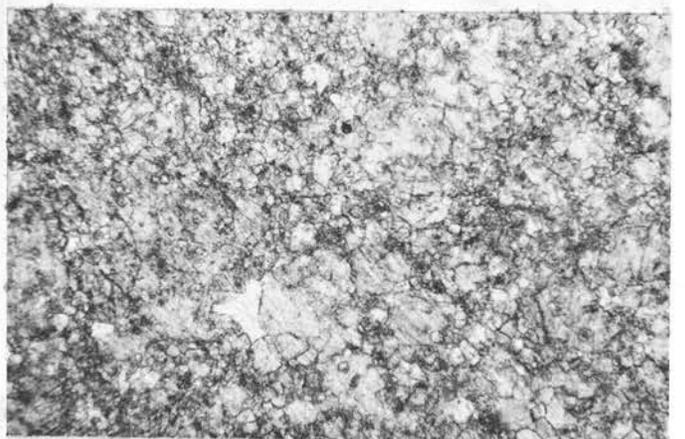
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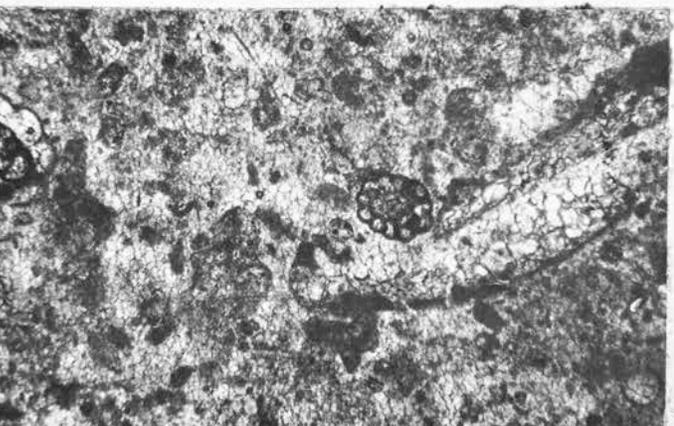
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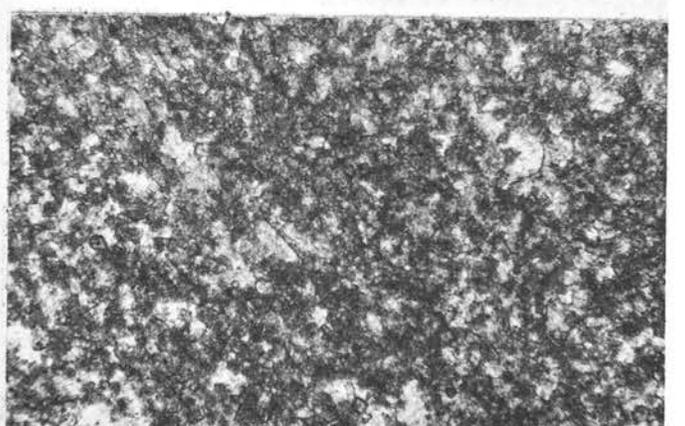
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6



7



8

PLATE

PEÑASCO CANYON, NACIMIENTO MOUNTAINS PHOTOMICROGRAPHS

(All photomicrographs 25 X)1

- . Dolomite with initial stages of dedolomitization; corroded dolomite rhombs 0.05 mm scattered and in masses, clear crystalline calcite replacing dolomite; about 70 per cent dolomite, 30 per cent calcite; 10 feet above Precambrian. SO-PC-3
2. Coarse-grained, pseudometamorphic poikilotopic calcite that contains rhombs of corroded dolomite; calcite is interpreted to have replaced gypsum and/or anhydrite that replaced dolomite; 30 per cent of the rock is dolomite in 40-micron rhombs; calcite is 70 per cent of rock; 22 feet above Precambrian. SO-PC-8
- 3, 4: 3. Dedolomite consisting of 50-micron-size calcite crystals; rock is believed to have been a fine lime mudstone, then a very fine sucrosic dolomite and dedolomite.
4. A thinsection of chert from this bed contains much of the original texture; a pelletoid, calcisphere, foraminiferal lime mudstone; 28 feet above Precambrian. SO-PC-8
5. Pelletoid, calcisphere, foraminifera, ostracod, lime mudstone, with voids filled with sparry calcite; 38 feet above Precambrian. SO-PC-12
- 6, 7: 6. Coarse-grained, pseudometamorphic, poikilotopic calcite that contains rhombs of corroded dolomite; calcite is interpreted to have replaced gypsum and/or anhydrite that replaced dolomite; corroded dolomite rhombs 50-micron size, 25 per cent of rock; calcite, 75 per cent of rock. 7. A thinsection of chert from the same level as 6; note that the relic texture is that of a burrowed, pelletoid, calcisphere, foraminiferal lime mudstone; 56 feet above Precambrian. SO-PC-16
8. Dolomite, sucrosic, dolomite 70-micron rhombs; pore filling is calcite; 65 feet above Precambrian. SO-PC-8

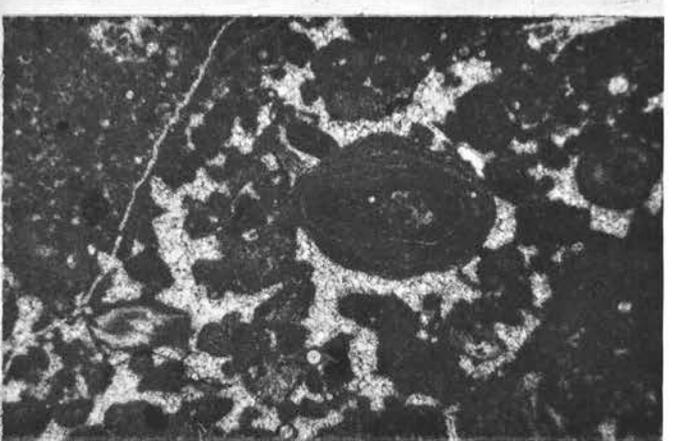
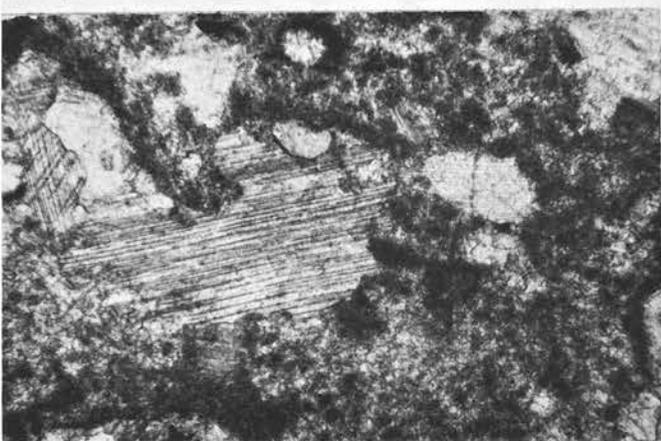
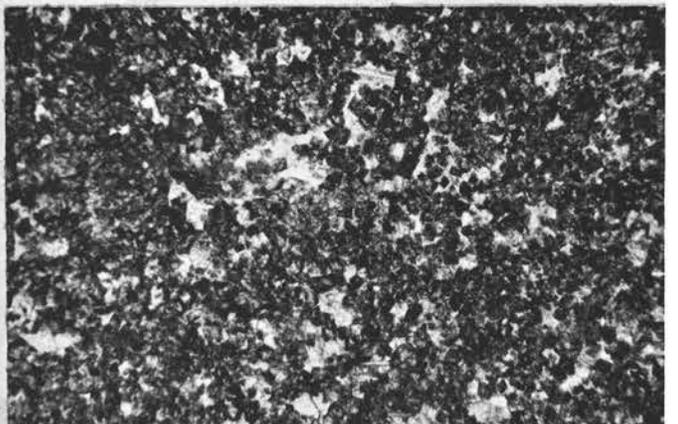
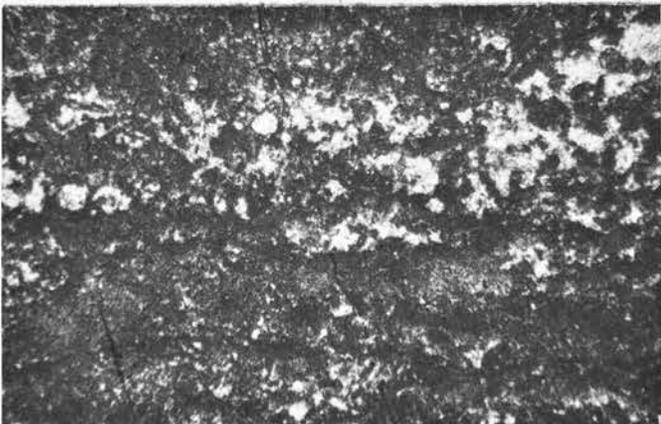
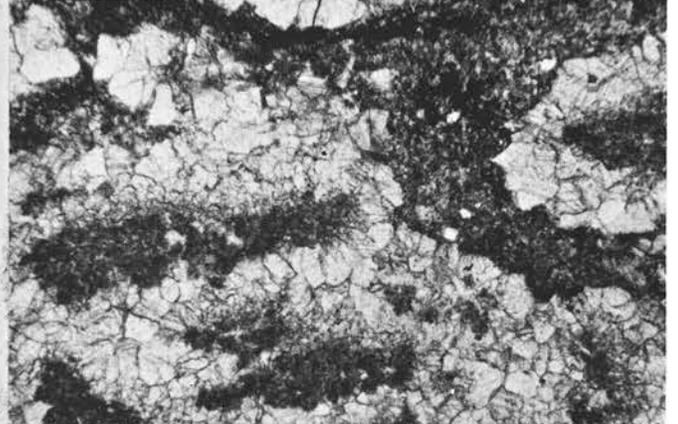
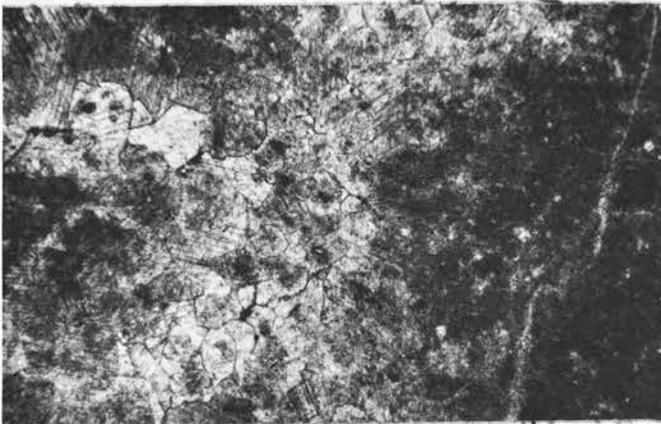
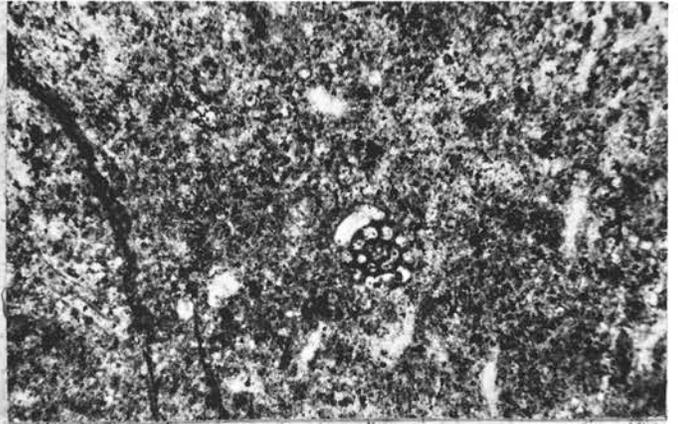
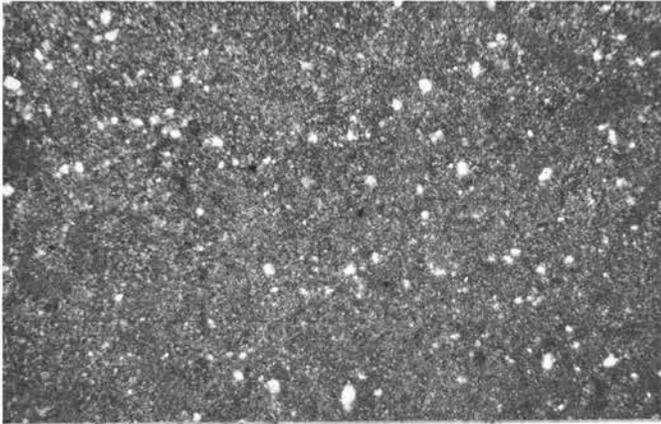
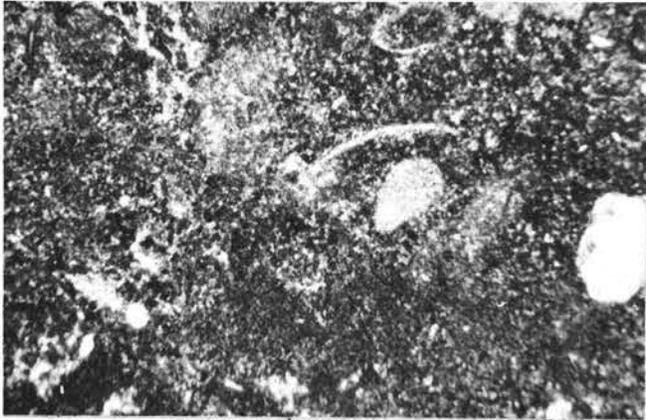


PLATE 2

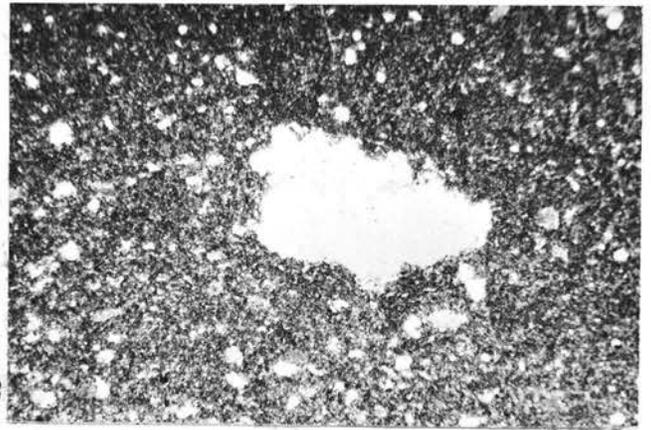
PLACITAS, SANDIA MOUNTAINS PHOTOMICROGRAPHS

(All photographs 25X)

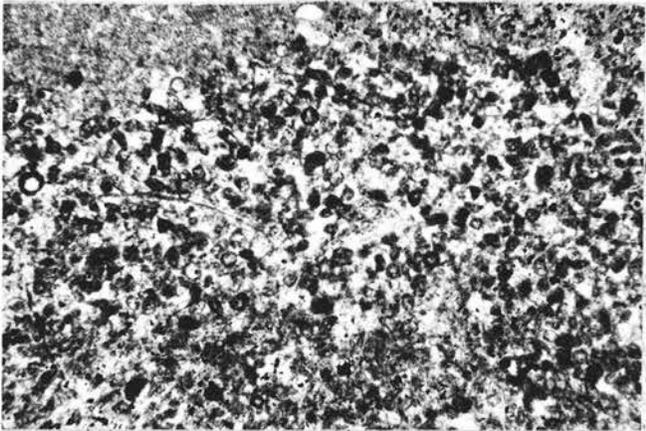
- I. Dolomite, very fine-grained with calcite pore filling; original rock was a lime mudstone; white crystals are celestite, abundant in the lower 20 feet of carbonates; 7 feet above Precambrian. (See pl. 5, fig. 1 for a 160 X photomicrograph) NM65A-1 + 7
2. Chert, preserved, calcispheres, ostracods, and *Endothyra* sp.; 12 feet above Precambrian. (See pl. 7, fig. 1 for a 160 X enlargement of this thinsection) NM65A-I +12
3. Calcareous dolomite; large crystals of poikilotopic calcite are interpreted to have replaced gypsum; calcite is surrounded by 50-micron dolomite rhombs; 23 feet above Precambrian. NM65A- x +23
4. Calcareous dolomite; dark areas, dolomite composed of 35- to 60-micron rhombs, clear calcite with sharp border to surrounding dolomite; poikilotopic calcite is believed to be a replacement of gypsum; 20 feet above Precambrian. NM65A-1+20
5. Lime mudstone; thinsection is made from a stromatolite; note banding and sparry calcite filling of former voids; 25 feet above Precambrian. NM65A-1 +25
6. Dolomite, sucrosic, void or porosity filled with sparry calcite; 30 feet above Precambrian. NM65A-1+30
7. Lime mudstone; large crystals are the result of calcite crystals growing at the expense of lime mudstone; excellent example of calcite neomorphism; 67 feet above Precambrian. NM65A-1+67
8. Pisolite; zone some 3 to 6 feet thick; unit is below Pennsylvanian unconformity; notice fine crystalline, sparry cement between pisolites and laminated layers; 70 feet above Precambrian. NM65A-16A2-+6



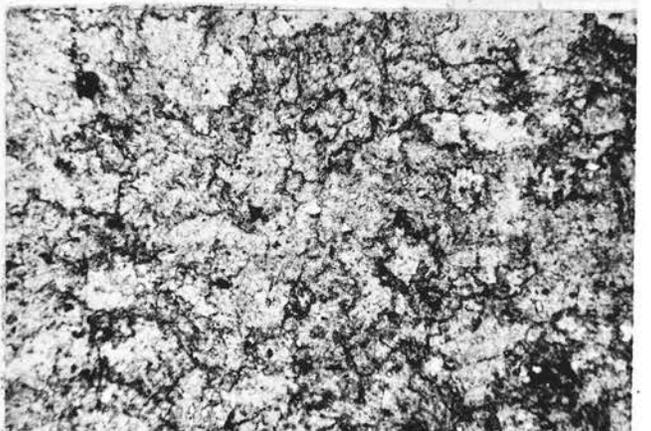
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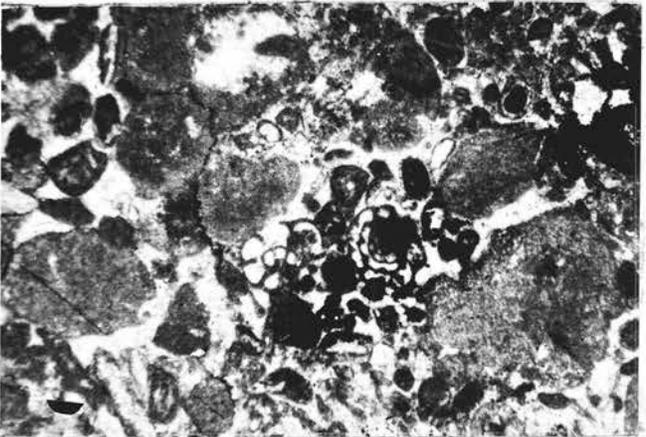
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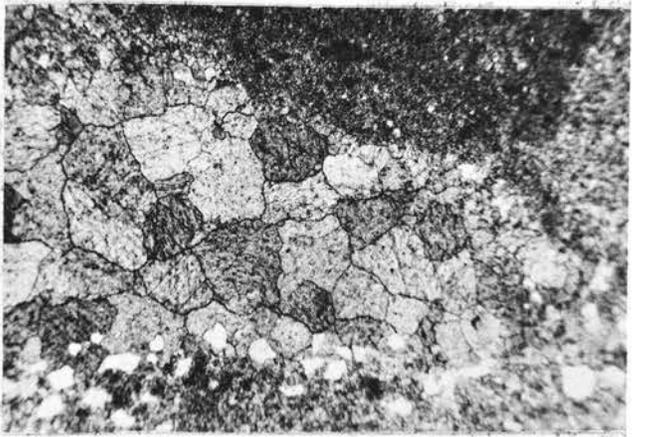
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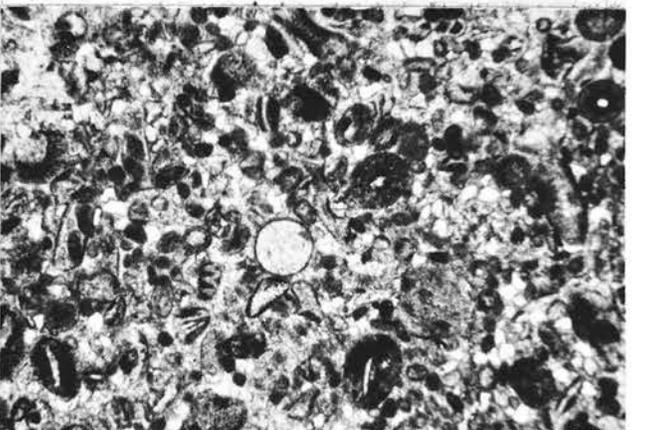
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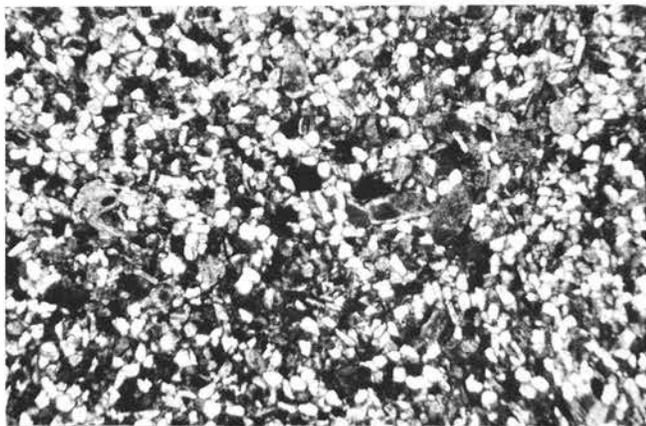
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PLATE 3

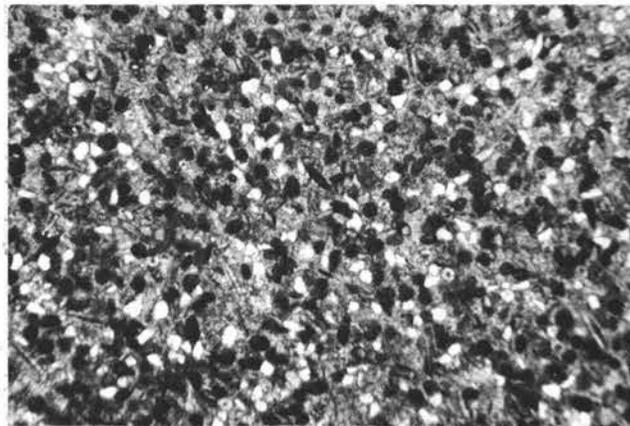
SANGREDECRISTO MOUNTAINS PHOTOMICROGRAPHS

(All photographs 25 X except fig. 6 which is 15 X)

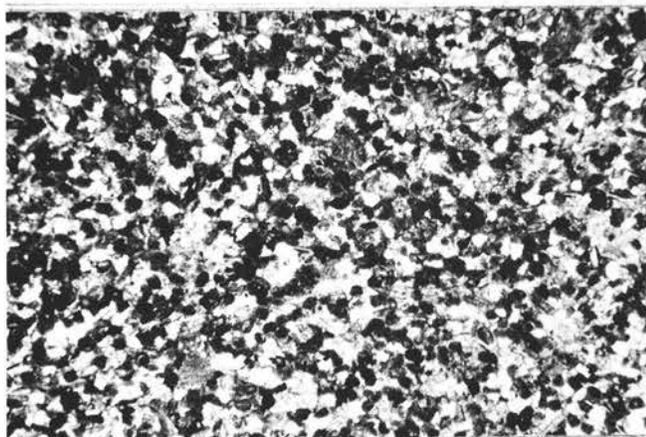
- I. Arenaceous ostracod, lime mudstones; large white areas are quartz sand grains; Coco City section; 29 feet above Precambrian. (See pl. 6, fig. 4 for 160 X photomicrograph of this thin section) NM65-17+29
2. Arenaceous calcareous dolomite; large white area is calcite that is interpreted to have replaced gypsum; dolomite groundmass has been corroded between rhombs and is in initial stages of dedolomitization; Tererro section; 6 feet above Precambrian. (See pl. 6, fig. 3 for 160 X photomicrograph of this thin section) NM65-15+ 6
3. Chert, with calcispheres, pellets, and ostracod shells; Tererro section; 19 feet above Precambrian. NM65-15+ 9
4. Coarse-grained, pseudometamorphic poikilotopic calcite containing corroded dolomite rhombs; calcite believed to have replaced gypsum that had enclosed dolomite (see text fig. 12, for detail); Tererro section 19 feet above Precambrian. NM65A-15+19
5. Echinoderm packstone clasts, breccia lens; note foraminifera; Tererro section; 33 feet above Precambrian. NM65A-15+33
6. Former cavity between clasts in breccia lens 15 X, floor of cavity has quartz sand lining; note sparry calcite filling that follows Bathurst's rule (1958), also lime mudstone clasts above sparry calcite; Tererro section; 40 feet above the Precambrian. NM65A-15+40
7. Arenaceous, ooid packstone with echinoderm, bryozoan, foraminifera, and pellets; Tererro section; 60 feet above Precambrian. NM65A-15+60
8. Arenaceous, ooid packstone with 0.1 mm quartz sand, ooids, bioclasts of bryozoan, echinoderm, and pellets; "large calcisphere" with sparry calcite filling is shown in center of photograph; Tererro section, 66 feet above Precambrian. NM65A-15+66



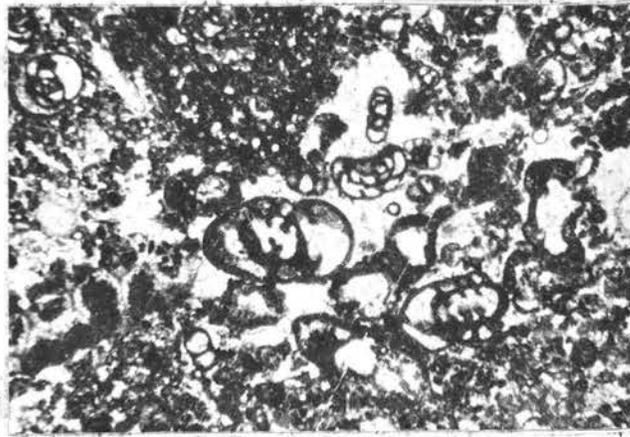
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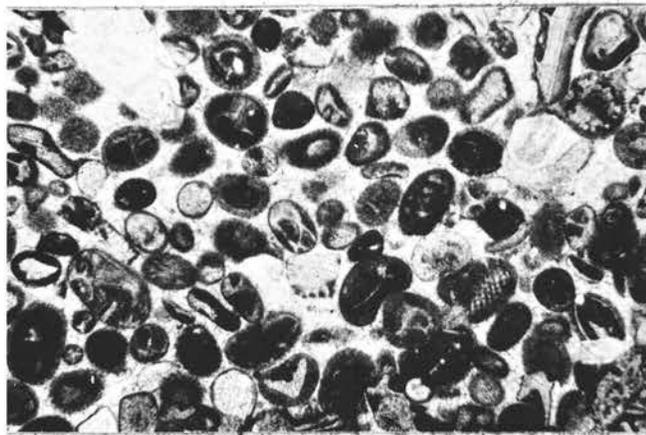
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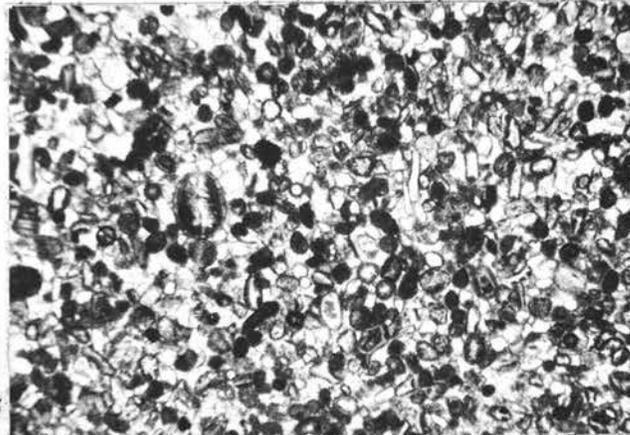
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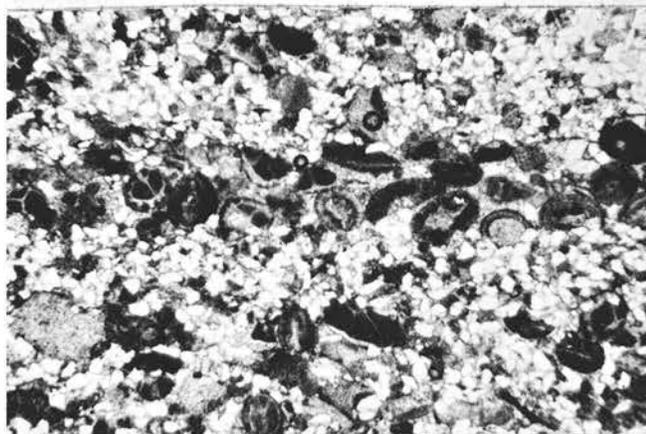
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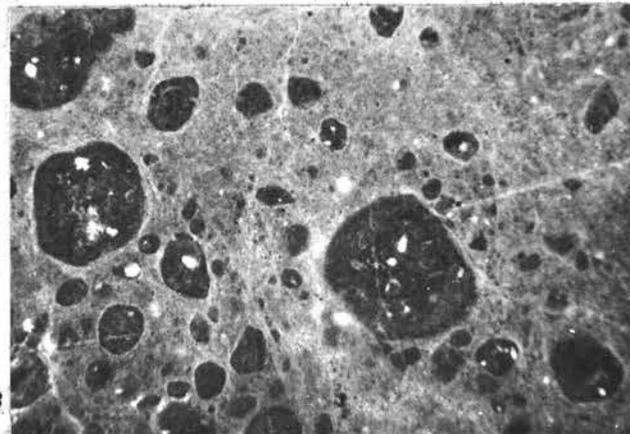
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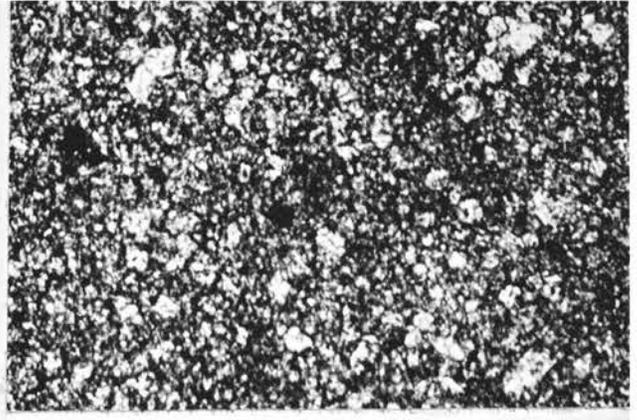
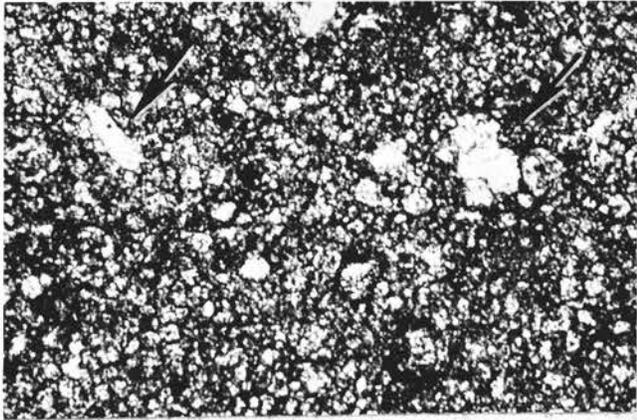
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PLATE 4

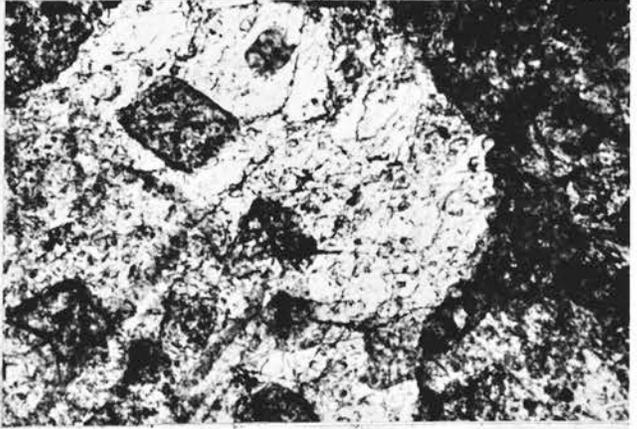
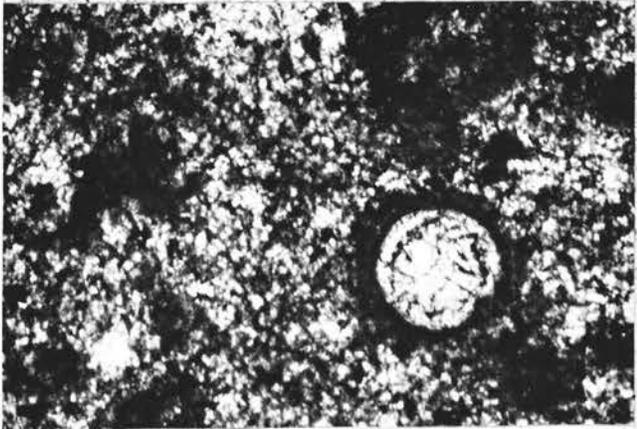
SANGRE DE CRISTO MOUNTAINS PHOTOMICROGRAPHS

(All photographs 25 X)

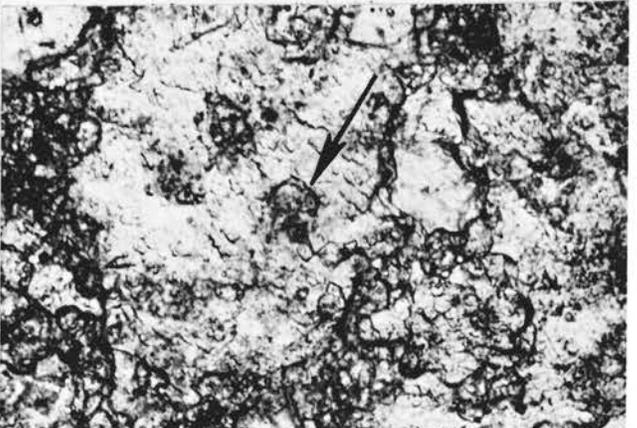
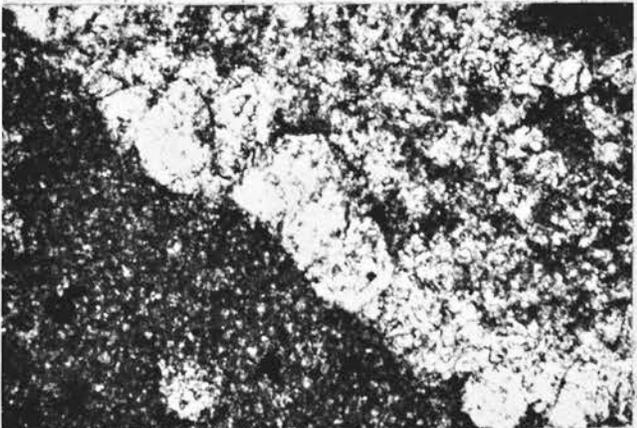
- x . Arenaceous packstone; quartz sand is 0.1 mm size; bioclasts of echinoderms, bryozoans; pore space filled with lime mud; Tererro section, Sangre de Cristo Mountains; 76 feet above Precambrian (compare with fig. 3). NM65A-15+76
2. Arenaceous, pelletoid packstone; two types: a soft form and hardened, brown pellets; fine bioclasts of echinoderm and bryozoan; Tererro section, Sangre de Cristo Mountains; 93 feet above Precambrian. NM65A-15+93
3. Arenaceous, pelletoid packstone, lithologically similar to fig. 1; this specimen is from the San Pedro Mountains section; 129 feet above Precambrian. NM65A-11+129
4. Foraminiferal wackestone, pellets, and calcispheres; Turquillo section, Sangre de Cristo Mountains; 6 feet above Precambrian. NM65A-16A₂+6
5. Ooid grainstone, rounded bioclasts of foraminifera, bryozoans, echinoderm, with oolitic coating; Turquillo section, Sangre de Cristo Mountains; 36 feet above Precambrian. NM65A-16+36
6. Arenaceous packstone, well sorted; some bioclasts with oolitic coating; Turquillo section, Sangre de Cristo Mountains; 45 feet above Precambrian. NM65A-16+45
7. Arenaceous packstone, quartz sand in 0.1 mm size; notice laminations of quartz sand and broken oolites and bioclasts; pore space filled with lime mud; Turquillo section, Sangre de Cristo Mountains; 57 feet above Precambrian. NM65-16+57
8. Lime mudstone, with 0.1 mm quartz sand; origin of large "dark balls" is unknown; mudstone is believed to be very shallow subtidal; Turquillo section, Sangre de Cristo Mountains; 73 feet above Precambrian. NM65A-16+73



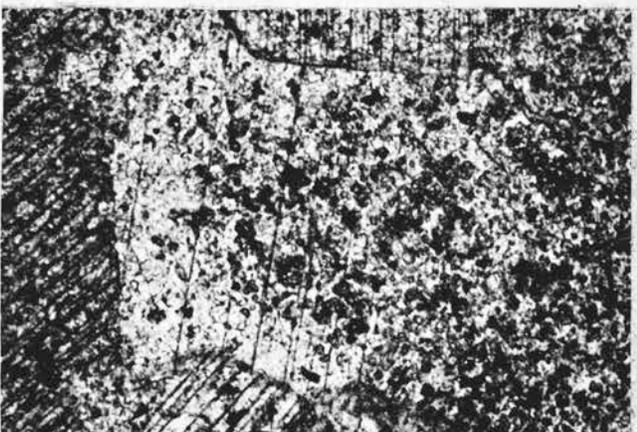
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PLATE 5

SANGRE DE CRISTO, SANDIA, AND NACIMIENTO MOUNTAINS

PHOTOMICROGRAPHS (All photomicrographs 160X)

1. Dolomite; arrows indicate angular to subrounded grains of detrital quartz; 7 feet above Precambrian; Placitas, Sandia Mountains. (See pl. 2, fig. 1 for 25 X photomicrograph of thin section) NM65A-1+ 7
2. Dolomite; Lujan Canyon section, Sangre de Cristo Mountains; 76 feet above Precambrian. NM65A-5-76
3. Dolomitic lime mudstone; Rio Pueblo, Sangre de Cristo Mountains; calcisphere in right center of photomicrograph; rock may represent a partial dedolomitization in which the old limestone fabric has been regenerated; 56 feet above Precambrian. NM65A-4+ 56
4. Large crystals of poikilotopic calcite with enclosed rhombs of dolomite; dark, surrounding rock is dolomite; calcite is interpreted as having replaced gypsum and/or anhydrite; notice sharp contact between calcite and dolomite; 20 feet above Precambrian, Placitas, Sandia Mountains. 65A-1+20
5. Large crystals of poikilotopic calcite containing corroded rhombs of dolomite that has a sharp contact with the 25-micron-rhomb dolomite masses; the rock is characterized by 1 to 10 mm bodies of fine-grained dolomite surrounded by pseudometamorphic calcite crystals containing inclusions of corroded dolomite rhombs; the calcite is interpreted as having replaced gypsum and/or anhydrite; Ponce de Leon Spring, Sangre de Cristo Mountains; 50 feet above the Precambrian. NM65A-2 +50
6. Coarse-grained pseudometamorphic-appearing poikilotopic calcite containing corroded rhombs of dolomite; arrow points to a typical, corroded dolomite crystal; Peñasco Canyon, Nacimiento Mountains; 23 feet above Precambrian. NM66A2+23
7. Coarse-grained pseudometamorphic poikilotopic calcite containing corroded rhombs of dolomite; calcite is interpreted to have replaced a gypsum and/or anhydrite that in turn replaced dolomite; 21 feet above Precambrian; Manuelitas Creek Gap, Sangre de Cristo Mountains. (See pl. 6, fig. 8 for a 25 X microphotograph for textural relationship of calcite crystals) NM65A-7+21
8. Coarse-grained pseudometamorphic poikilotopic calcite containing corroded rhombs of dolomite; calcite is interpreted to be a replacement of gypsum and/or anhydrite that in turn replaced dolomite; 26 feet above Precambrian; Placitas, Sandia Mountains. 65A-1+26

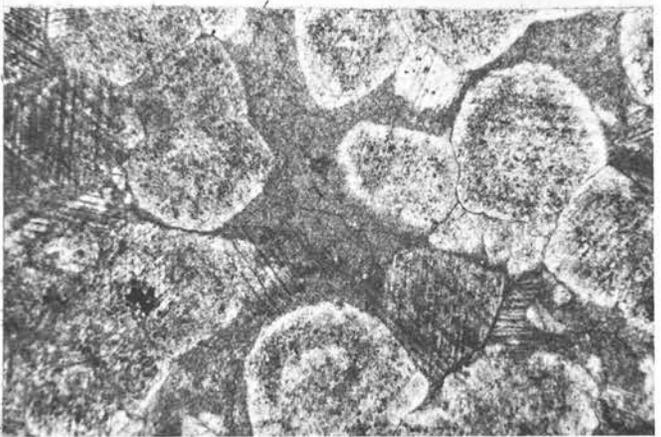
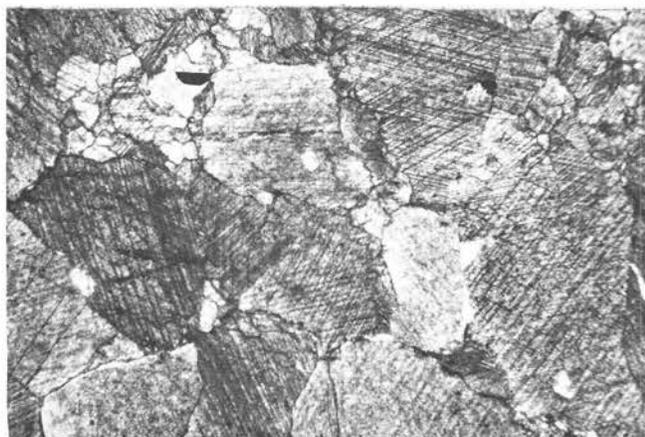
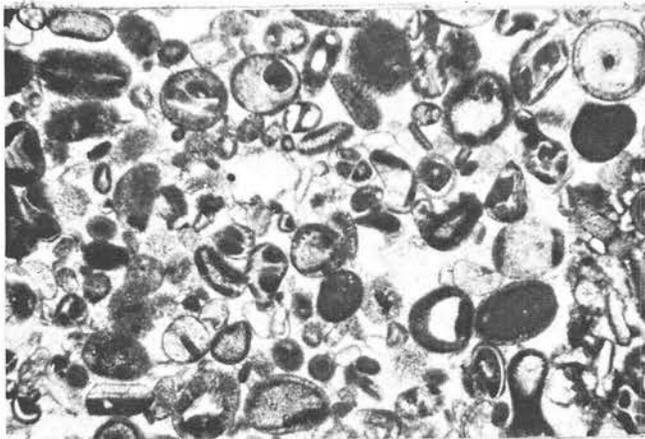
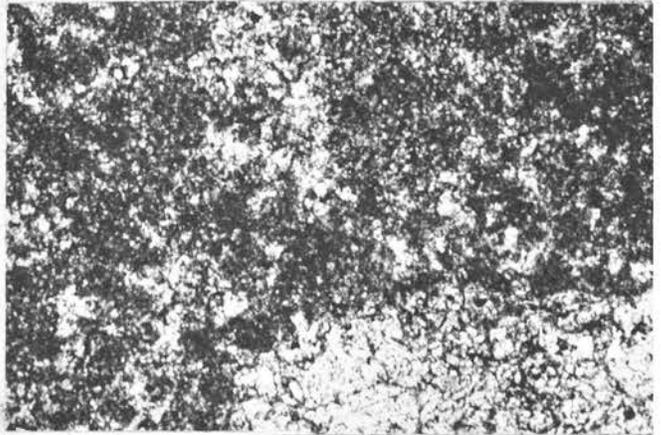
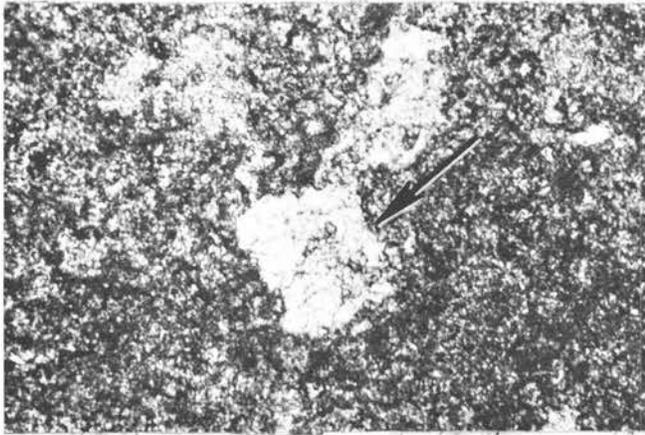
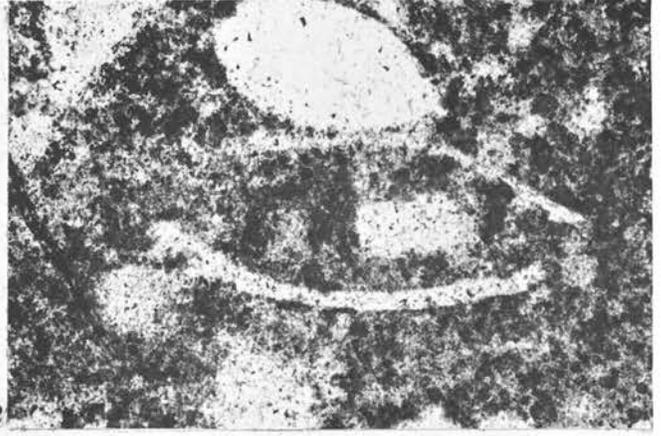
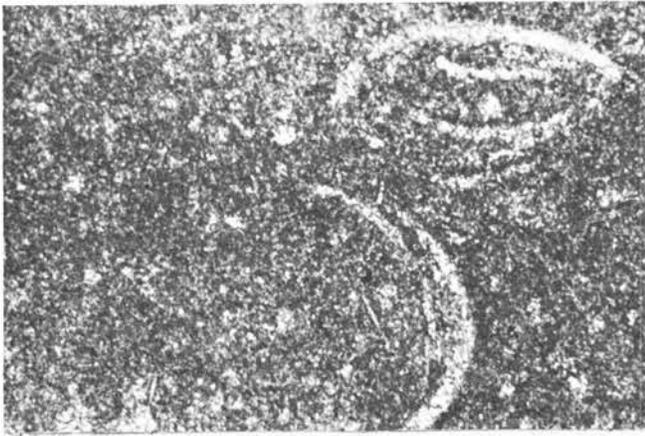


PLATE 6

SANGRE DE CRISTO MOUNTAINS PHOTOMICROGRAPHS

- . Lime mudstone, 75 X, ostracod shell; carbonate is free of detrital quartz sand and overlies arenaceous pelletoid packstones of Cycle 3; 66 feet above Precambrian; Manuelitas Creek Gap, Sangre de Cristo Mountains. NM65A-7B+66
2. Chert, 75 x, silica replacement of an ostracod wackestone, nodular chert within beds of dolomite; 57 feet above Precambrian; Ponce de Leon Springs, Sangre de Cristo Mountains. NM65A-2+57
3. Lime mudstone, 160 X; arrow points to calcite interpreted as pseudomorph after gypsum; the calcite suggests the relic form of gypsum in outline by rectangular re-entrance and straight sides; 6 feet above Precambrian, Tererro section, Sangre de Cristo Mountains. (See pl. 3, fig. 2 for a 25 X microphotograph of this thinsection) NM65-15+6
4. Lime mudstone, 160 X, ostracod-bearing; sample collected just below collapse breccia lens; has not been dolomitized or dedolomitized; 29 feet above Precambrian; Coco City section, Sangre de Cristo Mountains. NM65A-17+29
5. Packstone, ooid, 25 X, composed of rounded and coated grains of echinoderms, brachiopods, bryozoans, and a small amount of coated quartz sand; specimen collected from a fragment in the collapse breccia lens; lime mud between some of the grains has undergone "recrystallization" in the form of a grain growth to form a sparite; 26 feet above the Precambrian, Manuelitas Creek Gap, Sangre de Cristo Mountains. NM65A-17+8 (26)
6. Coarse-grained pseudometamorphic poikilotopic calcite, 160 X, containing corroded rhombs of dolomite; in bottom right corner is a dark area of dolomite; notice shape and straight contact between calcite and dolomite; calcite is interpreted to have replaced gypsum and/or anhydrite; 7 feet above Precambrian; Tijeras Canyon, Manzanita Mountains. NM66A-1+7
7. Coarse-grained pseudometamorphic poikilotopic calcite, 25 X, containing corroded rhombs of dolomite; calcite is interpreted to have replaced gypsum and/or anhydrite that replaced dolomite; 5 feet above Precambrian; Gallinas Canyon, Sangre de Cristo Mountains. NM65A-8+5
8. Coarse-grained pseudometamorphic, poikilotopic calcite, 25 X, containing corroded rhombs of dolomite; calcite is interpreted to have replaced gypsum and/or anhydrite that replaced dolomite; 21 feet above Precambrian; Manuelitas Creek Gap, Sangre de Cristo Mountains. (See pl. 5, fig. 7 for 160 X enlargement of corroded dolomite rhombs) NM65-7+2

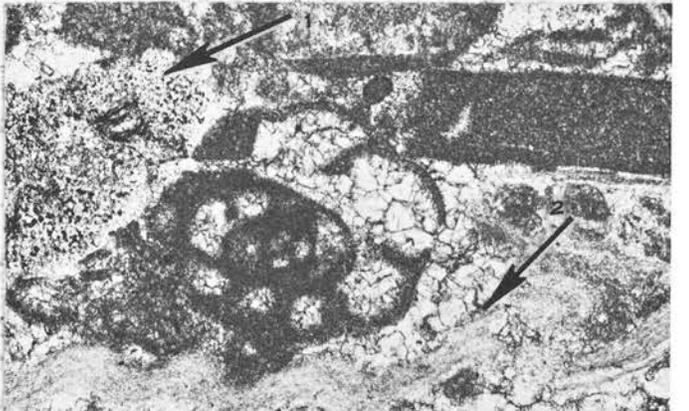
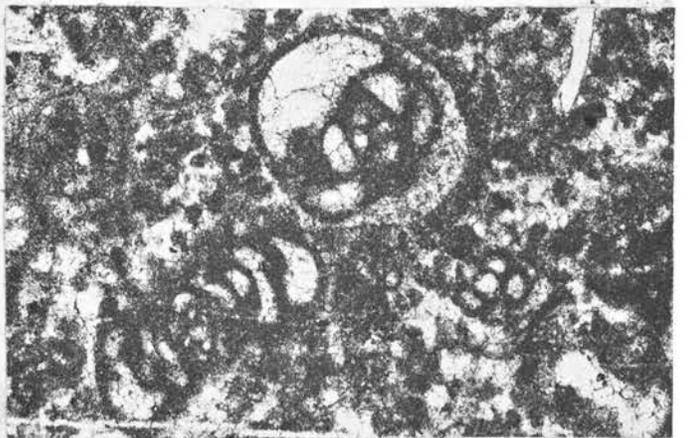
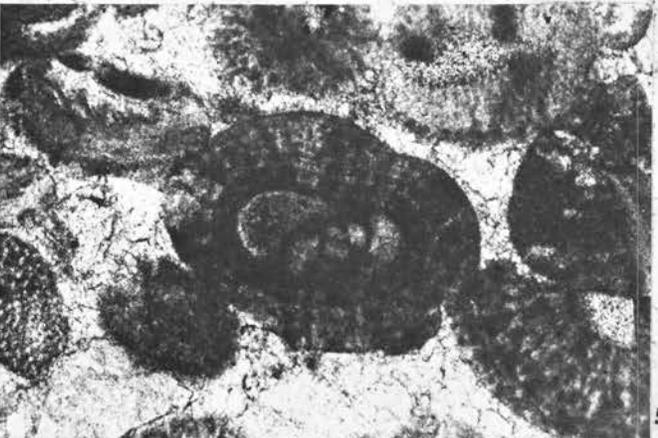
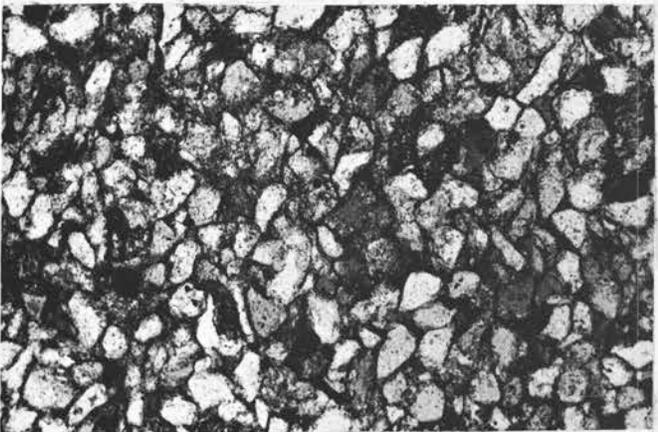
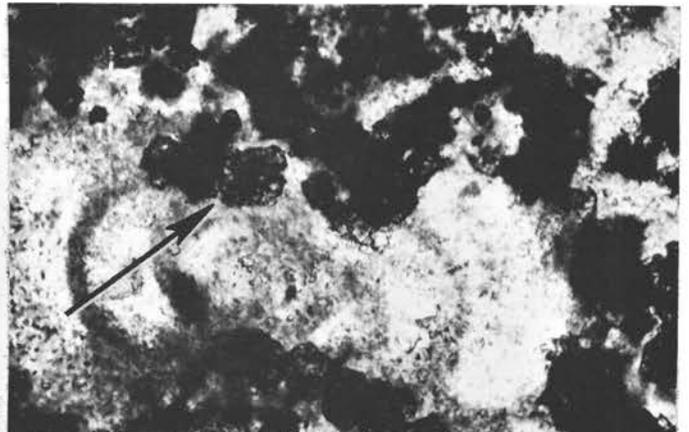
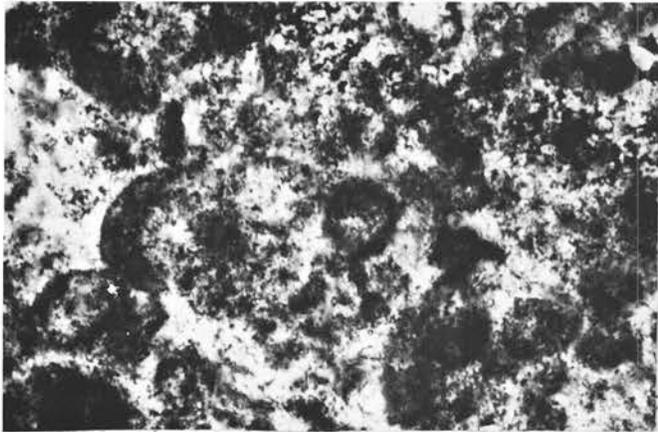


PLATE 7

SANDIA, SANGRE DE CRISTO, AND NACIMIENTO MOUNTAINS PHOTOMICROGRAPHS

- I. Chert, details of preservation at 160 X, 12 feet above Precambrian; Placitas, Sandia Mountains; the chert has replaced a pelletoid, foraminifera lime mudstone; the dark round bodies seen at 160 X are believed to have been pellets. (See text fig. 17 for an outcrop picture of the dark gray chert and pl. 2, fig. 2 for a thinsection photomicrograph at 25 X) NM65A-1+12
2. Chert, details of preservation at 160 X; Tererro, Pecos River Canyon, Sangre de Cristo Mountains; *Septabrinsiina parakrainica* is the same as Pl. 8, fig. 4; the fossil is preserved as chert; the arrow points to one of numerous brown rhombs of dolomite surrounded by chert; 20 feet above Precambrian. NM65A-15+20
3. Sandstone, with calcite cement, some pellets and abraded fossil bioclastics, crossed nichols, 75 X; Manuelitas Creek Gap, Sangre de Cristo Mountains; 44 feet above Precambrian. (See text figures 15 and 34 for details) NM65A-7+44
4. Arenaceous pelletoid and bioclastic packstone, 75 X; Gallinas Canyon, Sangre de Cristo Mountains; 40 feet above Precambrian; this rock type is typical of the arenaceous facies of Cycle 3; the dark shapes are pellets; the dark-gray areas are fragments of echinoderms and bryozoans between the light-colored subangular quartz. NM65-8+40
5. Grainstone, 75 X, oolitic, rounded and oolitic-coated bioclasts of echinoderm, bryozoans; foraminifera in center of photomicrograph has a thick oolitic coating composed of at least eight layers; 66 feet above Precambrian; Lujan Canyon, Sangre de Cristo Mountains. NM65A-5+66
6. Pelletoid packstone, 75 X, with strongly inflated *Endothyra* sp. in the upper center of the photograph; Turquillo, Sangre de Cristo Mountains; 6 feet above the Precambrian. NM65-16A₂+6
7. Lime mudstone, 75 X, with oblique view of a *Tournayella* sp.; Placitas, Sandia Mountains; 70 feet above Precambrian. NM65-1+70
8. *Endothyra* aff. *E. irregularis* (Zeller), 75 X, in a brachiopod, echinoderm packstone; Penasco Canyon, Nacimiento Mountains; 108 feet above Precambrian. Endothyroid is next to (1) an echinoderm fragment and (2) rests on a brachiopod shell surrounded by sparry calcite. NM66B-2+108

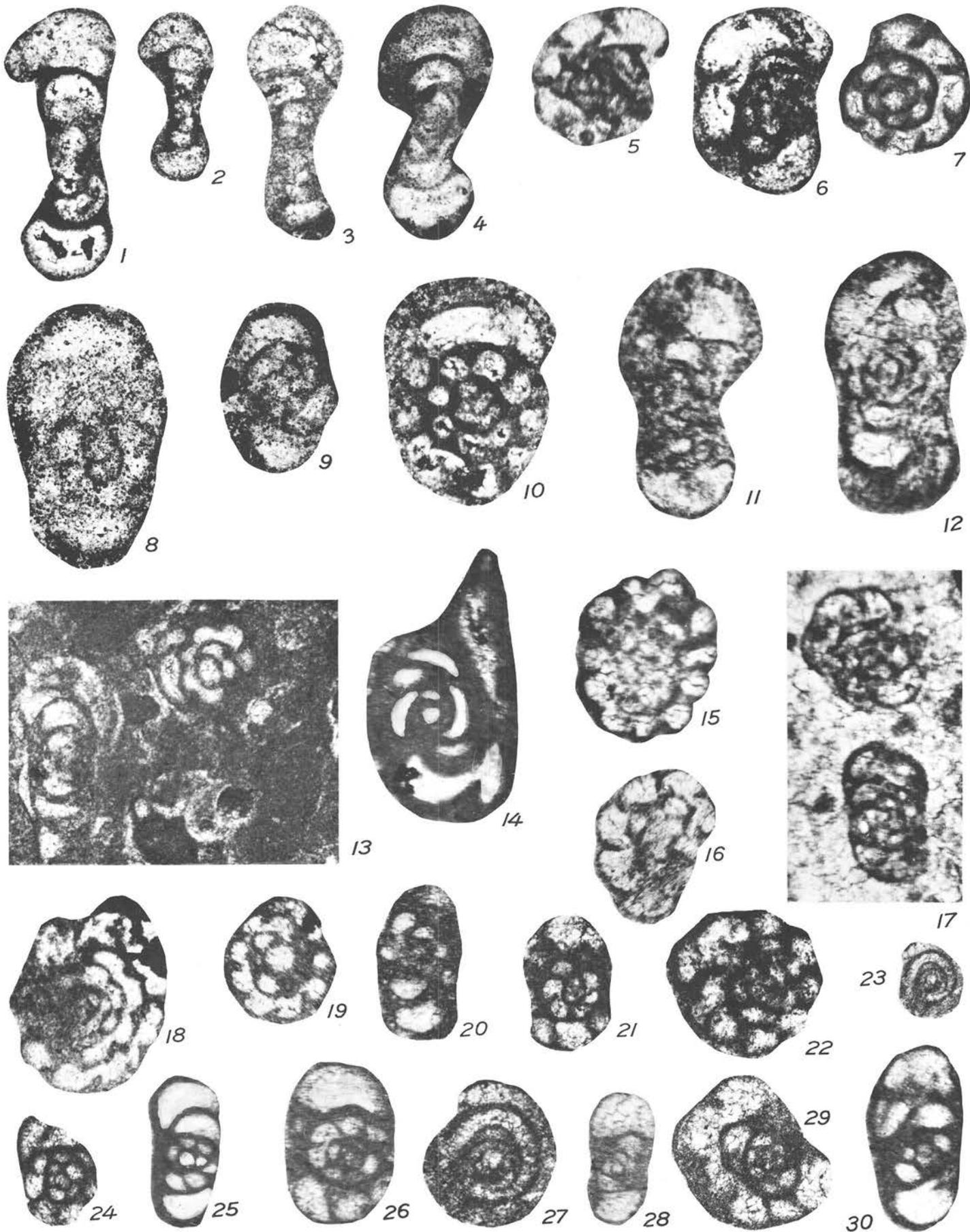
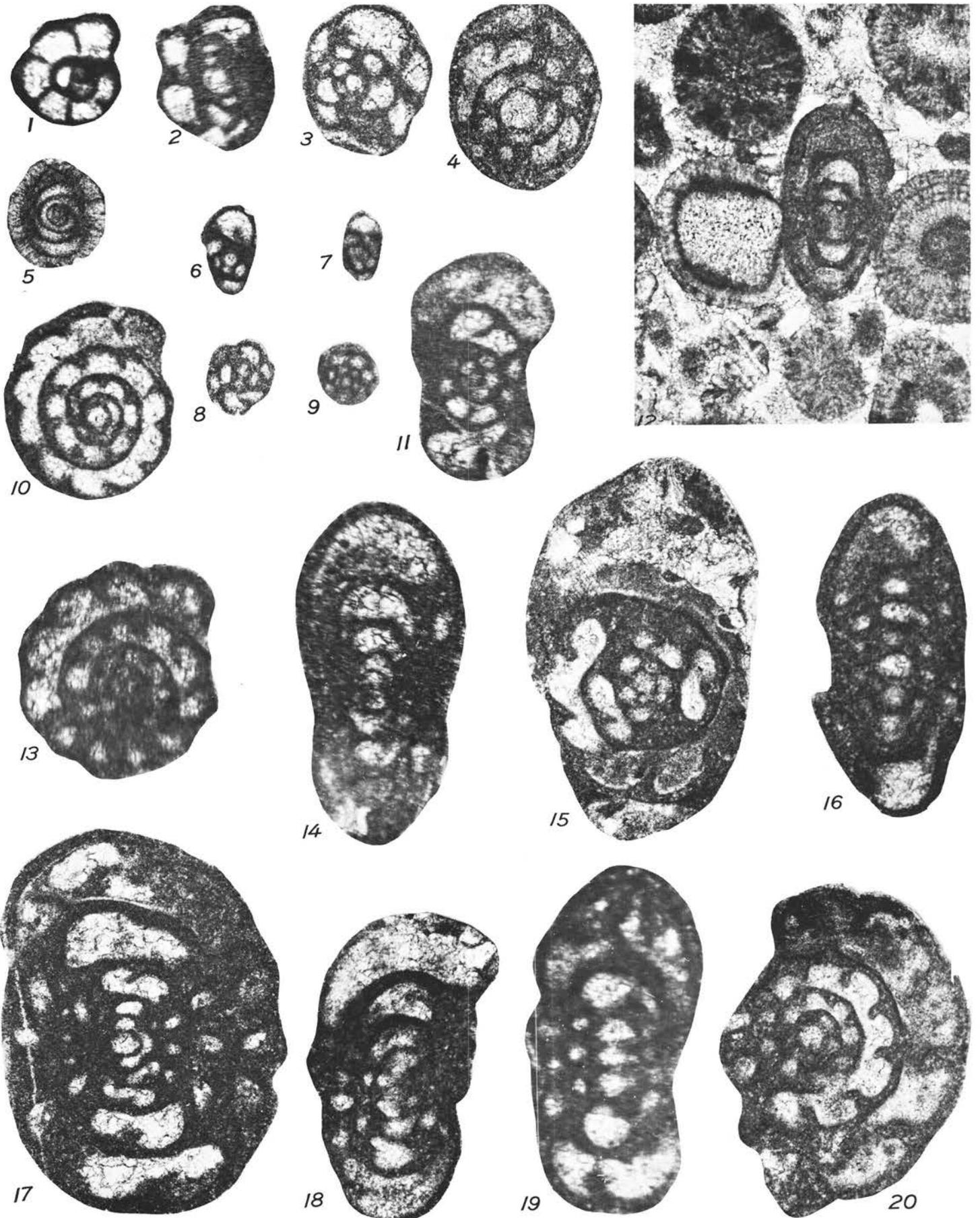


PLATE 8

SEPTABRUNSIINA, ENDOTHYRA, AND CHERNYSHINELLA

(Arroyo Peñasco Formation unless otherwise noted; all figs. 75 X, except fig. 27, which is 160 x)

Figures	Page
i-3. <i>Septabrunsiina parakraïnica</i> Skipp, Holcomb, and Gutschick, axial section, Placitas, Sandia Mountains; 16 feet above the Precambrian; preserved in chert. NM65A-1+16	
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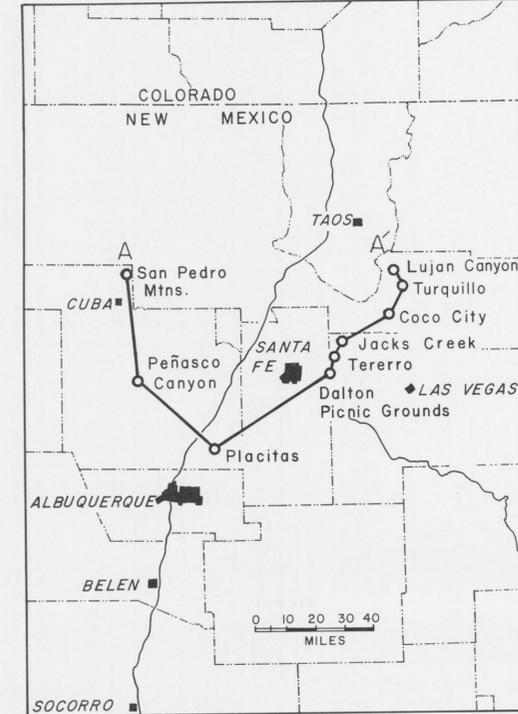
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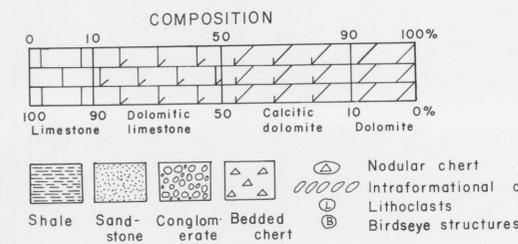
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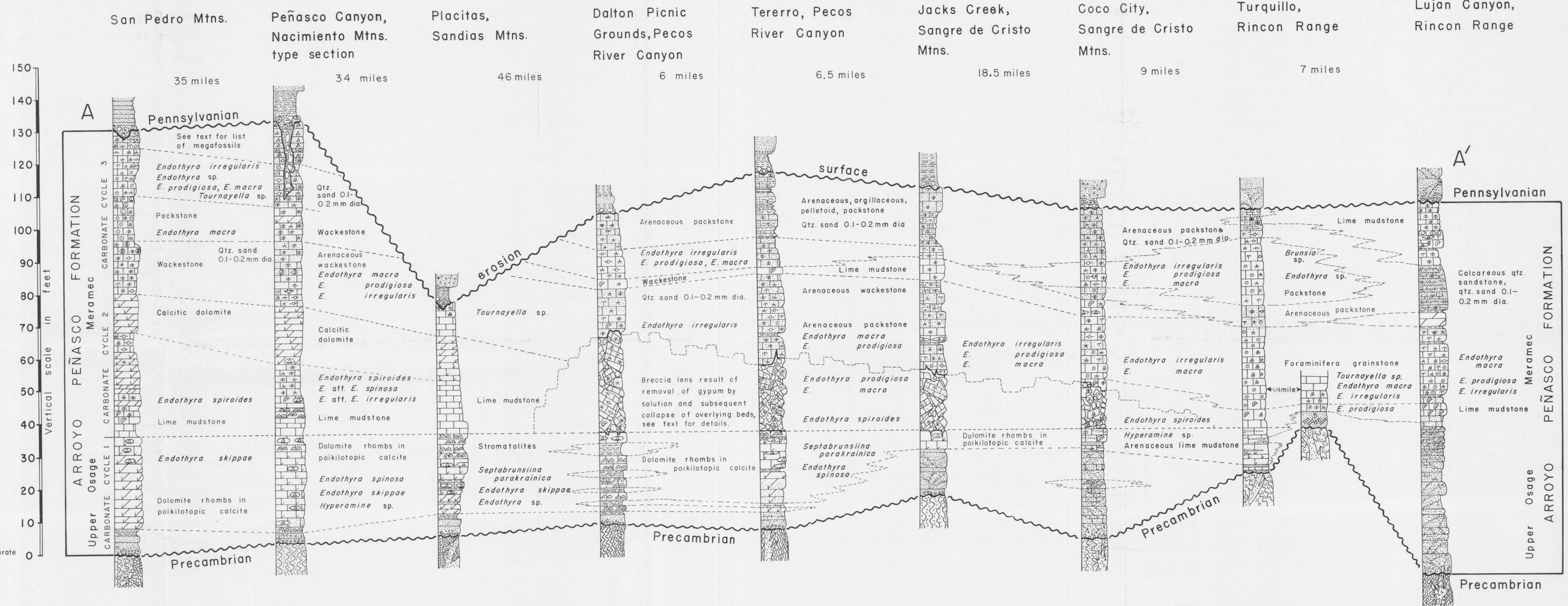


CARBONATE PARTICLES OTHER THAN FOSSILS

SIZE	mm	Mud	Coated	Particles
Silt	0.63	φ	Superficial ooid	Oolites
Sand	2.0	φ		Pisoid
Granule	4.0	φ		
Pebble		φ		

SYMBOLS FOR FOSSIL PARTICLES

- ⊕ Foraminifera
- ⊙ Corals
- ⊖ Brachiopods
- ⊗ Bryozoans
- ⊛ Echinoderms
- ⊕ Gastropods
- ⊖ Ostracod
- ⊗ Stromatolites
- ⊛ Plant remains



MISSISSIPPIAN CORRELATION CHART A-A'

