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Geology and mineral resources of Sierra Nacimiento and vicinity, New Mexico

by Lee A. Woodward

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A DIVISION OF

NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

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Preface

This report is the final result of a geologic mapping project begun in 1970 and completed in 1980. The mapping project focused on interpreting the structural development of the Nacimiento region; this report presents rock units, structure of the area, and mineral and energy resources.

Acknowledgments—The project was supported in large part by the New Mexico Bureau of Mines and Mineral Resources; part of the financial support came from the U.S. Geological Survey, Department of the Interior, under USGS grants 14–08–0001–G–255 and 14–08–0001–G–348.

Much of the geologic mapping was done at 1:24,000 scale by graduate students doing theses under my supervision, including John B. Anderson (1970), William H. Kaufman (1971), Richard K. Reed (1971), Otto L. Schumacher (1972), Richard L. Ruetschilling (1973), Harvey R. DuChene (1973), Ruben Martinez (1974), Gail G. Gibson (1975), Robert S. Timmer (1976), and Margaret A. Merrick (1980). This report would not be possible without their help. Twelve 7 1/2-min geologic quadrangle maps by me and my students were published by the New Mexico Bureau of Mines and Mineral Resources. These maps are the Cuba quadrangle (Woodward, McLelland, and others, 1972), San Pablo quadrangle (Woodward, Kaufman, and others, 1973), Rancho del Chaparral quadrangle (Woodward, Kaufman, and Reed, 1973), La Ventana quadrangle (Woodward and Schumacher, 1973a), Holy Ghost Spring quadrangle (Woodward and Martinez, 1974), Nacimiento Peak quadrangle (Woodward, McLelland, and Kaufman, 1974), San Miguel Mountain quadrangle (Woodward, DuChene, and Reed, 1974), Gallina quadrangle (Woodward, Gibson, and McLelland, 1976), San Ysidro quadrangle (Woodward and Ruetschilling, 1976), Gilman quadrangle (Woodward, DuChene, and Martinez, 1977), Jarosa quadrangle (Woodward and Timmer, 1979), and Regina quadrangle (Merrick and Woodward, 1982).

John W. Husler, staff chemist at the Department of Geology, University of New Mexico, performed the whole-rock and atomic-absorption spectrophotometric analyses of the Precambrian rocks. Thin sections and polished sections were prepared in the laboratories of the Department of Geology at the University of New Mexico.

Finally, I would like to thank the reviewers who suggested significant improvements in the paper; they, of course, are not responsible for my opinions nor for any errors I may have committed. The reviewers and their institutions are Elmer H. Baltz, Jr., U.S. Geological Survey, Kent C. Condie, New Mexico Institute of Mining and Technology, and Virginia T. McLemore and Donald L. Wolberg, both of the New Mexico Bureau of Mines and Mineral Resources.

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Albuquerque
January 10, 1984

Contents

Tables

Figures

Sheet

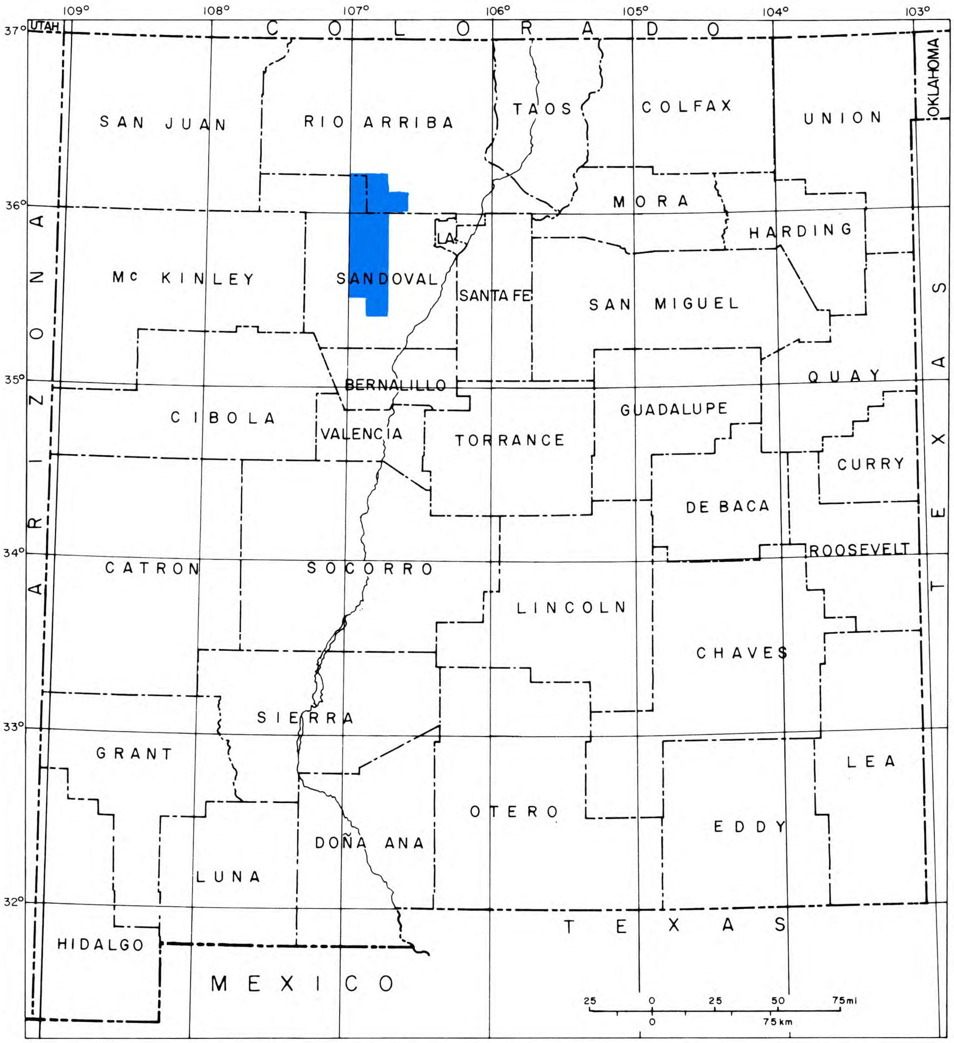


FIGURE 1—Index map of New Mexico showing location of Sierra Nacimiento and adjacent areas covered in this publication.

Abstract

Precambrian igneous, metasedimentary, and meta-igneous rocks of Proterozoic age occur in two major outcrop areas in the Nacimiento area. Clastic sediments and volcanic rocks accumulated and underwent regional synkinematic metamorphism prior to emplacement of plutonic igneous and meta-igneous rocks that range in composition from ultramafic to leucogranitic. Syenite of probable Ordovician or perhaps Cambrian age intrudes Precambrian rocks and is nonconformably overlain by Paleozoic strata.

Paleozoic strata, having a maximum composite thickness of 5,846 ft, include Mississippian, Pennsylvanian, and Permian units. Mississippian beds, which include, in ascending order, the Arroyo Peñasco and Log Springs Formations, are thin and only locally present. Pennsylvanian beds, which include, in ascending order, the Osha Canyon, Sandia, and Madera Formations, are marine deposits having a maximum thickness of 1,775 ft. Permian units are continental elastics and are, in ascending order, the Abo Formation, 100(?)-2,900(?) ft thick; the Yeso Formation, 10(?)-525 ft thick; the Glorieta Sandstone, 0-100 ft thick; and the Bernal Formation, 0-80 ft thick.

Mesozoic strata have a maximum composite thickness of 9,340 ft and include mainly clastic terrestrial deposits of Triassic and Jurassic age and mainly clastic marine Cretaceous beds. In ascending order the units are the Chinle Formation (Triassic); the Entrada Sandstone, Todilto Formation, and Morrison Formation (Jurassic); and the Dakota Formation, Mancos Shale, Mesaverde Group, Lewis Shale, Pictured Cliffs Sandstone, and Kirtland Shale and Fruitland Formation undivided (Cretaceous).

Terrestrial deposits of Paleocene and Eocene age include, in ascending order, the Ojo Alamo Sandstone, the Nacimiento Formation, and the San Jose Formation; these units have a maximum composite thickness of 2,325 ft. Three different facies of a Miocene continental deposit up to 1,000 ft thick comprise the Zia Sand, the Abiquiu Formation, and an unnamed volcaniclastic unit. Volcanics of the Paliza Canyon Formation (Pliocene) and the Bandelier Tuff (Quaternary) are present locally.

The Nacimiento uplift was initiated during the Laramide (Late Cretaceous—early Tertiary) and consists of a block tilted eastward and bounded on the west by reverse and thrust faults, with at least 10,000 ft of structural relief between the highest part of the uplift and the adjacent San Juan Basin. The uplift is internally segmented by high-angle faults. Laramide structures formed in a regional compressive stress field complicated by right shift between the uplift and the San Juan Basin, whereas the late Cenozoic evolution of the Rio Grande rift occurred as a result of crustal extension. Rejuvenation of some Laramide structures occurred during the late Cenozoic deformation.

Natural gas has been produced from the South Blanco Pictured Cliffs field in the Regina $7^1/_2$-min quadrangle, and the potential exists for the discovery of additional hydrocarbons. Copper has been extracted from sandstone-type deposits in the Chinle Formation (Triassic), but the potential for additional commercial production is low. Numerous occurrences of uranium-bearing minerals and radioactive anomalies have been reported, but, to date, only minor production is recorded for five localities. Travertine, gravel, and gypsum are present, but only the gypsum and gravel have been exploited. Coal was mined underground, but currently no coal is being mined commercially.

Introduction

Location

The Sierra Nacimiento is located in north-central New Mexico (Fig. 1) in Sandoval and Rio Arriba Counties. These mountains trend north over a distance of approximately 50 mi and are 6-10 mi wide. Twelve $7^1/2$-min quadrangles that cover most of the mountains are available as geologic maps published by the New Mexico Bureau of Mines and Mineral Resources (Fig. 2). These maps are the primary sources of information for this report.

GM-25. Geologic map of Cuba quadrangle, New Mexico.
GM-26. Geologic map of San Pablo quadrangle, New Mexico.
GM-27. Geologic map and sections of Rancho del Chaparral quadrangle, New Mexico.
GM-28. Geologic map and sections of La Ventana quadrangle, New Mexico.
GM-32. Geologic map and sections of Nacimiento Peak quadrangle, New Mexico.
GM-33. Geologic map and sections of Holy Ghost Spring quadrangle, New Mexico.
GM-34. Geologic map and sections of San Miguel Mountain quadrangle, New Mexico.
GM-37. Geology of San Ysidro quadrangle, New Mexico.
GM-39. Geology of Gallina quadrangle, Rio Arriba County, New Mexico.
GM-45. Geology of Gilman quadrangle, New Mexico.
GM-46. Geology of Regina quadrangle, Rio Arriba and Sandoval Counties, New Mexico.
GM-47. Geology of Jarosa quadrangle, New Mexico.

From these previously published maps a generalized bedrock geologic map and structure sections of the Sierra Nacimiento and adjacent areas were compiled (in back pocket) .

In addition to the Sierra Nacimiento, the following parts of adjacent geologic provinces are discussed: the eastern edge of the San Juan Basin, the southern Gallina—Archuleta arch, the southwest corner of the Chama Basin, the western part of the Jerez volcanic field, and the northwest part of the Albuquerque Basin of the Rio Grande rift (Fig. 2; map in back pocket).

Two principal paved highways are present, NM-44 in the southern and western parts of the area and NM-96 in the northwest and north. Another highway that is partly paved, NM-126, crosses the area and divides it into a northern third and southern two-thirds (Fig. 2). Numerous forest roads, abandoned logging roads, and trails provide access to large parts of the area. Much of the northern part of the mountains, however, is roadless, because it is within the San Pedro Parks Wilderness.

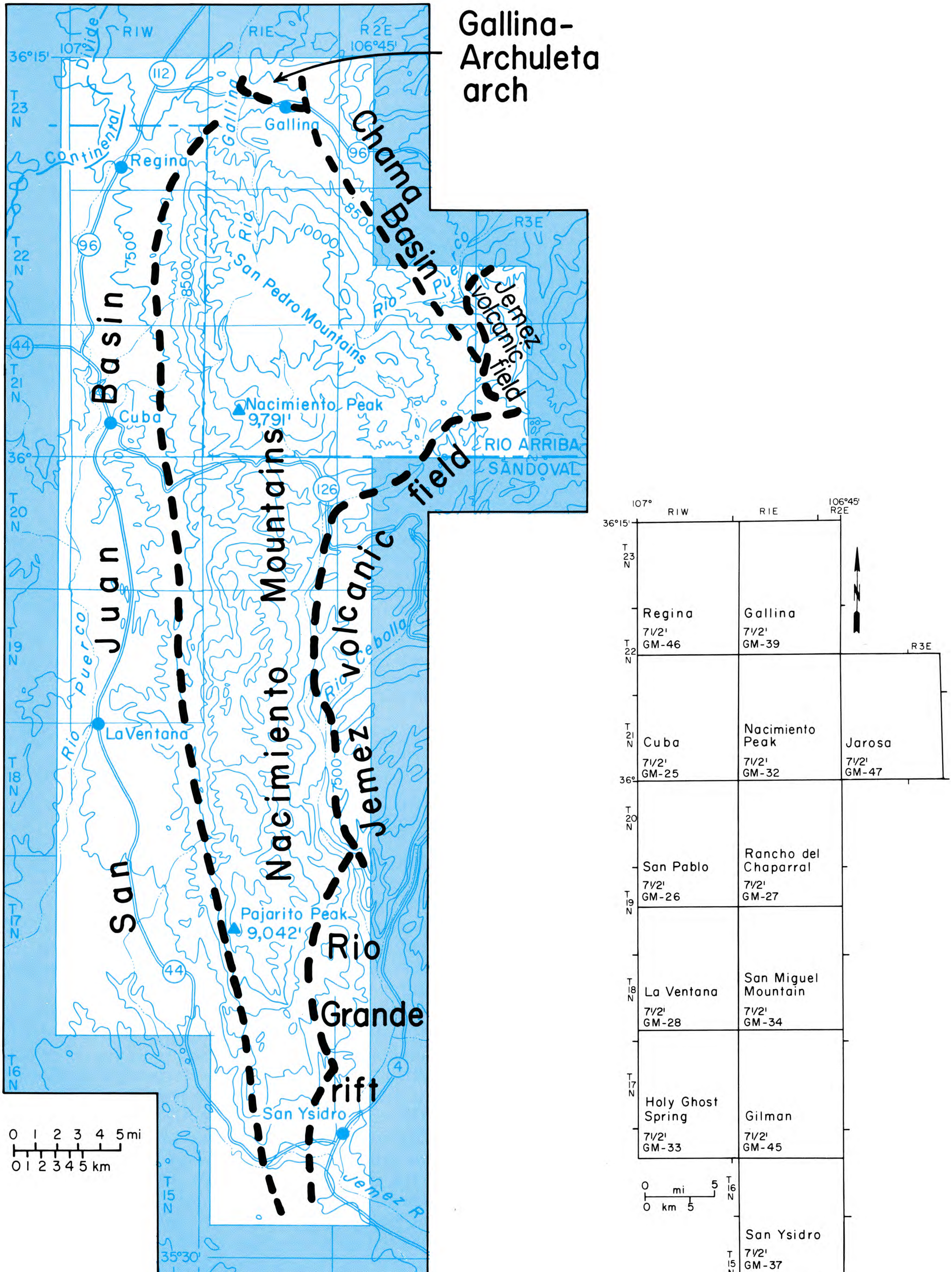


FIGURE 2—Location map showing Sierra Nacimiento and adjacent geologic provinces, San Juan Basin, Gallina–Archuleta arch, Chama Basin, Jerez volcanic field, and the Albuquerque Basin of the Rio Grande rift, and index map to the $7^1/2$-min quadrangles that cover the area.

Physiography

Total relief in the area is approximately 5,180 ft; the highest point is slightly over 10,600 ft at San Pedro Peaks in the Nacimiento Peak quadrangle, and the lowest point is a little less than 5,420 ft in the southeast corner of the San Ysidro quadrangle. The steep western escarpment of the mountains has a maximum topographic relief of approximately 3,000 ft. whereas the more gentle eastern slope generally has less relief because of the higher elevation at the eastern foot of the range.

Although the northern end of the range is the highest part, it is characterized by rounded and gentle summits, due, in large part, to the fact that the range is at its widest here and has undergone less intensive erosion. This northern part is commonly called San Pedro Mountains on topographic maps; however, it is in structural and topographic continuity with the rest of the range and is, therefore, considered to be part of the Sierra Nacimiento in this report. Progressing southward from the San Pedro Peaks, the highest and most distinctive landmarks are Nacimiento Peak (9,801 ft), Blue Bird Mesa (9,247 ft), San Miguel Mountain (9,473 ft), and Pajarito Peak (9,042 ft).

Drainage is radial from the San Pedro Peaks, but the southern part of the range is drained by major south-flowing streams that parallel the crests of the mountains (Fig. 2). All the streams shown in Fig. 2 drain to the Rio Grande, which in turn flows to the Gulf of Mexico; the northwest corner of the Regina quadrangle drains to the Pacific Ocean, because the Continental Divide trends northeasterly along the low hills northwest of Regina.

Rio de las Vacas, Rio Cebolla, Rito Cafe, Jerez Creek, Rio Gallina, and the eastern Rio Puerco are perennial streams in this area, but the western Rio Puerco, San Jose Creek, and Rio Salado are intermittent in their lower reaches. Numerous smaller streams in the high country of the northern part of the area are also perennial. In the southern part of the range, nearly all of the smaller streams are intermittent.

Other aspects of the physiography that are directly related to the geomorphic evolution of the area are discussed in the appropriate places in the sections that follow.

Previous work

Renick (1931) mapped (scale 1:125,000) the western side of the Sierra Nacimiento and the adjacent part of the San Juan Basin as part of a study dealing mainly with ground water. Another geologic map (scale approximately 1:95,000) by Wood and Northrop (1946) includes all the area of this report. Baltz (1967) included the Tertiary rocks along the western side of the Sierra Nacimiento in a geologic map (scale 1:63,360). R. L. Smith and others (1970) included the eastern part of the area in a map (scale 1:125,000) concerned principally with Cenozoic volcanic rocks and generally with earlier rocks. A very generalized map that appears to be based largely on Renick's (1931) map was published by Santos and others (1975) as part of an evaluation of the mineral resources of the San Pedro Parks Wilderness. More detailed maps were done by Acosta (1973) in the northern Jarosa and southeast Gallina quadrangles and by Hutson (1958) in the northern Regina quadrangle as parts of 1.5. theses. Other works, mainly involving mineral deposits and stratigraphy, are cited and acknowledged in the appropriate places in the following sections.

Rocks and formations

Rocks and sediments ranging in age from Precambrian to Quaternary are present in the Nacimiento area. Precambrian crystalline igneous and metamorphic rocks are overlain unconformably by Mississippian, Pennsylvanian, and Permian strata. Maximum composite thickness of Paleozoic, Mesozoic, and Cenozoic surface-accumulated rocks is approximately 19, 286 ft; this thickness is not present at any one locality, however. The maximum composite thicknesses are: Paleozoic strata, 5,846 ft; Mesozoic strata, 9,340 ft; and Cenozoic rocks, 4,100 ft (Table 1) . Despite the impressive thickness of the composite stratigraphic sequence, the presence of regional disconformities and low-angle unconformities results in major stratigraphic breaks with large segments of geologic time not being represented in the rock record.

Precambrian

Two principal exposures of Precambrian rocks occur in the southern and northern Sierra Nacimiento (Woodward, Martinez, and others, 1974; Woodward, McLelland, and Husler, 1977). Inasmuch as more differences than similarities are apparent between these two areas, they are described separately. Also, paucity of radiometric dates compounds the problem of correlations between the two terranes. The major similarity is the presence of metavolcanic and metasedimentary rocks as inclusions within gneissic rocks that were emplaced as plutons. These occurrences suggest a greenstone terrane in both areas prior to emplacement of the plutons.

Precambrian basement rocks probably have had a subtle but profound influence on the later geological development of the region; they are potential source rocks for younger mineral deposits (Woodward, Kaufman, and Schumacher, 1974; Woodward, Kaufman, and others, 1974; LaPoint, 1974) and have controlled some Cenozoic structures (Cordell, 1976) .

Northern Nacimiento area

Only a generalized geologic map (Fig. 3) is presented here, but the reader interested in the details

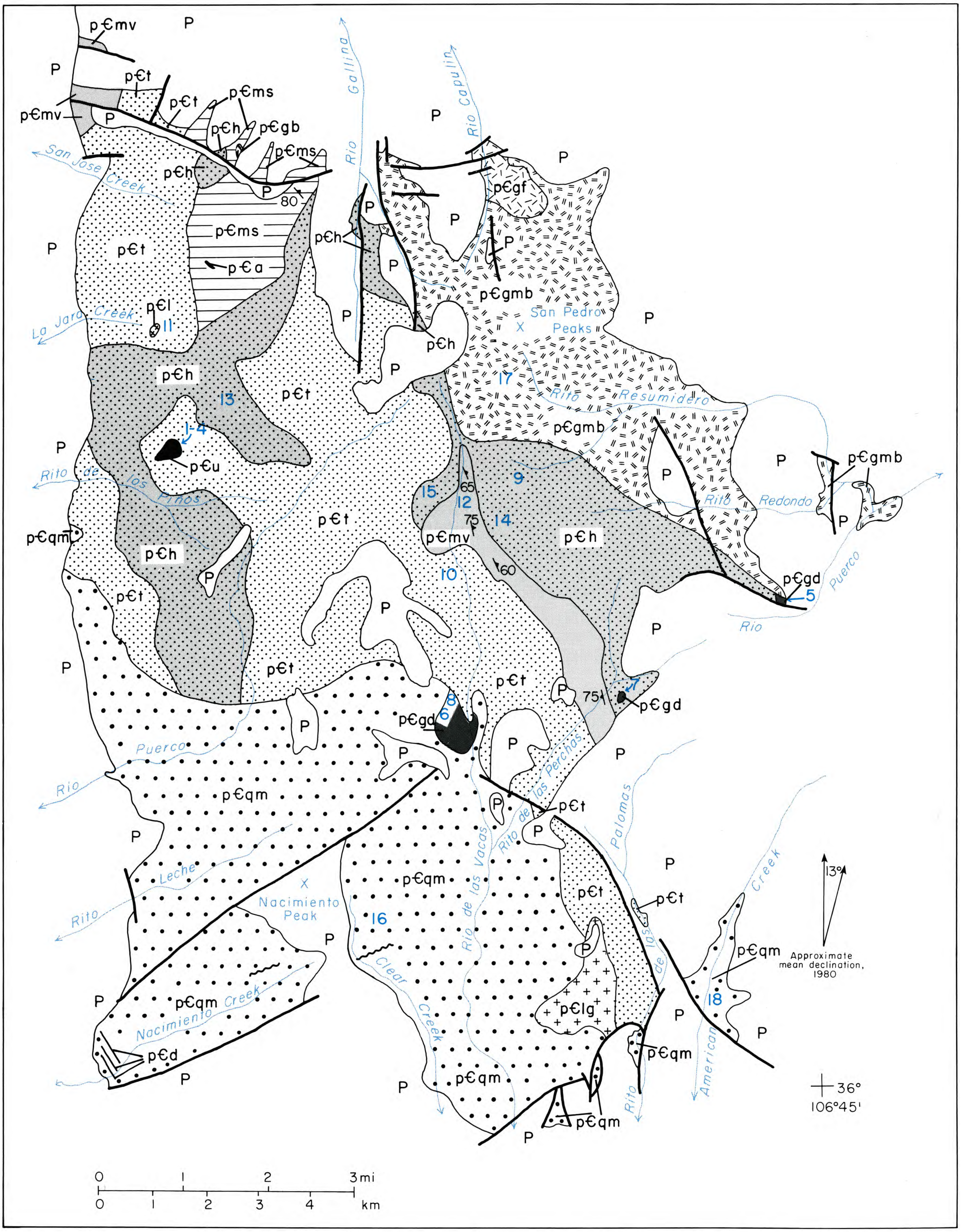
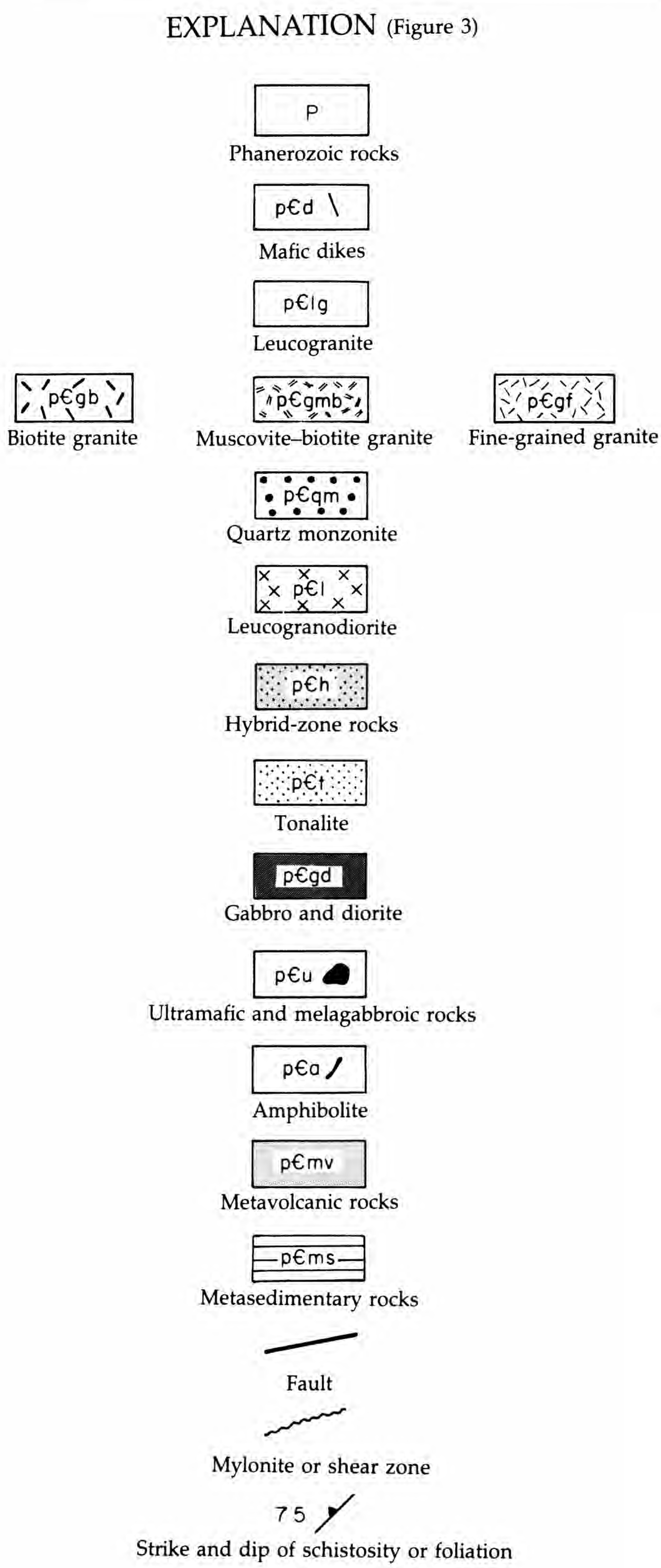


FIGURE 3—Generalized geologic map of Precambrian rocks of northern Sierra Nacimiento, New Mexico (modified from Woodward, McLelland, and Husler, 1977). Numbered localities are keyed to text and chemical analyses shown in Table 2. No analysis is available for locality 18. Relations shown in explanation are tentative.

of the geology can consult the 1:24,000-scale maps published by the New Mexico Bureau of Mines and Mineral Resources (Fig. 2; p. 8). Fourteen Precambrian rock units were mapped in the northern Sierra Nacimiento. Metasedimentary and metavolcanic rocks appear to be the oldest; they are followed by plutonic igneous rocks ranging in composition from ultramafic to leucogranitic. The rocks are described in their probable chronologic order from oldest to youngest, and their generalized distribution is shown in Fig. 3.



Metasedimentary rocks (p€ms)-Very fine grained, light-tan to medium-gray metasedimentary rocks are exposed in the northwest part of the area (Fig. 3). These rocks are meta-quartz wacke, meta-arkose, metaquartzite, metagraywacke, and silty argillite . They range from mineralogically and texturally mature rocks containing 98% quartz to rocks containing feldspar and quartz clasts in an extremely fine grained matrix of chlorite and sericite that makes up 60% of the rock. These latter immature and poorly sorted rocks are by far the most abundant. Textures range from granoblastic to moderately schistose, with minor amounts of porphyroblastic chlorite and biotite. Intercalated with the metasediments are minor amounts of metavolcanics and amphibolites that are described below. Numerous inclusions of metasedimentary rocks occur within tonalite (p€t) in the Regina quadrangle, but they are too small to be shown on Fig. 3.

The metasediments were sandstone, arkose, graywacke, and silty shale prior to undergoing regional synkinematic metamorphism in the greenschist facies. Schistosity is not strong, but, where present, it trends northwest and dips steeply.

Metavolcanic rocks (p€mv)-Metavolcanic rocks are exposed mainly in an elongate, northwest-trending roof pendant (Fig. 3, locality 12), as minor intercalations in the metasedimentary sequence, and in outcrops in the northwest corner of the Precambrian exposures in the Regina quadrangle (Fig. 3). Minor inclusions within plutonic rocks are found elsewhere in the area. The composition of the metavolcanics ranges from felsic to mafic.

The metavolcanics in the northwest-trending roof pendant in the Nacimiento Peak quadrangle are gray, pink, and light greenish gray, with a blastoporphyritic texture consisting of relict phenocrysts of quartz up to 3.0 mm in diameter in a very fine grained xenoblastic aggregate of quartz, albite, and microcline with accessory biotite and white mica. Foliation, which is weak and defined by faint compositional banding and alignment of reddish-brown biotite, trends northwest and dips steeply. The normative minerals calculated from a single chemical analysis (Table 2, no. 12) indicate that this rock is best classified as a meta-quartz latite (= meta-dellenite), assuming metasomatic changes have been minor. Chemically, the rock is intermediate between Nockolds' (1954) average dellenite and rhyolite.

Felsic metavolcanics that occur as inclusions in tonalite in the Regina quadrangle range from dacite to rhyodacite. These metavolcanic rocks were formed by regional metamorphism of felsic volcanics. The foliation is due probably to penetrative deformation during regional metamorphism, although some may be attributed to relict primary flow. After regional metamorphism, the metavolcanics were locally metasomatized near the contacts with a tonalite intrusion, resulting in growth of oligoclase poikiloblasts. Nonmetasomatized metavolcanics, analyzed by the Rb-Sr method, give ages of 1,800 ± 50 m.y. (Brookins, 1974).

TABLE 1—Stratigraphic table showing bedrock units.

Erathem	System	Rock units	Measured thickness (ft)	Symbol
CENOZOIC	Quaternary	Bandelier Tuff	0–650	Qbt
	Tertiary and/or Quaternary	terrace and pediment deposits	0–30	TQtp
		travertine	0–50	QTt
	Tertiary	Paliza Canyon Formation	0–45	Tpc
		Abiquiu Formation	0–400	(Ta)
		Zia Sand	0–1,000	(Tz)
		volcaniclastic rocks	350–450	(Tv)
		San Jose Formation	800–1,400	Tsj
		Nacimiento Formation	500–800	Tn
		Ojo Alamo Sandstone	70–125	Toa
MESOZOIC	Cretaceous	Kirtland Shale and Fruitland Formation undivided	85–240	Kkf
		Pictured Cliffs Sandstone	0–65	Kpc
		Lewis Shale	1,500–2,000	Kl
		Mesaverde Group (Kmv): La Ventana Tongue of Cliff House Sandstone	15–900	Klv
		Mesaverde Group (Kmv): Menefee Formation	265–700	Kmf
		Mesaverde Group (Kmv): Point Lookout Sandstone	40–275	Kpl
		Mancos Shale	2,000–2,200	Km
		Dakota Formation	80–210	Kd
	Jurassic	Morrison Formation	400–1,020	Jm
		Todilto Formation	14–150	Jt
		Entrada Sandstone	100–300	Je
	Triassic	Chinle Formation (TRc): upper shale member	400–600	TRu
		Chinle Formation (TRc): Poleo Sandstone Lentil	0–135	TRp
		Chinle Formation (TRc): Salitral Shale Tongue	0–335	TRs
		Chinle Formation (TRc): Petrified Forest Member (includes upper shale member, Poleo Sandstone Lentil, Salitral Shale Tongue)	1,070	(TRpf)
		Chinle Formation (TRc): Agua Zarca Sandstone Member	0–210	TRa
PALEOZOIC	Permian	Bernal Formation	0–80	Pb
		Glorieta Sandstone	0–100	Pg
		Yeso Formation	10(?)–525	Py
		Abo Formation	100(?)–2,900(?)	Pa
	Pennsylvanian	Madera Formation	0–1,775	IPm
		Sandia Formation	0–225	IPs
		Osha Canyon Formation	0–71	IPoc
	Mississippian	Log Springs Formation	0–50	Mls
		Arroyo Peñasco Formation	0–120	Map
	Cambrian–Ordovician	syenite		€Os
PRECAMBRIAN		metamorphic and plutonic igneous rocks		p€

TABLE 2—Chemical analyses and molecular (modified CIPW) norms of Precambrian rocks of northern part of Sierra Nacimiento. Numbers (1-17) refer to localities shown in Fig. 3 (from Woodward, McLelland, and Husler, 1977).

Description	Ultramafic and melagabbroic rocks				Gabbro and diorite				Tonalite		Leuco-granodiorite	Metavolcanic rock	Hybrid-zone rocks			Quartz monzonite	Muscovite-biotite granite
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	45.55	46.09	46.66	46.94	49.25	50.00	51.56	52.31	66.91	68.26	75.71	74.92	71.43	77.06	77.21	71.06	77.51
Al_2O_3	10.30	10.70	10.75	9.89	15.15	15.78	11.99	14.80	14.67	14.65	13.15	11.40	13.55	12.20	11.80	14.80	13.00
Fe_2O_3	5.84	3.80	4.64	3.90	6.87	3.14	2.79	2.69	2.61	2.44	0.30	2.34	1.44	1.02	0.76	1.48	0.44
FeO	5.95	6.73	6.88	7.04	8.26	5.25	6.04	4.64	2.74	2.48	0.31	1.09	1.40	0.34	0.45	1.23	0.13
MgO	19.20	18.00	16.99	17.80	5.25	8.48	10.34	7.98	1.30	1.10	0.38	0.17	0.80	0.12	0.15	1.03	0.15
CaO	7.60	8.00	8.33	8.30	8.95	11.35	8.30	10.91	3.41	2.65	0.89	0.97	2.40	0.60	0.57	2.26	0.26
Na_2O	1.28	1.50	1.62	1.38	2.26	2.16	2.36	1.95	4.14	4.03	4.13	3.58	3.45	3.52	3.26	3.18	3.40
K_2O	0.57	0.71	0.80	0.64	0.60	0.53	1.61	0.94	1.87	1.79	3.70	3.80	3.80	4.25	4.60	3.48	4.82
$H_2O(+)$ $(+CO_2)$	3.77	2.93	2.06	2.66	1.50	2.27	2.45	2.22	1.47	0.96	0.87	0.62	0.84	0.54	0.33	0.80	0.40
$H_2O(-)$	0.14	0.14	0.10	0.24	0.07	0.12	0.11	0.08	0.02	0.15	0.07	0.16	0.06	0.10	0.02	0.04	0.00
TiO_2	0.53	0.56	0.60	0.51	1.30	0.62	1.22	0.49	0.64	0.79	0.05	0.34	0.50	0.16	0.15	0.42	0.10
P_2O_5	0.17	0.22	0.18	0.17	0.16	0.09	0.52	0.165	0.17	0.16	0.025	0.07	0.120	0.02	0.026	0.12	0.01
MnO	0.180	0.176	0.179	0.176	0.231	0.147	0.151	0.135	0.101	0.176	0.017	0.077	0.060	0.019	0.021	0.057	0.035
SrO	0.056	0.057	0.058	0.044	0.020	0.044	0.088	0.050	0.030	0.32	0.014	0.009	0.025	0.010	0.007	0.022	0.001
total	101.14	99.61	99.84	99.69	99.87	99.98	99.53	99.35	100.08	99.96	99.62	99.54	99.87	99.96	99.35	99.98	100.25
total Fe (as Fe_2O_3)	12.45	11.28	12.28		16.05	8.97	9.50		5.66							2.85	0.59
L.O.I.	3.22	2.33	1.55		0.61	1.76	1.79		1.17							0.66	0.39
FeO after L.O.I.	1.03	1.31	2.26		0.21	0.66	0.14		0.00							0.00	0.00
$SO_4^{=}$	(−)	(−)	(−)		(−)	(−)			(−)								

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Q	0.0	0.0	0.0	0.0	6.52	0.92	1.04	4.91	24.68	28.56	33.01	35.91	29.08	36.79	37.31	31.20	36.13
Or	3.37	4.23	4.74	3.81	3.71	3.20	9.75	5.72	11.34	10.87	22.26	23.20	22.98	25.64	27.88	21.00	28.83
Ab	11.52	13.57	14.57	12.50	21.26	19.81	21.73	18.02	38.16	37.18	37.36	33.21	31.70	32.28	30.03	29.17	30.91
An	20.72	20.52	19.74	19.07	30.83	32.48	17.81	29.71	16.31	13.32	4.32	3.94	10.51	2.93	2.73	10.71	1.24
Di	12.89	14.54	16.52	17.17	11.73	19.64	16.92	20.01	0.0	0.0	0.0	0.47	0.77	0.0	0.0	0.0	0.0
Hy	23.05	17.26	16.60	22.60	16.18	19.52	26.90	17.76	5.42	4.48	1.31	0.25	2.45	0.34	0.42	3.30	0.42
Ol	21.24	24.64	21.76	19.66	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mt	6.12	4.00	4.86	4.11	7.52	3.35	2.99	2.90	2.80	2.62	0.32	2.08	1.54	0.51	0.80	1.58	0.19
Il	0.74	0.79	0.84	0.72	1.90	0.88	1.74	0.70	0.92	1.13	0.07	0.49	0.71	0.23	0.21	0.60	0.14
He	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.30	0.0	0.38	0.01	0.0	0.18
Ap	0.36	0.46	0.38	0.36	0.35	0.19	1.11	0.37	0.36	0.34	0.06	0.15	0.26	0.04	0.06	0.26	0.02
Thornton-Tuttle normative differentiation index	14.60	17.49	18.87	15.97	29.90	22.94	31.52	28.02	73.07	75.56	93.04	91.40	83.18	94.44	94.98	81.15	95.92

Metavolcanic rocks of intermediate to mafic composition are most common in the Regina quadrangle in the northwest part of the Precambrian terrane. These rocks form more extensive exposures than do the other metavolcanic and metasedimentary rocks, although they also are present elsewhere as xenoliths. The original compositions of these rocks are difficult to determine due to extensive alteration. These rocks are dark green or gray, fine grained, poorly to moderately foliated, and are composed of chlorite (50%), plagioclase (25%), quartz (10%), calcite (10%), pyrite (3%), and epidote (2%) . Foliation is defined by the partial alignment of chlorite.

The chlorite in these rocks probably replaced original igneous pyroxene, as judged from relict textures. Whether hornblende was an intermediate product, formed from the pyroxene during metamorphism and later destroyed, is not known. Sodic plagioclase forms randomly oriented idiomorphic to hypidiomorphic grains. Plagioclase relicts are present and originally comprised approximately 15% of the rock. Quartz is found as small xenomorphic grains in the ground-mass of these rocks, and the pyrite forms hypidiomorphic to skeletal crystals that are disseminated throughout the rock. Epidote is present as fine-grained aggregates and may either be a product of metamorphism or later alteration.

Microscopically, these mafic rocks show blastophitic textures. This relict texture is represented by randomly oriented idiomorphic to hypidiomorphic plagioclase laths in an unoriented felted mass of chlorite. The mineralogy and texture suggest that these rocks were originally intermediate to mafic flows or subvolcanic intrusives.

Amphibolite (p€a)-A few small lenses of amphibolite, up to 30 ft long and 3 ft wide, are surrounded by metasedimentary rocks in the northwest part of the area. The amphibolite is fine grained, dark greenish gray, and slightly schistose. It is composed of mostly subhedral to euhedral hornblende and sodic plagioclase that is altered to epidote, sericite, and chlorite. Trace amounts of opaque minerals and quartz are present.

These rocks appear to be derived from basic igneous dikes and sills injected into the sedimentary rocks prior to regional metamorphism.

Ultramafic and Melagabbroic rocks (p€u)—A body of ultramafic and melagabbroic rock (p€u) in the Cuba quadrangle (Fig. 3, localities 1-4) approximately 0.5 mi across was marginally assimilated by tonalite. Near the core of the body, the rock is dark gray to black, fine to medium grained, and composed of 45-50% hypersthene, 15-30% labradorite, 5-10% hornblende, 5-10% olivine, and 5-10% biotite, with minor amounts of chlorite, opaque minerals, and epidote. Modally, these rocks are near the transition between melagabbro and pyroxenite. Four chemical analyses of rocks from this unit (Table 2, nos. 1-4) more closely resemble Nockolds' (1954 average olivine-rich alkali basalt than average pyroxenites or other ultramafic rocks, although some metasomatism may have occurred to the protoliths. Normative color indices range from 58.76 to 62.02.

Although the evidence is not conclusive, this unit appears to have been emplaced as a hypabyssal igneous body of mafic to ultramafic composition. Its original extent and configuration are unknown, because this unit is surrounded by younger tonalite that displaced and assimilated the margins of the body.

Gabbro and diorite (p€gd)-Three small bodies ranging in composition from gabbro to diorite were assimilated marginally by younger tonalite and quartz monzonite. These mafic rocks are dark gray to black, fine to medium grained, and granular. The modal classification for many specimens is either gabbro or diorite, depending on whether color index or plagioclase composition is chosen as the determining factor.

A specimen from locality 6 (Fig. 3) is composed of 25% pyroxene (augite and hypersthene), 15% hornblende, 45% plagioclase (mostly andesine), and minor amounts of biotite, chlorite, opaque minerals, epidote, sericite, and a trace of quartz. At locality 5 (Fig. 3), the rock consists of approximately 25% hornblende, 5% biotite, 60% plagioclase (ranging from labradorite to andesine), 5% quartz, minor amounts of opaque minerals and epidote, and traces of pyroxene, apatite, and chlorite. The rock at locality 7 (Fig. 3) contains 30% hornblende, 10% biotite, 2% pyroxene, 50% plagioclase (mostly andesine), 5% quartz, and minor amounts of opaque minerals, apatite, epidote, sphene, and myrmekite.

Chemically these rocks (Table 2, nos. 5, 6, 7, and 8) more closely resemble Nockolds' (1954) average pyroxene—gabbro composition than average diorite composition. Normative color indices range from 39.10 to 43. 18, and normative anorthite content for plagioclase ranges from 60.62 to 63.64.

These mafic igneous rocks probably were emplaced as small hypabyssal bodies. Their original extent and configuration are not known, because they have been engulfed and partly assimilated by younger intrusive rocks.

Tonalite (p€t)—Gray, medium-grained, equigranular tonalite (Fig. 3, localities 9 and 10) intrudes the metasediments, metavolcanics, ultramafic—melagabbroic rocks, and the gabbro—diorite bodies. The tonalite is composed of approximately 60% plagioclase (mostly oligoclase, but locally andesine), 25% quartz, up to 10% microcline, 5-10% biotite, and minor amounts of epidote, chlorite, sphene, and opaque minerals. Locally, the rock is granodiorite containing abundant, large pink megacrysts of microcline that appear to have formed metasomatically near contacts where the tonalite was intruded by younger quartz monzonite (p€qm) .

Two chemical analyses of the tonalite (Table 2, nos. 9 and 10) are very similar to Nockolds' (1954) average biotite tonalite.

The mechanism of emplacement of this pluton is not known, although it is clearly of igneous origin. In the western part of the outcrop area, a northwest-trending foliation may be either primary-flow structure formed during emplacement or gneissic texture imparted by later synkinematic metamorphism.

Hybrid-zone rocks (p€h)—The hybrid zone (Fig. 3, localities 13, 14, and 15) consists of numerous irregularly shaped bodies of tonalite and pink porphyry that are too small to map individually at 1:24,000 scale (Woodward, McLelland, and Kaufman, 1974; Woodward, Gibson, and McLelland, 1976). The porphyry consists of quartz and milky-white oligoclase megacrysts up to 5.0 mm long in a very fine grained, pink groundmass of microcline, quartz, sodic plagioclase, and minor biotite. Contacts between the hybrid-zone rocks and the tonalite are broadly gradational.

The porphyry appears to have formed by recrystallization of the metavolcanics, with growth of oligoclase porphyroblasts near the contacts with the tonalite. Chemically, the porphyry (Table 2, nos. 13, 14, and 15) is very similar to the metavolcanics (Table 2, no. 12).

Leucogranodiorite (p€l)—A small body of leucogranodiorite (Fig. 3, locality 11; Table 2, no. 11) appears to be intrusive into the tonalite in the northwest part of the area. The leucogranodiorite is fine to medium grained and pink weathering; it has a weak foliation defined by narrow, gently undulating bands of quartz and feldspar surrounded by a xenomorphic granular mosaic of quartz, oligoclase, and microcline. Biotite occurs in fine-grained, elongate lenses parallel to the foliation. The biotite is replaced mostly by chlorite and is accompanied by minor amounts of apatite and opaque minerals.

Brookins (1974) reported a radiometric age of 1,840 ± 170 m.y. for rocks from this unit.

Quartz monzonite (p€qm)—Pinkish-gray quartz monzonite from locality 16 (Fig. 3; Table 2, no. 16) is composed of euhedral to anhedral pink microcline megacrysts up to 1.5 cm long in a medium-grained groundmass of blue-gray quartz, pink microcline, greenish-gray sodic plagioclase, and minor biotite. Plagioclase is euhedral and sericitized, whereas the microcline is fresh and, in the groundmass, is anhedral. Locally, the microcline megacrysts are mantled with sodic plagioclase, giving rapakivi texture. The quartz monzonite along the erosional inlier at American Creek (Fig. 3, locality 18) is equigranular, lacking megacrysts. Similar quartz monzonite is exposed in the northeast part of the San Pablo quadrangle.

The quartz monzonite has partly assimilated and locally metasomatized the older host rocks, especially the tonalite. Short, discontinuous shear zones trending east-northeast and up to 1 ft wide produced cata-clastic rocks ranging from flaser gneiss to mylonite; the age of shearing is not known but is presumed to be Precambrian. L. T. Silver (personal communication 1972) reported a U-Pb analysis on zircons from this quartz monzonite that yielded an age of 1,730 ± 20 m y.

Muscovite-biotite granite (p€gmb)–This rock (Fig. 3, locality 17) is pink and weakly porphyritic, with elongate megacrysts of pink microcline widely scattered in a medium-grained groundmass of smoky quartz, pink microcline, and pinkish-gray sodic plagioclase. Muscovite, biotite, and a trace of garnet are accessory minerals. Locally, the granite contains irregularly shaped bodies of simple pegmatite. Only the southwest margin of the pluton is exposed; it is marked by a fine-grained aplitic border facies. A single chemical analysis (no. 17) is shown in Table 2.

A small body of pink, fine-grained, muscovite-biotite granite occurs within this coarse granite (Fig. 3, locality 17) and may represent another facies of the larger pluton.

Biotite granite (p€gb)–An erosional inlier of pink, medium-grained biotite granite is exposed in the northwest part of the area. This rock is composed of microcline microperthite, quartz, sodic plagioclase, and accessory biotite. The relation of this rock to the muscovite-biotite granite is not known, but the biotite granite might be an extension of the larger granite pluton. The minor difference in composition could be caused by assimilation of the surrounding metasediments by the biotite granite.

Leucogranite (p€lg)—A body of leucogranite approximately 1.0 mi long is intrusive into the quartz monzonite (Fig. 3); a few other bodies of leucogranite are present but are too small to be shown in Fig. 3. This rock is pink and fine grained and consists of microcline, quartz, sodic plagioclase, and a trace of biotite. Numerous xenocrysts up to 1.0 cm long of blue-gray quartz and milky-white plagioclase appear to be derived from the quartz-monzonite host.

Mafic dikes (p€d)–Several north-northwest-trending mafic dikes intrude the quartz monzonite in the southwest part of the area. These dikes are up to 20 ft wide and 0.7 mi long and show well-developed primary-flow structures. They are dark greenish gray, very fine grained and are composed of approximately 50% plagioclase (mostly albite), 20% greenish-brown biotite, 10% chlorite, 10% epidote, and minor amounts of opaque minerals (mostly pyrite), calcite, and hornblende.

Plagioclase is intensely altered to epidote, and the biotite is partly chloritized. This rock is mineralogically similar to kersantite but lacks the characteristic lamprophyric texture (ferromagnesian phenocrysts in a groundmass in which the ferromagnesian minerals are notably idiomorphic) .

Summary–My interpretation of the principal events in the Precambrian geologic history in the northern Sierra Nacimiento, from oldest to youngest, is as follows:

1) Deposition of very fine grained graywacke and related immature sediments and accumulation of silicic volcanics occurred about 1,800 ± 50 m.y. ago.
2) Mafic dikes and sills were injected into the sedimentary rocks.
3) Regional metamorphism imparted a northwest-trending schistosity to the metasediments and metavolcanics.
4) Ultramafic to diorite hypabyssal plutons were emplaced.
5) Tonalite intruded the older rocks noted above and locally caused contact metamorphism of the metavolcanic rocks.
6) A small body of leucogranodiorite intruded the tonalite, perhaps during the waning stages of synkinematic metamorphism.
7) Quartz monzonite was emplaced and marginally metasomatized the tonalite, resulting in growth of microcline porphyroblasts.
8) Granite bodies were emplaced.
9) Mafic dikes were injected into the quartz monzonite.
10) East-northeast-trending shear zones locally produced mylonite and flaser gneiss zones in the quartz monzonite.

Southern Nacimiento area

The Precambrian rocks of the southern Sierra Nacimiento are described in their suggested chronologic order from oldest to youngest. In many cases, the structural and chronologic relationships are not known; no radiometric ages are published for any of these rocks. The major chronologic problems concern the relations between the gneissic units in the northern and southern parts of the area, because these gneisses are separated by a younger intrusive granitic body. Thus, the chronologic order is uncertain and subject to revision.

Distribution of the major rock units is shown on Fig. 4, a generalized geologic map. Those readers interested in more precise locations of the various rocks are referred to the 1:24,000 scale maps published by the New Mexico Bureau of Mines and Mineral Resources (Fig. 2; p. 8).

Mafic metavolcanic rocks (p€mvm)–Mafic xenoliths ranging in size from a few inches to several tens of feet in diameter are found in the gneissic and gra-

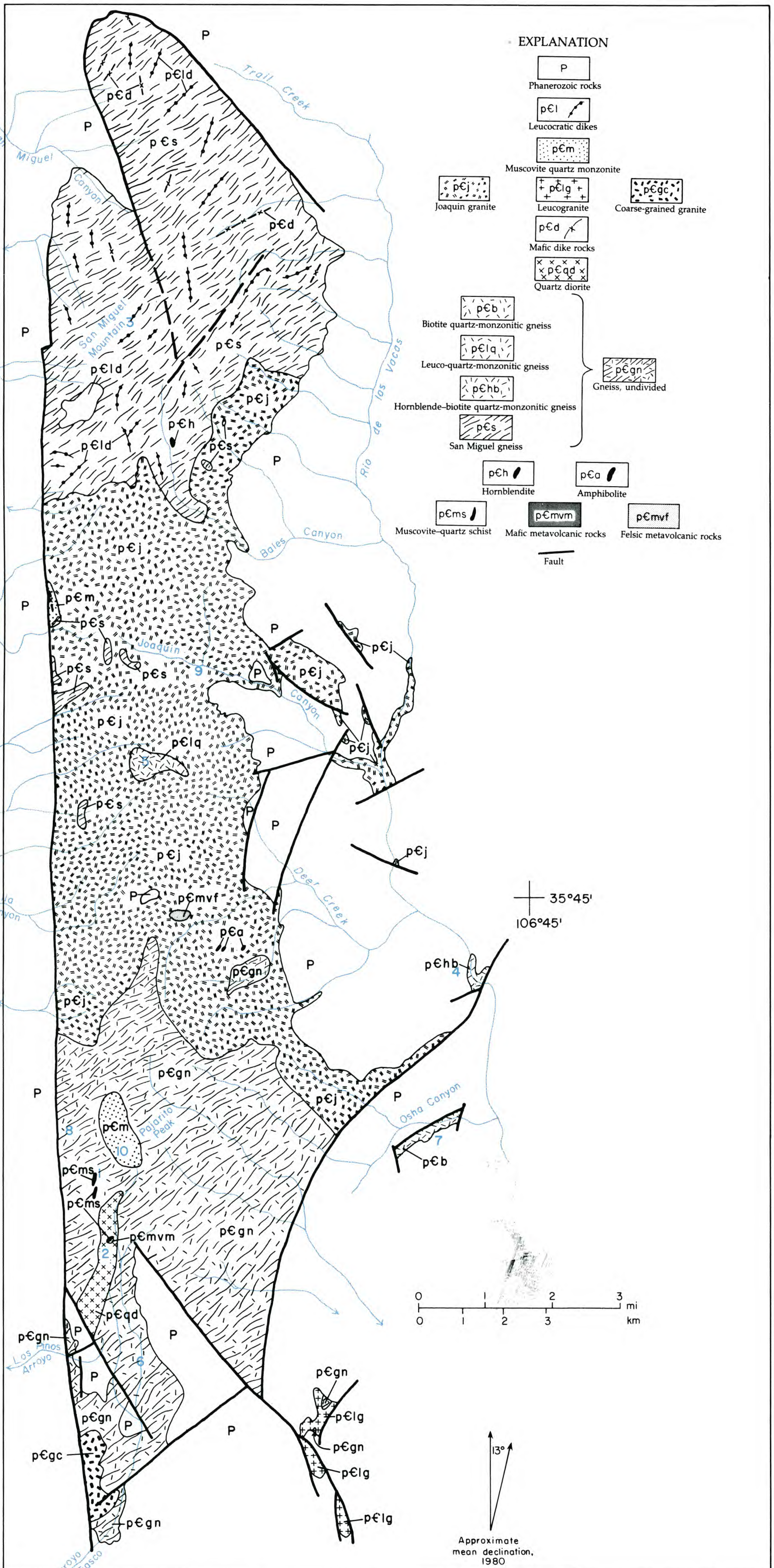


FIGURE 4—Generalized geologic map of Precambrian rocks of southern Sierra Nacimiento, New Mexico (modified from Woodward, Martinez, and others, 1974). Numbers showing localities are keyed to text. Relations shown in explanation are tentative.

nitic units. The xenoliths are generally dark greenish gray and fine grained with schistosity ranging from weak to strong. Most specimens are composed of nearly equal amounts of plagioclase (An_{40-50}) and common hornblende with trace amounts of apatite, sericite, zircon, epidote, and opaque minerals. Some samples also contain minor amounts of quartz and(or) biotite.

Schistosity in some of the xenoliths is truncated by the enclosing gneissic rocks, suggesting that the xenoliths underwent regional synkinematic metamorphism prior to being engulfed by the igneous parents of the gneissic rocks. The stable association of andesine with epidote indicates that the grade of metamorphism reached the staurolite-almandine subfacies of the amphibolite facies (Winkler, 1976). These mafic rocks appear to be remnants of mafic volcanic rocks into which the igneous parent rocks of the gneisses intruded.

Felsic metavolcanic rocks (p€mvf)–These rocks form inclusions or roof pendants surrounded by granite and are very fine grained, strongly schistose meta-rhyolite(?). The rocks are light brown and are composed of tiny (<0.01 mm) crystals of quartz and alkali feldspar(?) that form elongate lenses parallel with the schistosity. A minor amount of mica is present. The entire rock is stained by iron oxide. The texture suggests that this rock is a denitrified and synkinematically metamorphosed ash-flow tuff.

Minor amounts of very fine grained, schistose amphibolite occur intercalated with the felsic metavolcanics and probably represent mafic tuffs or flows.

Muscovite-quartz schist (p€ms)–A few lenses of pinkish-gray, fine-grained muscovite-quartz schist are enclosed by muscovite-biotite quartz-monzonitic gneiss south of Pajarito Peak (Fig. 4, locality 1). Locally, the foliation of the schist is sharply truncated by the gneiss, suggesting that the schist was metamorphosed prior to being engulfed by the igneous parent of the gneiss.

The schist occurs in lenses up to 4 ft in width and several hundred feet in length. Average composition of the schist is approximately 60% quartz and 35% muscovite with minor amounts of garnet and biotite. Schistosity is strong and is marked by thin layers of aligned muscovite and elongate, intensely sutured quartz. Idiomorphic garnet porphyroblasts have bowed out the schistosity. The schist was derived from argillaceous quartzose sandstone.

Hornblendite (p€h)—A body of hornblendite approximately 200 ft across is rimmed by amphibolite that grades into the surrounding San Miguel gneiss. The hornblendite is black, fine grained, and consists of 85% common hornblende, 7% orthopyroxene, 6% biotite, 1% plagioclase, and trace amounts of apatite, opaque minerals, and chlorite. A weak schistosity is marked by elongate hornblende and biotite. Relict orthopyroxene, rimmed by hornblende, has the optical properties of enstatite, but microprobe analysis indicates that its composition is that of bronzite. The margin of the hornblendite body grades into amphibolite containing nearly equal amounts of hornblende and andesine. The amphibolite in turn merges with the surrounding gneiss.

Available evidence suggests that the hornblendite was originally an ultramafic rock composed principally of orthopyroxene that later was uralitized and marginally feldspathized by granodioritic magma. The hornblendite and surrounding granodiorite underwent regional synkinematic metamorphism that reached the lower amphibolite facies and imparted the northeast-trending foliation to the hornblendite and the surrounding San Miguel gneiss.

San Miguel gneiss (p€s)—The most extensive Precambrian unit in the northern part of the southern Sierra Nacimiento is a quartz-monzonitic to granodioritic gneiss that is named for exposures on San Miguel Mountain (Fig. 4, locality 3). The gneiss is salmon pink to light pinkish gray and fine to coarse grained with lenticular foliation that trends northeast.

The San Miguel gneiss is composed of 16-32% microcline, 29-36% plagioclase (An_{27-33}), 25-30% quartz, 2-9% biotite, and minor amounts of opaque minerals, muscovite, chlorite, and myrmekite. Trace amounts of zircon, apatite, sphene, epidote, and sericite are present. Plagioclase occurs as subhedra in the groundmass and as subhedral megacrysts up to 5.0 mm across; some grains have bent or broken twin lamellae. Anhedral to subhedral microcline forms crystals in the groundmass, as well as megacrysts up to 12.0 mm in diameter. Undulatory, sutured, anhedral quartz forms elongate aggregates parallel with the foliation. Dark-brown biotite is present as fine-grained plates aligned in lenses in the foliation. Gneissic texture is due to segregation of biotite into lenses, to elongate quartz lenses, and to feldspar megacrysts.

Within the outcrop area of the San Miguel gneiss, subordinate zones occur where the rock is best described as biotite-quartz-feldspar schist or as schistose gneiss. The texture ranges from fine grained and schistose to gneissose layering of coarse-grained quartz-feldspar lenses with fine-grained schist. The schist contains approximately 15% biotite that, at some localities, is mostly chloritized. As much as 11% microcline is present in some specimens, but much of the microcline has been mylonitized and sericitized. Fine-grained quartz and plagioclase (An_{25-30}) each make up approximately 30% of the schist.

Contacts between the schistose rock and the more abundant variety of San Miguel gneiss are gradational and are transected by the trend of foliation. The outcrops of schistose rock are not shown on Fig.4, but Reed (1971) mapped them separately at a scale of 1:12,000. Reed (1971, p. 85) suggested that the schist, which differs from the ordinary San Miguel gneiss by being slightly richer in biotite and more strongly sheared, represents zones of assimilation of mafic rocks by the igneous parent of the gneiss. He further suggested that the schist was more intensely sheared as a result of the greater abundance of biotite.

Thus, the San Miguel gneiss is a granodioritic to quartz-monzonitic pluton that underwent regional synkinematic metamorphism, resulting in the northeast-trending foliation. The grade of metamorphism probably reached the lower amphibolite facies, as judged from the mineral assemblage of the synchronously metamorphosed hornblendite body.

Hornblende-biotite quartz-monzonitic gneiss (p€hb)–Hornblende-biotite quartz-monzonitic gneiss is exposed at an erosional inlier at the Guadalupe Box (Fig. 4, locality 4) . Contacts with the other Precambrian units are covered by younger strata, and therefore, the structural and chronologic relations are not known.

The gneiss is pinkish gray and coarsely foliated, with microcline porphyroblasts up to 1.5 cm in diameter in a coarse-grained matrix of plagioclase, quartz, and mafic minerals. Average composition of the gneiss is 33% plagioclase (An_{27}), 24% microcline, 23% quartz, 4% hornblende, and 4% biotite. Minor amounts of chlorite, sphene, opaque minerals, and epidote occur along with traces of apatite, calcite, zircon, myrmekite, and leucoxene .

Leuco-quartz-monzonitic gneiss (p€lq)—Leuco-quartz-monzonitic gneiss crops out as an irregularly shaped inclusion or roof pendant within the Joaquin granite in the San Miguel Mountain quadrangle (Fig. 4, locality 5). This gneiss is fine to medium grained and light pinkish gray and has subtle, but coarse, foliation. Folia consist of quartzose layers that alternate with feldspar-rich layers. In contrast with the other gneisses, this unit is conspicuous in lacking large microcline crystals.

Contacts with the surrounding Joaquin granite are sharp but highly sinuous with projections of granite extending into the gneiss. Thus, at the 1:24,000 scale of the mapping (Woodward, DuChene, and Reed, 1974), the contact is approximate and has a straighter trace than seen on the outcrop. Foliation of the gneiss is sharply truncated by the contact with the granite.

The leuco-quartz-monzonitic gneiss is composed of 33% plagioclase (An_{25}), 28% microcline, 32% quartz, and 4% biotite. Minor amounts of epidote and opaque minerals and traces of white mica, apatite, and myrmekite occur.

Biotite quartz-monzonitic gneiss (p€b)–Biotite quartz-monzonitic gneiss occurs at two localities in the southern part of the Sierra Nacimiento, at Jack Rabbit Flats (Fig. 4, locality 6) and east of Osha Canyon (Fig. 4, locality 7) . Because these two gneissic bodies are separated by a cover of younger sedimentary rocks, their relations to each other are uncertain. However, because of lithologic similarity, they are described under the same heading.

Fine- to coarse-grained, pinkish-gray to dark-gray, faintly foliated gneiss underlies most of Jack Rabbit Flats. The gneiss is mostly quartz monzonitic but locally is granodioritic. Numerous inclusions of quartz-diorite gneiss are present in this unit. The average composition is 35% microcline, 33% quartz, 26% plagioclase (An_{26-28}), 5% brown biotite, and traces of opaque minerals and apatite. Foliation, defined by biotite lenses and elongate microcline porphyroblasts, trends from N. 20° E. to N. 45° W.

On the east side of Osha Canyon (Fig. 4, locality 7) pink biotite quartz-monzonitic gneiss is exposed. Locally, weathered mafic minerals give the exposed surfaces a greenish tinge. This gneiss is coarsely foliated with microcline porphyroblasts up to 8.0 mm in diameter in a medium-grained matrix of quartz, plagioclase, and biotite.

The gneiss consists of 36% plagioclase ($Án_{26}$), 33% microcline, 20% quartz, and 9% biotite. Minor amounts of opaque minerals, epidote, muscovite, sphene, and leucoxene occur along with traces of apatite, hornblende, chlorite, and zircon.

Gneiss, undivided (p€gn)–In the southern part of the area several types of gneiss similar to those described, plus muscovite—biotite quartz-monzonitic gneiss, are complexly interlayered and, therefore, are mapped as gneiss undivided. Only the muscovite—biotite quartz-monzonitic gneiss is described here, because the other types present already have been discussed.

Fine- to medium-grained, orange-pink gneiss forms the steep scarp west of Pajarito Peak (Fig. 4, locality 8). This rock is principally quartz monzonitic in composition but locally is granodioritic. The average composition is 39% quartz, 31% microcline—microperthite, 23% plagioclase (An_{24-28}), 4% brown biotite, and 2% muscovite. Foliation trends north and is defined by lenses of biotite plates showing a weak preferred orientation.

A few lenses and layers of mica—quartz schist up to 400 ft long are enclosed by the gneiss. The mica—quartz schist apparently was engulfed and partly assimilated by the igneous parent of the gneiss. Thus, the high quartz content and the presence of muscovite in the gneiss may be due to assimilation.

Quartz diorite (p€qd)–Dark-gray, faintly to moderately foliated, medium-grained quartz diorite occurs near Los Pinos Canyon (Fig. 4, locality 2). It consists of 50% plagioclase (An_{35-38}), 20% quartz, 12% hornblende, 12% biotite, and minor amounts of opaque minerals, chlorite, epidote, sphene, and apatite. Normally zoned plagioclase is subhedral to euhedral and has bent and broken twin lamellae. Mafic minerals are also subhedral to euhedral, whereas the quartz is interstitial and anhedral. Foliation, defined by elongate clusters of mafic minerals, trends approximately N. 20° E.

The quartz diorite grades into the surrounding quartz-monzonitic gneisses through a zone up to 1, 000 ft wide where microcline euhedra, up to 5.0 cm long, occur in a medium-grained matrix of quartz diorite. The texture of the quartz diorite clearly indicates that it was derived from an igneous parent rock, because the plagioclase and mafic minerals are mostly euhedral, and the quartz is interstitial.

Joaquin granite (p€j) The Joaquin granite, named for exposures along Joaquin Canyon (Fig. 4, locality 9), is the most widespread Precambrian unit in the central part of the southern Sierra Nacimiento.

The granite is pink, fine to medium grained, and hypidiomorphic granular to slightly porphyritic in some areas having microcline megacrysts. Subtle foliation is present locally and is most common in the southern part of the area. Near the contact with the older gneisses, the rock may be quartz monzonitic, but the predominant lithology is granite having the following composition: 40-50% microcline—microperthite, 1821% plagioclase (An_{24}), 24-37% quartz, 2-3% biotite, and 1% muscovite. Minor amounts of opaque minerals, chlorite, sericite, and myrmekite are present along with traces of apatite, sphene, zircon, and epidote. Microcline occurs as anhedral to subhedral crystals 0.5-1.0 mm across. Inclusions of euhedral plagioclase oriented parallel to crystal outline of the microcline suggest a magmatic origin for the granite (Hibbard, 1965) .

The granite intrudes the gneiss with sharp, locally chilled contacts. Numerous dikes and apophyses of granite extend into the gneiss, and inclusions and(or) roof pendants of gneiss are common near the margins of the granite. The contact was mapped where granite becomes the dominant lithology. Gneissic inclusions in various stages of assimilation occur in the granite, suggesting that magmatic stoping and assimilation were important factors in emplacement. Emplacement by dilation may have taken place also, but the lack of exposure of the entire margin of the Joaquin granite pluton precludes definite proof of this possibility.

Leucogranite (p€lg)–Leucogranite is pink, medium to coarse grained and consists of microcline, oligoclase, and quartz. This unit forms small irregularly shaped intrusions and dikes in the southern part of the Sierra Nacimiento, mainly in the Gilman and San Ysidro quadrangles. The larger bodies may include dikes and zones of pegmatite, aplite, and fine-to medium-grained pink quartz monzonite.

Coarse-grained granite (p€gc)—This granite is considerably coarser grained than the granites previously described, as it may have crystals up to 1.0 cm in diameter. It is pink and composed of microcline, oligoclase, quartz, and minor amounts of biotite. Locally, it is weakly foliated, but at most localities it has directionless texture.

Mafic dike rocks (p€d)–Mafic dikes up to 4 ft in width were emplaced in the San Miguel gneiss and related rocks prior to regional synkinematic metamorphism. Although the dike rocks are commonly schistose, they show relict lamprophyric texture insofar as the phenocrysts are ferromagnesian and the groundmass also contains idiomorphic ferromagnesian minerals. Hornblende spessartite is the most common type of mafic dike rock and contains approximately 50% hornblende, 25% plagioclase (An_{40-50}), and minor amounts of quartz, epidote, biotite, and potassium feldspar.

The mafic dike rocks are fine grained and dark green to black. Most of the dikes are poorly exposed, and only those that are longitudinally continuous are shown in Fig. 4.

Muscovite quartz monzonite (p€m)–Fine-grained, buff muscovite quartz monzonite underlies Pajarito Peak (Fig. 4, locality 10) . This rock has directionless texture and is in sharp contact with the adjacent gneisses.

Leucocratic dike rocks (p€ld)–Dikes and irregularly shaped bodies of aplite, pegmatite, and granite to quartz monzonite, emplaced in gneisses and the Joaquin granite, appear to be the youngest Precambrian rocks in the area. The dikes and irregularly shaped bodies range in width from a few inches to several hundred yards. Some of the dikes can be traced for as much as 1.0 mi. Aplite, pegmatite, and granitic rocks may occur in the same dike, accompanied by textural and compositional zoning. Microcline and quartz are the predominant minerals, with lesser amounts of sodic plagioclase and minor amounts of muscovite and biotite. These bodies appear to have been emplaced by dilation.

Summary–The outline of the Precambrian geologic history of the southern part of the Sierra Nacimiento, presented below, is tentative and subject to revision.

1) Argillaceous quartzose sandstone and basic igneous rocks, possibly volcanics, accumulated; the original stratigraphic relationship between the rocks is not known.
2) The basic igneous rocks and sandstone underwent regional synkinematic metamorphism, producing the schistose mafic xenoliths and muscovite—quartz schist.
3) An ultramafic body, probably consisting mostly of orthopyroxene, was emplaced or formed as a crystal cumulate.
4) The igneous parent of the San Miguel gneiss was emplaced, at least in part, by stoping and assimilation of a terrane of mafic schist. The ultramafic body was also engulfed and probably uralitized and partly feldspathized. Quartz-monzonitic bodies in the southern part of the area may have been emplaced prior to, during, or after emplacement of the San Miguel gneiss.
5) Quartz diorite was emplaced in the southern part of the area.
6) Mafic dike rocks were emplaced by dilation in the parent of the San Miguel gneiss.
7) Regional, synkinematic metamorphism imparted north- to northeast-trending foliation in the rocks.
8) The Joaquin granite was emplaced as a magma, possibly by dilation with minor stoping and assimilation. Primary-flow structures that formed during emplacement resulted in gneissic texture in parts of the pluton, especially near the southern end. Leucogranite and coarse-grained granite in the southern part of the area may have been emplaced about the same time.
9) Muscovite quartz monzonite was emplaced near Pajarito Peak.
10) Leucocratic dikes and small, irregularly shaped plutons consisting of pegmatite, aplite, and granitic rocks were injected into the rock units previously noted.

Cambrian—Ordovician(?)

Distinctive brick-red syenite of probable Ordovician or possible Cambrian age is present in the Gilman quadrangle in the southern end of the Sierra Nacimiento (map, in back pocket). Initially, these rocks were considered to be Precambrian (Woodward, DuChene, and Martinez, 1977) because they are of igneous origin and are nonconformably overlain by Pennsylvanian strata. However, lithologically identical rocks in the Pedernal Hills and Lobo Hill east of Albuquerque have yielded a whole-rock Rb—Sr isochron age of about 469 ± 7 m.y., with maximum possible ages of 496 and 604 my. for the two occurrences (Loring and Armstrong, 1980). Thus, on the basis of lithologic similarity, these unusual and rare rocks in the Sierra Nacimiento and the Pedernal Hills are tentatively considered to be of Ordovician or possibly Cambrian age.

The syenite is fine to coarse grained and composed mostly of orthoclase that is subhedral to anhedral, slightly microperthitic, and 0.1-5.0 mm in diameter. It contains 1-2% magnetite that is slightly oxidized to form hematite. Trace amounts of interstitial quartz, subhedral sodic plagioclase, euhedral zircon, and euhedral apatite also occur. The red color of the rock is caused by a pervasive, dusky, iron-oxide staining of the feldspar.

The syenite occurs in small dikes and irregularly shaped small plutons that are up to 1,500 ft long. These bodies are intrusive into Precambrian gneiss and leucogranite.

Mississippian

In the Sierra Nacimiento, the Precambrian rocks are overlain locally and nonconformably by the Arroyo Peñasco Formation, a unit of Mississippian age. The Arroyo Peñasco, in turn, is overlain locally and unconformably by the Log Springs Formation, a unit that has not yielded fossils but is interpreted as Mississippian (Chesterian) in age (Armstrong and Ma-met, 1979) .

Arroyo Peñasco Formation

Strata of the Arroyo Peñasco Formation are preserved only in small blocks that were down warped prior to extensive erosion that removed the Arroyo Peñasco from the higher, intervening areas before deposition of Pennsylvanian strata. As a result, this formation is present in only three localities in the Sierra Nacimiento: in the northwest in the Regina quadrangle, in the south at Peñasco and Los Pinos Canyons, and at Guadalupe Box in the Gilman quadrangle (map, in back pocket) .

Development of the nomenclature of the Arroyo Peñasco Formation is complex; a brief review is given below. Read and others (1944) first recognized the distinctness of these rocks in north-central New Mexico and mapped them as the lower limestone member of the Sandia Formation (Pennsylvanian) . The lower gray limestone member was mapped and described by Wood and Northrop (1946) in the Sierra Nacimiento; they thought this lower limestone member was of pre-Pennsylvanian age in the Sierra Nacimiento but, in the absence of paleontological data, assigned it to the Pennsylvanian. Read and Wood (1947) later suggested that this member was equivalent to the Leadville Limestone (Mississippian).

In 1955 Armstrong proposed the name Arroyo Peñasco Formation for the lower gray limestone member of the Sandia Formation in the Nacimiento, Sandia, and Sangre de Cristo Mountains of north-central New Mexico and designated its type section in SW$^1/_4$SW$^1/_4$ sec. 5, T. 16 N., R. 1 E., in Los Pinos and Peñasco Canyons, Nacimiento Mountains. He also reported that the unit contained a Meramecian endothyrid fauna.

Fitzsimmons, Armstrong, and Gordon (1956) listed a fauna of megafossils from exposures of the Arroyo Peñasco Formation on the northwest side of the Sierra Nacimiento in the Regina quadrangle and from its type section. Armstrong (1958) described part of the Meramecian endothyrid fauna of the Arroyo Peñasco Formation and demonstrated that, at the type section and in the Sangre de Cristo Mountains, the rocks had the same lithologies and endothyrid species; thus, they were of the same (Meramecian) age. Subsequent micropaleontological work has shown that the Arroyo Peñasco Formation is of late Osage, Meramec, and Chester Age (Armstrong, 1967) . Armstrong (1967) also believed the upper Osage part of the Arroyo Peñasco Formation to be biostratigraphically equivalent to the Kelly Formation of the Ladron, Lemitar, and Magdalena Mountains in central New Mexico.

Baltz and Read (1960) divided the pre-Pennsylvanian sandstone and carbonate rocks of the Sangre de Cristo Mountains into two formations, the Espiritu Santo and the Tererro. The Tererro Formation was divided into three members; in ascending order, they are the Macho, Manuelitas, and Cowles Members. Armstrong (1967, pp. 5-8) considered Baltz and Read's (1960) Espiritu Santo and Tererro Formations of the Sangre de Cristo Mountains to be laterally equivalent parts of his (Armstrong, 1955) Arroyo Peñasco Formation. He recognized the Arroyo Peñasco in the Sandia, Manzano, and Manzanita Mountains, as well as in the Sierra Nacimiento and Sangre de Cristo Mountains. Because of its extent and the formations it includes, the Arroyo Peñasco was raised to group rank in north-central New Mexico (Armstrong and Mamet, 1974) . However, these units within the Arroyo Peñasco cannot be mapped individually at a 1:24,000 scale, and therefore, the Arroyo Peñasco was mapped and described as a formation rather than as a group on the New Mexico Bureau of Mines and Mineral Resources geologic maps of the Sierra Nacimiento.

Armstrong (1967) reported the following sequence of strata and depositional history for the Arroyo Peñasco. The basal unit is transgressive and is composed of siltstone, 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 Osagean Age. The lowest cycle reflects initial deposition of a shallow-marine lime mud followed by stromatolitic intertidal to supratidal carbonate deposits. Cycle 2 is shallow-marine to intertidal echinoderm wackestone to lime mudstone and dolomite containing a sparse fauna of *Endothyra.* Cycle *3* is shallow-marine wackestone to arenaceous oolitic to ooid—echinoderm packstone ending as subtidal lime mudstone to intertidal dolomite. The ooid facies contains a microfauna of Meramecian Age. Late Mississippian and Early Pennsylvanian uplift resulted in extensive erosion and removal of the Arroyo Peñasco Formation.

At Los Pinos and Peñasco Canyons, the type locality for the Arroyo Peñasco, the formation is approximately 130 ft thick and consists of mostly limestone with subordinate sandstone and conglomerate. The basal 2-5 ft consists of white, subangular, coarse-grained, quartzose sandstone to pebble conglomerate. This is followed by 10 ft of intercalated calcareous sandstone and dark-gray limestone and 100 ft of dark- to light-gray, thick to massively bedded limestone with nodular black chert that weathers tan brown and black. The upper 14 ft consists of creamy-white chert, stained red to pink and is the main fossil-bearing zone. The lower contact is a nonconformity with the Precambrian gneiss, and the upper contact is an unconformity with numerous solution cavities filled with hematitic, red shale from the Log Springs Formation. At the type locality the Arroyo Peñasco forms a prominent north-facing dipslope in a complex down-faulted block that developed during the Cenozoic.

The Arroyo Peñasco Formation at the Guadalupe Box Canyon consists of *8* ft of interbedded white or gray, medium-grained sandstone and light-gray calcareous shale overlain by 17 ft of dense, brownish-gray to gray, recrystallized limestone intercalated with calcareous, gray shale. The top of the limestone is brecciated and filled with Log Springs shale.

In the Regina quadrangle the Arroyo Peñasco caps the highest ridges in the east-central portion of the quadrangle and reaches a maximum thickness of approximately 120 ft with the upper part of the section eroded. It rests unconformably on Precambrian rocks and is unconformably overlain by the Madera Formation (Pennsylvanian). The lower *5* ft of the Arroyo Peñasco consists of white, medium- to coarse-grained, locally conglomeratic quartz sandstone and is overlain by 10 ft of poorly exposed, thin-bedded sandstone, shale, and limestone. The limestone beds in this portion reach a maximum thickness of 7 inches and commonly show crenulations. Above these beds are approximately 25 ft of dense, tan to gray, finely crystalline, cherty limestone that occurs in beds 1-2 ft thick. The uppermost portion of this formation consists of approximately 30 ft of dense, gray, finely crystalline limestone with white chert.

For detailed petrographic descriptions and faunal lists concerning the Arroyo Peñasco Formation the reader is referred to the articles by Armstrong (1955), Fitzsimmons and others (1956), Armstrong (1958), Armstrong and Holcomb (1967), Armstrong (1967), and Armstrong and Mamet (1974, 1979).

Log Springs Formation

The Log Springs Formation was named by Armstrong (1955) for exposures in Peñasco Canyon in the southwest Sierra Nacimiento (Gilman quadrangle) where it unconformably overlies the Arroyo Peñasco Formation and is unconformably overlain by limestone of Early Pennsylvanian (Morrow) age. In the type area the Log Springs Formation consists of 8-10 ft of red, hematitic shale overlain by 30-40 ft of dusky-red to orange, arkosic to conglomeratic sandstone. The lower contact is an unconformity, and numerous solution cavities in the Arroyo Peñasco Formation are filled with the basal red shale of the Log Springs Formation. The basal shale is 10 ft thick and consists of deep-red, ferruginous shale that contains numerous oolites of hematite up to 2 inches in diameter. The upper 45 ft consists of arkosic, crossbedded, argillaceous, dusky-red to mottled pale-orange, lenticular sandstone interbedded with red shales and a few conglomeratic beds. The conglomerates are thick bedded and contain rounded pebbles to cobbles of chert and limestone from the Arroyo Peñasco Formation and gneiss, greenstone, and quartzite of Precambrian age. In general, the formation becomes coarser toward the top.

At the Guadalupe Box, only the lower 2-5 ft of the Log Springs Formation is present. It is dark-red shale containing numerous pebble-size hematite nodules. The unit is discontinuous in outcrop, generally forming dark-red slopes that are covered by abundant, loose, hematite nodules.

In the northern Sierra Nacimiento (Regina quadrangle), evidence that the Log Springs Formation was once present is prevalent; hematite nodules are found scattered in float capping the ridge in sec. 1, T. 22 N., R. 1 W. The Osha Canyon and Sandia Formations (Pennsylvanian) are absent in the northern Nacimiento area, and the Arroyo Peñasco Formation is overlain by the Madera Formation (Pennsylvanian).

The Log Springs Formation is interpreted as totally terrestrial (Armstrong, 1967). The basal hematitic shale of the Log Springs Formation is a residual soil, while the upper part of the formation consists of coarse detrital material derived from Mississippian limestone and Precambrian metamorphic rocks (Armstrong, 1967). No recognizable fossils have been found in the formation, but, based on paleontologic evidence from the overlying Morrowan limestone and on the characteristics of the lower shale beds of the Log Springs Formation, Armstrong and Mamet (1979) assigned an age of Late Mississippian (Chester) to the unit.

Pennsylvanian

The largest outcrops of Pennsylvanian rocks are along the north end and east flank of the Sierra Nacimiento (map, in back pocket). Less extensive outcrops occur along the southern and southwest margins of the range. Pennsylvanian strata exposed at Guadalupe Box range in age from Morrow to Virgil (DuChene, 1974). Progressively younger Pennsylvanian rocks onlap Precambrian rocks to the northwest and southwest, thinning to zero edge along the southern and northern parts of the crest of the Sierra Nacimiento (Fig. *5).* Three Pennsylvanian formations have been recognized in this region, and they are, in ascending

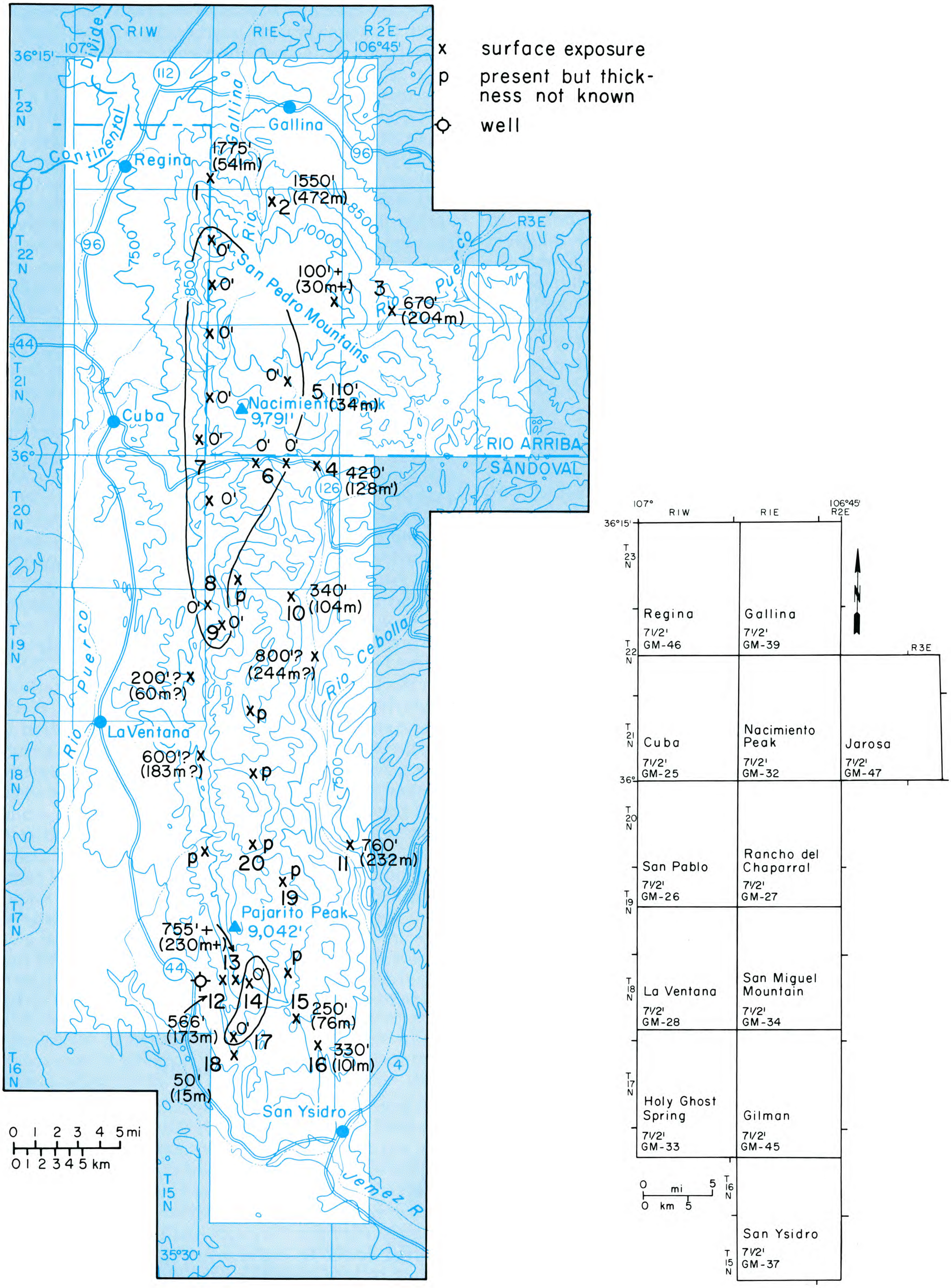


FIGURE 5—Locations of measured sections and critical outcrops of the Madera Formation and other Pennsylvanian formations in the Sierra Nacimiento with thicknesses in feet and meters for the Madera. Some numbered localities are keyed to text and Fig. 7.

order, the Osha Canyon, Sandia, and Madera Formations. Of these, the Madera has, by far, the greatest extent.

Osha Canyon Formation

This unit was named by DuChene and others (1977) for exposures of Morrowan limestone and shale near Guadalupe Box in the Gilman quadrangle (Fig. 5, locality 11). This unit is present also at Los Pinos and Peñasco Canyons (Fig. 5, locality 13) in the southern Nacimiento area, as well as southwest of Guadalupe Box.

Northrop and Wood (1945) first recognized a Morrowan fauna near the base of the Pennsylvanian section near Guadalupe Box. Wood and Northrop (1946) included the rocks containing this fauna in the lowest part of their upper clastic member of the Sandia Formation. Armstrong (1955) recognized that Morrowan rocks lie unconformably on the Log Springs Formation in Los Pinos and Peñasco Canyons and at Guadalupe Box. Additionally, the upper surface of the Morrowan strata is an unconformity that is overlain by the arkosic part of the Madera Formation at Los Pinos and Peñasco Canyons and by the Sandia Formation at Guadalupe Box (Armstrong, 1955) . The Osha Canyon Formation also crops out at several places southwest of Guadalupe Box, and, at most of these places, the unit rests nonconformably on Precambrian crystalline rocks.

The following is taken from the work of DuChene and others (1977). The Osha Canyon Formation at the type section is 71 ft thick (Fig. 6) and is composed of two distinct parts. The lower 31 ft consists of highly fossiliferous, light-gray to white, slightly arenaceous, bioclastic, ledge-forming limestone in 1-7-inch-thick beds, intercalated with fossiliferous, calcareous, light-gray shale. Fragments and whole specimens of corals and brachiopods are common, as are pieces of echinoids, crinoids, and bryozoans. The upper 40 ft of the formation consists of light-gray to light-tan shale with abundant, small nodules of gray limestone near the top. This part of the formation is less fossiliferous than the lower part and generally forms slopes.

The Osha Canyon Formation is exposed also as thin bands on the southeast slope of Peggy Mesa and along the slopes of Osha Canyon, approximately 1.5 mi southwest of the type section (Fig. 5, localities 5, 19, and 20) . In both areas the Osha Canyon is represented by only part of the basal bioclastic limestone beds containing *Schizophoria oklahomae.* It lies unconformably on Precambrian granite and gneiss and is overlain unconformably by the Sandia Formation.

A significant Osha Canyon outcrop (Fig. 5, locality 13) is present in Pinos and Peñasco Canyons (Martinez, 1974), the type locality for the Arroyo Peñasco and Log Springs Formations ($5^1/_2$ sec. 5, T. 16 N., R. 1 E.). Here, the Osha Canyon Formation consists of 30-40 ft of massive, gray to light-brown, highly bio-clastic limestone interbedded with thin shale. The lower beds have large quantities of subangular, coarse sand-to gravel-size quartz clasts. The formation stands out as low cliffs above the Log Springs Formation, which it overlies with angular unconformity, and fills chan nels as much as 3 ft deep cut into the Log Springs (Martinez, 1974). The upper Osha Canyon contact forms an angular unconformity with the arkosic member of the Madera Formation, because the Sandia Formation is absent here.

Fossils in the Osha Canyon Formation and their paleoecological significance were described and discussed by DuChene and others (1977).

Sandia Formation

The "Sandia Series" was proposed by Herrick (1900) for clastic sediments resting above "basal quartzite" in the southern Sandia Mountains. Gordon (1907) designated the Sandia Formation as the lower unit of the Magdalena Group of central New Mexico and included all of the sedimentary rocks between the Kelly Limestone and the Madera Limestone that occur in the Magdalena Mountains. In the Nacimiento Mountains Wood and Northrop (1946) subdivided the Sandia Formation into a lower limestone member and an upper clastic member.

The Sandia Formation as described herein is restricted to the upper clastic member of Wood and Northrop (1946) minus the Morrowan Osha Canyon Formation, the lowest part of Wood and Northrop's upper clastic member. It includes the sequence of primarily clastic sedimentary rocks between the underlying Osha Canyon Formation and the lowest laterally continuous limestone of the overlying Madera Formation.

The Sandia Formation is up to 225 ft thick near Guadalupe Box (Fig. 5, locality 11) but thins by sedimentary onlap to zero edge approximately 2.5 mi to the north and west. The Sandia Formation is present for approximately 5 mi to the south, where it thins to approximately 50 ft and rests directly on Precambrian rocks. The formation is absent at Peñasco Canyon (Fig. 5, locality 13) and in the central and northern parts of the Sierra Nacimiento, where younger Pennsylvanian and Permian strata rest on Precambrian rocks.

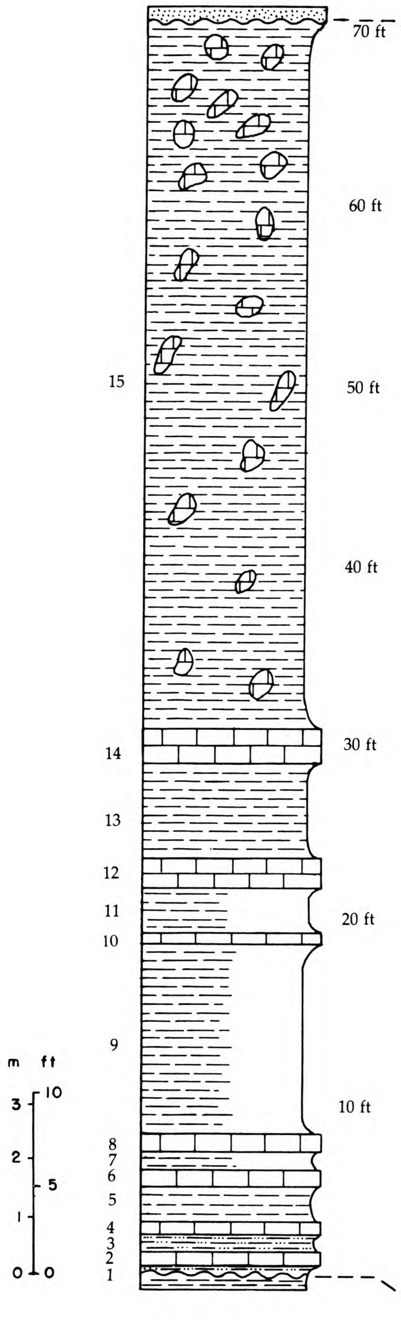
At Guadalupe Box the Sandia Formation consists of massive, coarse-grained, beige to light-brown, ledge-forming quartz sandstone overlain by interbedded, slope-forming, green, gray, and yellow shales; yellow, fine-grained silty sandstone; and gray, thin-bedded, argillaceous, highly fossiliferous limestone. Based on paleontologic evidence, the Sandia Formation is considered to be of Lampasas (Atoka) Age (Wood and Northrop, 1946).

Madera Formation

The Madera Formation was named by Keyes (1903) for exposures near La Madera in the Sandia Mountains. It was included in the Magdalena Group by Gordon (1907). Wood and Northrop (1946) subdivided the Madera into a lower gray limestone member and an upper arkosic limestone member in the Sierra Nacimiento.

The Madera is exposed on the flanks of the range except on the west-central margin where Permian strata rest on Precambrian rocks. In the Nacimiento area the most complete section of the formation is found at

Guadalupe Box, where 760 ft of strata are exposed. At this locality the gray limestone member is in gradational contact with the underlying Sandia Formation (Wood and Northrop, 1946) . This member is characterized by dense, fossiliferous, dark-gray, locally cherty limestone in beds ranging in thickness from a few inches to several feet. Intercalated with the limestone are thin beds of arkosic sandstone and gray, fossiliferous, calcareous shale. Wood and Northrop's (1946) arkosic member gradationally overlies the gray limestone member and is gradationally overlain by the Abo Formation. The arkosic member consists of arkosic, gray limestone and pink arkose intercalated with fossiliferous, calcareous shale. Feldspar fragments in the limestone and the arkose are pink and are up to 1.0 inch in diameter. The arkose be-



Unit	Lithology	Thickness (equivalents) ft	*(m)*
	Sandia Formation (Pennsylvanian). Sandstone, buff, poorly sorted, feldspathic; weathered to angular blocks that slump onto and partly cover underlying shale.		
	Unconformity.		
	Osha Canyon Formation		
15	Covered interval that consists of light-gray to light-tan shale containing abundant dark-gray limestone nodules ranging up to 3 inches, commonly 1–2 inches. Nodules are fossiliferous, but fossils are rare. Nodules weather out of shale and partly cover slope, especially near top of unit.	40	*(12.2)*
14	Limestone, greenish-gray, gray-weathering, coarsely crystalline, fossiliferous; fossils replaced by pink or gray calcite. Beds are 3–6 inches thick; unit forms ledge.	2	*(0.6)*
13	Covered slope that consists of pale greenish-tan and gray, calcareous, fissile shale; fossils rare or absent.	5.5	*(1.7)*
12	Limestone, greenish-gray, gray-weathering, coarsely crystalline, fossiliferous; fossil fragments commonly replaced by pink calcite. Beds are 1–6 inches thick; unit forms ledge.	1.5	*(0.5)*
11	Covered slope; probably shale.	2.5	*(0.8)*
10	Limestone; similar to unit 4. Beds are 3–6 inches thick; unit forms ledge.	0.7	*(0.2)*
9	Covered slope; probably shale.	10.8	*(3.3)*
8	Limestone, grayish-tan, gray-weathering, crystalline, fossiliferous; contains brachiopods and fragments of brachiopods, bryozoans, crinoids, and unidentified fossil material. Beds are 3–5 inches thick; unit forms ledge.	1.0	*(0.3)*
7	Covered slope; probably shale.	1.0	*(0.3)*
6	Limestone; gray with pink calcite fossil fragments; weathers brownish gray; very fossiliferous; nearly a brachiopod coquina; *Composita* and *Hustedia* common; also contains fragments of crinoids and a few rounded, coarse sand-size quartz grains. Beds are 4–7 inches thick; unit forms ledge.	1.0	*(0.3)*
5	Covered slope that consists of very light gray, fossiliferous shale.	2.0	*(0.6)*
4	Limestone, grayish-tan, brownish-gray-weathering, fossiliferous. Fossils consist of crinoid fragments and unidentified material. Fossils are etched in relief on weathered surfaces. Beds are 3–6 inches thick; unit forms ledge.	0.7	*(0.2)*
3	Muddy carbonate sand, gray, very poorly sorted, unconsolidated to slightly consolidated; consists of silt to coarse sand-size fossil fragments including brachiopods, bryozoans, echinoids, and unidentified material; also includes pebble-size fragments of gray, fossiliferous limestone. Unit forms slopes.	1.0	*(0.3)*
2	Limestone, grayish-tan, brown-weathering, crystalline, fossiliferous. Fossils include brachiopods, bryozoans, and crinoid columnals. Fossils are etched in relief on weathered surfaces. Unit contains a few rounded, medium sand-size quartz grains. Beds are 3–6 inches thick; unit forms ledge.	0.7	*(0.2)*
1	Muddy carbonate sand, whitish-gray, very poorly sorted, poorly consolidated. Grains range from clay to coarse sand size and consist of fragments of brachiopods, bryozoans, echinoids, crinoids, foraminifers, and unidentified fossil material.	0.5	*(0.1)*
	Total thickness of *Osha Canyon Formation.*	70.9	*(21.6)*
	Unconformity.		
	Log Springs Formation (Mississippian). Red, hematitic shale.		

FIGURE 6—Type section of Osha Canyon Formation, Guadalupe Box, Gilman $7^1/_2$-min quadrangle. Section was measured along top of ridge on east side of Guadalupe Box, lat 35°44'00"N., long 106°45'45"W., just east of State road 485, 1.2 mi north of the village of Gilman, Sandoval County, New Mexico (from DuChene and others, 1977).

comes increasingly abundant upward in the section until it predominates near the top of the unit. The uppermost part of the Madera is intercalated with reddish-brown sandstone, mudstone, and shale lithologies similar to the overlying Abo Formation. Carbonate becomes less abundant near the top of the formation and occurs as nodular limestone beds from 1 to 3 inches thick. Based on paleontologic evidence, Wood and Northrop (1946) determined that the gray limestone member ranges in age from Lampasas (Atoka) to early Desmoines and that the arkosic member ranges in age from Desmoines to Virgil.

The Madera Formation rests on the Sandia Formation at Guadalupe Box but is disconformable on the Osha Canyon Formation at Los Pinos and Peñasco Canyons; elsewhere in the southern part of the Sierra Nacimiento, the Madera Formation is nonconformable on Precambrian crystalline rocks. Near Joaquin Mesa, the gray limestone member rests nonconformably on Precambrian rocks. Farther to the north and west, this member is missing, and the arkosic member rests on the Precambrian. In the north-central and southern parts of the range, the Madera is absent, and Permian strata rest on Precambrian rocks (Fig. 7) .

The upper contact of the Madera with the Abo Formation was placed at the top of the stratigraphically highest, thick bed of fossiliferous limestone. In the northern Sierra Nacimiento the Madera and the Abo laterally intertongue, insofar as the uppermost limestone beds of the Madera pinch out to the southeast. Thus, the Madera—Abo contact is stratigraphically higher in the Regina quadrangle than in the southeast Gallina quadrangle. This intertonguing is seen near the common boundary of these two quadrangles.

The Madera Formation is abundantly fossiliferous at many localities, commonly containing a fauna of brachiopods, fusulinids, bryozoans, and crinoids. A list of Pennsylvanian fossils of the Nacimiento—Jerez area was published by Northrop (1974), who summarized most of the earlier work.

Paleotectonic interpretation

The present Sierra Nacimiento is superimposed on an ancient highland that began to develop in latest Mississippian or Early Pennsylvanian time. Wood and Northrop (1946, fig. 6) showed this highland as a north-trending positive feature, which Read and Wood (1947) referred to as the Peñasco axis. This feature influenced Pennsylvanian sedimentation in north-central New Mexico by providing a source for clastic material; gradually it was reduced to an island in an advancing Pennsylvanian sea.

Uplift of the Peñasco axis probably began after the deposition of the Arroyo Peñasco Formation. The unconformities on the Arroyo Peñasco, Log Springs, and Osha Canyon Formations suggest pulsating uplift in Late Mississippian and Early Pennsylvanian time. These episodes of uplift established the Peñasco axis as a strong positive feature that was almost transgressed by the Pennsylvanian sea and nearly buried by sediments. This transgression is recorded in the sequence of onlapping marine clastic and carbonate rocks that progressively cover the Peñasco axis. The large amount of arkose in the arkosic member of the Madera Formation suggests that an additional period of uplift may have rejuvenated the Peñasco axis, allowing a flood of detrital material to be washed into the sea during Desmoines, Missouri, and Virgil time. Martinez (1974) noted that the Madera on the southwest side of the Nacimiento Mountains is more arkosic and conglomeratic than it is to the east, and he attributed this difference to an asymmetrical uplift, suggesting that the Peñasco axis had a steep west side and a gently sloping east side. The clasts in the conglomerates in the Madera on the west side probably were not transported far, suggesting that the west side was a fault scarp.

The end of the Pennsylvanian marine sedimentation in north-central New Mexico is marked by interfingered marine and continental sedimentary rocks. The sea alternately was pushed back by continental detrital material and then advanced over the terrestrial deposits until the area remained above sea level and subaerial conditions prevailed. This episode of regression is recorded in the gradational contact between the Madera and Abo Formations.

Permian

Four formations of Permian age are present in the Sierra Nacimiento. In ascending order, they are the Abo, Yeso, Glorieta, and Bernal Formations. The Abo appears to be gradational with Pennsylvanian strata where they are present and elsewhere lies nonconformably on Precambrian crystalline rocks. Permian strata are unconformably overlain by Upper Triassic rocks. The unconformity cuts stratigraphically lower to the north; only the Abo and Yeso Formations are present in the northern part of the range. Baars (1962, 1974) suggested that the Permian rocks range from Wolfcampian to Guadalupian based on regional correlations.

Abo Formation

The Abo Formation was named by Lee (1909) for red beds exposed in Abo Canyon in the southern Manzano Mountains, but he did not give a precise type section. Later, Needham and Bates (1943) described a type section near the villages of Abo and Scholle in Valencia and Torrance Counties. Wood and Northrop (1946) mapped the Permian red beds of the Sierra Nacimiento as the Abo and Yeso Formations, south of 36° north latitude, and as the Cutler Formation, north of that line. They believed that the Yeso Formation graded laterally into rocks lithologically similar to the Abo to the north, and, thus, the Cutler was mapped as the equivalent of the Abo and Yeso. My mapping, however, shows that the Abo and Yeso Formations can be distinguished at the northernmost Permian outcrops in the Sierra Nacimiento, and, therefore, these units were used rather than the Cutler.

To the west the Abo is equivalent to the Supai Formation and to the east it grades into the upper part of the Sangre de Cristo Formation (Baars, 1962). Based

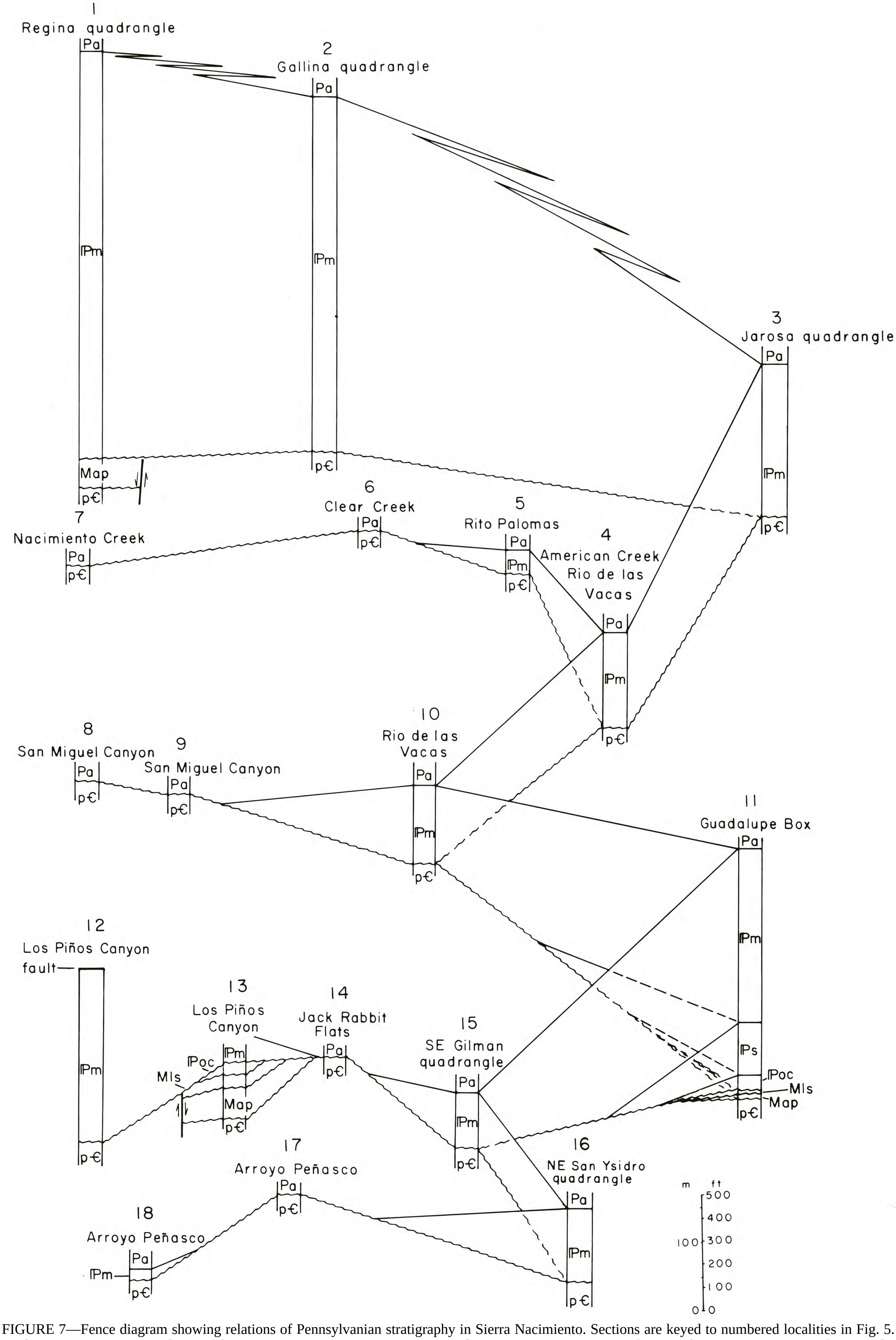


FIGURE 7—Fence diagram showing relations of Pennsylvanian stratigraphy in Sierra Nacimiento. Sections are keyed to numbered localities in Fig. 5. Rock units are: **p€ =** Precambrian rocks, **Map =** Arroyo Peñasco Formation, **Mls** = Log Springs Formation, ℙ**oc** = Osha Canyon Formation, ℙ**s** = Sandia Formation, ℙ**s =** Madera Formation, and **Pa =** Abo Formation.

on vertebrate paleontologic evidence, Romer (1960) reported the age of the Abo and Cutler Formations as Wolfcampian.

The Abo Formation consists of brownish-red mudstone intercalated with brownish-red to maroon shale and lenticular beds of dark-red, poorly sorted, coarse-grained arkosic sandstone. Thin beds of medium-gray limestone interbedded with shale and sandstone occur near the base of the formation. The limestone beds become thinner and increasingly nodular upward in the section. In the northern part of the Sierra Nacimiento are numerous conglomerate beds containing pebbles and cobbles of Precambrian metaquartzite. The Abo (Fig. 8) ranges in thickness from approximately 100(?) ft (Woodward, McLelland, and others, 1972) to approximately 2,900(?) ft (Gibson, 1975).

The nature of the basal contact of the Abo with the Madera has been the subject of controversy. Renick (1931) and Hutson (1958) reported that the Permian red beds in the vicinity of San Pedro Mountain rest unconformably on beds of the Magdalena Group. Thompson (1942) regarded the contact between Abo and Pennsylvanian (Virgilian) beds as unconformable in northern New Mexico. Wood and Northrop (1946), Baars (1962), Schumacher (1972), DuChene (1973), and Merrick (1980) reported that the contact between the Abo and the Madera is gradational in the Sierra Nacimiento. Field evidence throughout the area of this report clearly shows that the contact between the Abo and the Madera is gradational with much intertonguing of beds. Where the Madera is absent, the Abo rests nonconformably on Precambrian crystalline rocks. The upper contact of the Abo with the Yeso Formation is conformable.

Baars (1962) suggested that the source area for the Abo Formation was the San Luis and Brazos highlands to the north, but, during early Abo time, sediments were derived from the Peñasco high in the central part of the present Sierra Nacimiento. The evidence is the presence of Precambrian quartz monzonite fragments, identical to the underlying basement rock, in the Abo in the Rancho del Chaparral and San Pablo quadrangles.

Burial of the Peñasco high must have occurred during middle and late Abo time, because the average grain size decreases upward, indicating that the source area for the middle and upper Abo was outside the mapped area. According to Read (1950) the source area was to the north, and the clastics were deposited under predominantly floodplain conditions. This is supported by the variability and lenticular nature of many individual beds and by cross-stratification. The proximity to Permian seas of southern New Mexico and the widespread nature of the mudstone suggest that the Abo of the Sierra Nacimiento area was deposited at or near sea level on a broad floodplain that may have been periodically invaded by shallow marine waters as judged from intertonguing with marine limestones at the top of the Madera Formation.

Yeso Formation

The Yeso Formation was named by Lee (1909) for exposures at Mesa del Yeso in Socorro County, where it rests conformably on the Abo Formation and is conformably overlain by the Glorieta Sandstone (Needham and Bates, 1943). In southeast New Mexico the Yeso Formation contains numerous units of limestone and evaporites, which thin northwestward as the clastic components increase. Needham and Bates (1943) assigned the Yeso to the lower two thirds of the Leonard Series.

Wood and Northrop (1946) divided the Yeso Formation into the lower Meseta Blanca Sandstone Member and the upper San Ysidro Member in the Sierra Nacimiento. They stated that the San Ysidro Member intertongues with the Meseta Blanca Sandstone in the northern Sierra Nacimiento. The formation was mapped as one unit although the Meseta Blanca and San Ysidro Members were recognized at numerous localities in the southern part of the Sierra Nacimiento.

The Meseta Blanca Member consists of reddish-orange, well-sorted, moderately well cemented, fine- to medium-grained quartzose sandstone. The beds range in thickness from 2 to 4 ft near the base to as much as 25 ft near the top of the member. The upper beds are broadly cross-stratified and form prominent, rounded cliffs and steep, round slopes.

The San Ysidro Member consists of reddish-brown and dark-red, fine-grained sandstone and interbedded siltstone. Several thin beds of dense, medium-gray, nonfossiliferous limestone occur near the top of the unit. The limestone beds are up to 5 ft thick although most are only a few inches thick. The sandstone beds are up to 3 ft thick and tend to be slightly undulose and lenticular, especially in the upper part. The San Ysidro Member generally forms steep slopes above the massive cliffs of the Meseta Blanca Member.

The Yeso Formation ranges in thickness from a maximum of 525 ft at Guadalupe Box in the Gilman quadrangle (DuChene, 1973) to a minimum of 10(?) ft (Gibson, 1975) in the eastern part of the Gallina quadrangle (Fig. 9). A general northward thinning of the Yeso is partly depositional and partly post-Yeso and pre-Chinle erosion.

In the southern Sierra Nacimiento the Yeso Formation is conformably overlain by the Glorieta Sandstone, but, in the northern part of the range, the unconformity at the base of the Triassic strata has cut through the Glorieta, and the Chinle Formation (Upper Triassic) rests with a slight angular unconformity on the Yeso. The variations in thickness of the Yeso (Fig. 9) suggest that the Peñasco axis locally had intermittent tendencies to be structurally high after deposition of the Yeso and prior to deposition of the overlying Chinle Formation.

The Meseta Blanca Sandstone Member was interpreted as migrating beach and bar deposits by Read (1950) and as marine sands by Baars (1962). Baars (1962) also suggested that the sediments of the San Ysidro Member are probably reworked material derived from the Cutler Formation and redeposited in a marine environment. The Meseta Blanca has been equated with the De Chelly Sandstone of northeast Arizona by Baars (1962). However, Irwin (1969) considered the Meseta Blanca to be equivalent to the upper Supai Formation in the Holbrook, Arizona, area.

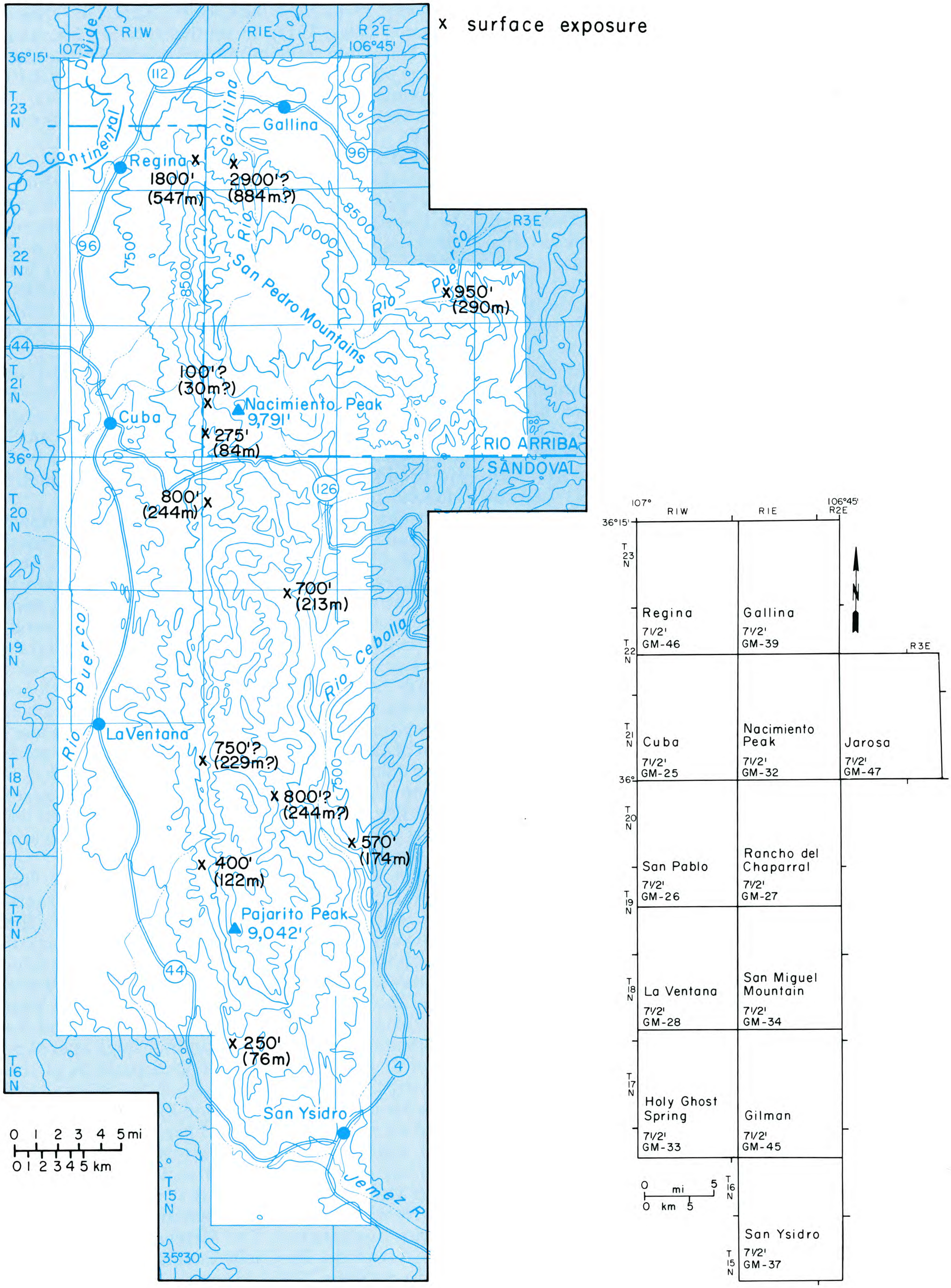


FIGURE 8—Thickness (in feet and meters) of Abo Formation at various localities in the Sierra Nacimiento area.

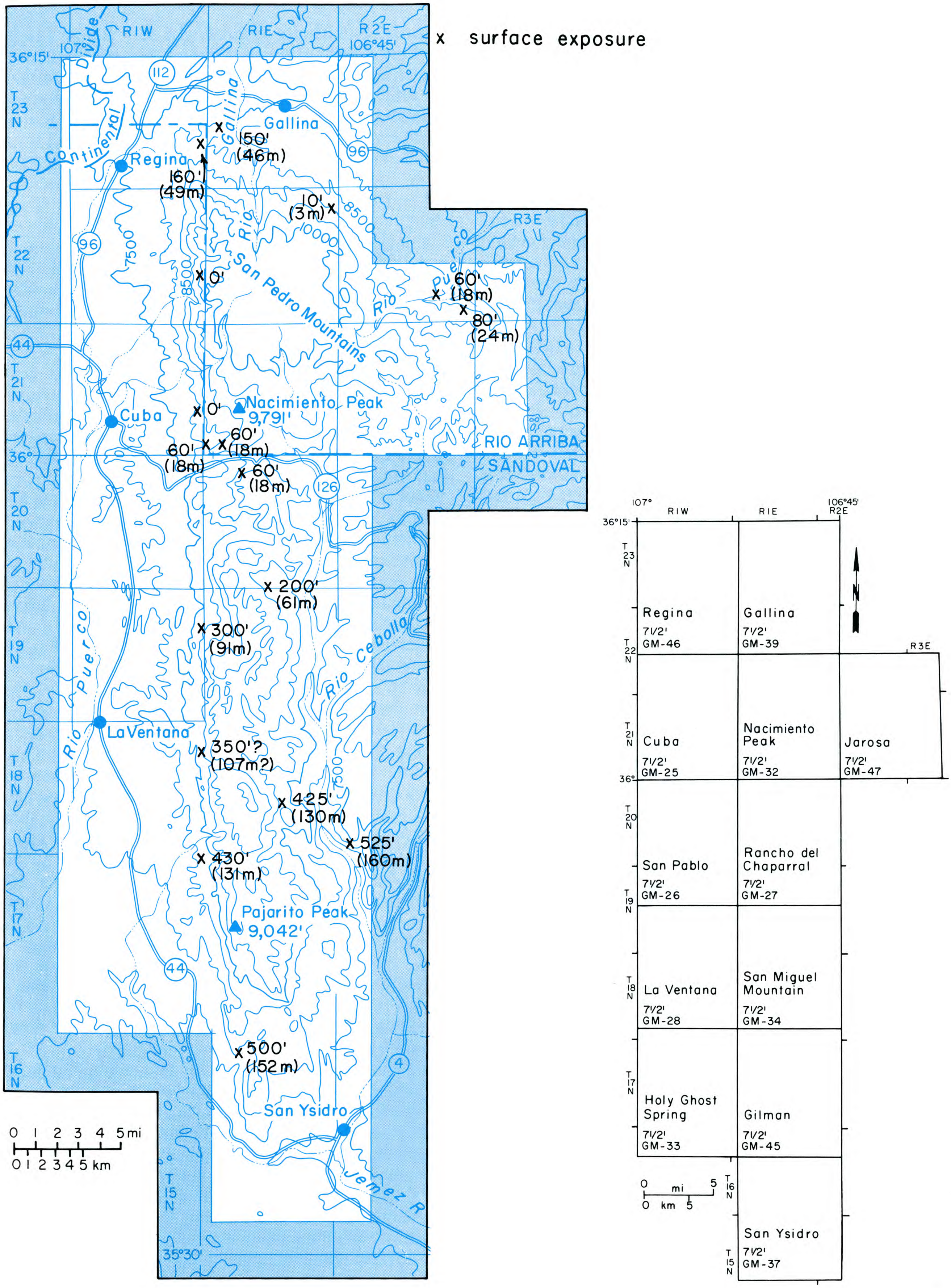


FIGURE 9—Thickness (in feet and meters) of Yeso Formation at various localities in the Sierra Nacimiento area.

Glorieta Sandstone

The "Glorieta Sandstones" were originally named by Keyes (1915) for the main body of the "Dakotan Series" (Cretaceous) in the southern Rocky Mountains. However, Hager and Robitaille (1919, in Wilmarth, 1938) included the Glorieta in the Permian System by associating it with the Yeso Formation. Wood and Northrop (1946) considered the Glorieta to be the basal member of the San Andres Formation in the Sierra Nacimiento. Needham and Bates (1943) recommended that the Glorieta be assigned to formation status because of its wide distribution, persistence of lithology, bold topographic expression, and stratigraphic importance. They described the type section for exposures at Glorieta Mesa near the village of Rowe, San Miguel County.

The Glorieta Sandstone is present only in the southern part of the Sierra Nacimiento, because it is cut out by an unconformity at the base of the Triassic strata near the north end of La Ventana quadrangle.

The Glorieta Sandstone is white to pale yellowish-gray, fine- to medium-grained, thick-bedded, broadly cross-stratified quartz arenite. Locally, along the western flank of the range in the Holy Ghost Spring quadrangle, the unit contains thick lenses of gypsum (Martinez, 1974) .

In outcrop the Glorieta forms prominent, white cliffs that are commonly stained reddish-brown by material leached from the overlying Bernal Formation. The topographic expression and lithologic character of the Glorieta allow it to be readily distinguished from the adjacent Yeso and Bernal Formations.

The Glorieta Sandstone is conformable on the Yeso and is conformably overlain by the Bernal Formation except where the unconformity at the base of the Triassic has cut into the Glorieta. Where the Bernal overlies it, the Glorieta ranges in thickness from approximately 100 ft in the San Ysidro and Gilman quadrangles to 80 ft in the San Miguel Mountain quadrangle and 50 ft in La Ventana quadrangle.

The Glorieta is considered to be correlative with the San Angelo Formation of Texas by R. E. King (1945) and with the Coconino Sandstone of Arizona by Baars (1962), who assigned an upper Leonard Age to the Glorieta based on its stratigraphic position and suggested that it was deposited in a littoral to upperneritic environment with local enlian conditions.

Bernal Formation

The Bernal Formation was named by Bachman (1953) for outcrops near the village of Bernal in San Miguel County. Wood and Northrop (1946) recognized it as a distinct lithologic unit in the Nacimiento area but mapped it as the upper member of the San Andres Formation.

In the Nacimiento area the Bernal consists of red, saddle- and slope-forming sandstone and siltstone. The formation is composed of fine- to medium-grained, thin-bedded, reddish-brown to purplish-brown, poorly sorted sandstone with subordinate amounts of gray-tan, medium-grained sandstone. Quartz is the main constituent, and grains are subrounded to subangular.

In the San Ysidro quadrangle near Jemez Pueblo, the Bernal Formation contains a 2-ft-thick fossiliferous limestone bed approximately 20 ft above the base of the unit (Ruetschilling, 1973, p. 25). This bed probably represents the northern limit of carbonates that are correlative with the San Andres Formation to the south. The Bernal was deposited in a lagoonal and intertidal environment and is considered to be the shoreward, red-bed facies of the San Andres Formation (Baars, 1962) .

The Bernal Formation is conformable with the underlying Yeso Formation and is unconformably overlain by the Chinle Formation (Triassic). Baars (1962) believes that the unconformity involves the last half of the Permian and earliest Triassic time and that the unconformity is slightly angular; northward truncation of the Bernal by erosion in the central Sierra Nacimiento demonstrates this. The northernmost exposures of the Bernal in the Sierra Nacimiento area are in the vicinity of the San Miguel mine in La Ventana quadrangle and at Joaquin Mesa in the San Miguel Mountain quadrangle.

The thickness of the Bernal ranges from 30 ft at Joaquin Mesa (San Miguel Mountain quadrangle) to 65 ft in La Ventana quadrangle and 80 ft in the Holy Ghost Spring, San Ysidro, and Gilman quadrangles. The northward pinchout appears to be due to depositional thinning, as well as post-Bernal erosion.

Baltz and Bachman (1956) consider the Bernal to be correlative with the Whitehorse Group of Guadalupe Age in southeast New Mexico.

Triassic

Chinle Formation

The Chinle Formation was named by Gregory (1917) for exposures in Chinle Valley, Arizona. Lucas (1901, in Gregory, 1917) dated the Chinle as Late Triassic based on paleontological evidence. The Chinle Formation is widely exposed along the north, west, and south margins of the Sierra Nacimiento. Wood and Northrop (1946) divided the Chinle into four map units in the northern Sierra Nacimiento. In ascending order, they are Agua Zarca Sandstone Member, the Salitral Shale Tongue, the Poleo Sandstone Lentil, and the upper shale member. In the southern part of the Sierra Nacimiento area, Wood and Northrop (1946) divided the Chinle into the Agua Zarca Sandstone Member and the overlying shale member. Stewart and others (1972) modified the terminology used by Wood and Northrop for the Chinle in the southern Nacimiento area. They did not consider the Agua Zarca Sandstone to be present in the San Ysidro quadrangle; for strata mapped by Wood and Northrop as Agua Zarca, they recognized a new informal unit the sandstone member of the Chinle. They also correlated the Chinle shale member of Wood and Northrop with the Petrified Forest Member of the Chinle. In my mapping I have used the terminology of Wood and Northrop (1946) except for use of the Petrified Forest Member in the southern part of the range (Fig. 10) .

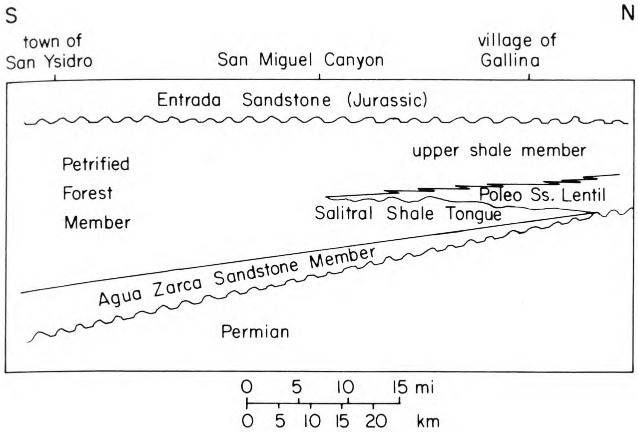


FIGURE 10—Diagrammatic section showing stratigraphic relations of units in Chinle Formation (Triassic) in the Sierra Nacimiento area.

Agua Zarca Sandstone Member–Wood and Northrop (1946) named the Agua Zarca Sandstone Member of the Chinle Formation for exposures along Agua Zarca Creek in Rio Arriba County.

The Agua Zarca consists of white to light-buff, very thick bedded, medium- to coarse-grained, friable, quartzose sandstone and is locally conglomeratic, micaceous, and arkosic. Interbedded gray-clay zones up to 1.0 ft thick and opalized zones occur locally. Lenticular channels of crossbedded conglomerate and conglomeratic sandstone are common in the lower part of the Agua Zarca. These channels are characterized by light- to dark-gray metaquartzite cobbles up to 6 inches in diameter, fossil wood, and clay galls. Some of the channel deposits are mineralized, and a few have been mined for copper. Grain size decreases, and bedding becomes thinner upward, with fine- to medium-grained sandstone in thin beds. Reddish colors also become more common toward the top of the member, particularly in the southern part of the range. Interbedded shale becomes more abundant near the top of the Agua Zarca, forming a transitional contact with the overlying Petrified Forest Member in the southern part of the range and the overlying Salitral Shale Tongue farther north.

Stewart and others (1972, pp. 206-207) considered the basal sandstone and conglomerate of the Chinle Formation in the San Ysidro quadrangle to be an informal sandstone member and not the Agua Zarca Sandstone Member on the basis of minor differences in lithologies and possible differences in source area based on measurements of crossbedding directions. The work of Ruetschilling (1973), however, indicates that the crossbedding in the lower part of the Agua Zarca has a predominantly southern dip, whereas crossbedding in the upper part of the unit is dipping almost exclusively in a northerly direction, giving a bimodal distribution different from directions reported by Stewart and others (1972, pp. 23-24). Also, the only section of their sandstone member that they refer to specifically in their text (Stewart and others, 1972, p. 22, fig. 8, lic. A and NM-13, San Ysidro, pp. 206-207) is crossed by at least two faults ($S^1/_2$ sec. 36, T. 16 N., R. 1 E.), which they did not mention in their stratigraphic section. These faults are downthrown to the east and give the upper part of the unit, which has a northern crossbed dip direction and is not conglomeratic, an erroneously increased thickness.

The Agua Zarca lies unconformably on Permian strata and has a gradational contact with the overlying Salitral Shale Tongue and Petrified Forest Member in the Nacimiento area. Thickness of the Agua Zarca ranges from zero in the Gallina and Jarosa quadrangles to a maximum of 210 ft in La Ventana quadrangle (Fig. 11). In the Regina, Gallina, and Jarosa quadrangles, where the Agua Zarca is too thin to be shown separately, the Agua Zarca and Salitral were mapped as one unit.

Kurtz (1978) and Kurtz and Anderson (1980) interpreted the Agua Zarca in the northern Nacimiento area to be a fluvial unit derived from a northern source area, probably from the Brazos uplift in northern New Mexico. Stewart and others (1972) suggested that the Agua Zarca in the southern part of the Sierra Nacimiento (their informal sandstone member) was derived from a source area to the south.

Salitral Shale Tongue—Wood and Northrop (1946) named the Salitral Shale Tongue of the Chinle Formation for strata at Salitral Creek, Rio Arriba County. The valley-forming Salitral consists of maroon and light-gray shale that contains abundant calcareous concretions up to 7 inches in diameter. Subordinate, but ubiquitous, green shale is present, and very coarse grained, green to light-gray, limy sandstone occurs locally within this member.

The contact with the underlying Agua Zarca is conformable, and the contact with the overlying Poleo Sandstone Lentil is a disconformity. The Salitral was mapped as an individual unit only as far south as San Miguel Canyon in the San Pablo quadrangle because, to the south, the overlying Poleo Sandstone is absent, and, due to poor exposures, the contact between the Salitral and upper shale member could not be located precisely. Therefore, the Salitral and upper shale were mapped as the Petrified Forest Member or as the upper member of the Chinle Formation south of San Miguel Canyon.

Thickness of the Salitral ranges from a maximum of 335 ft in the San Pablo quadrangle to zero in the central part of the Gallina quadrangle. Thus, the Salitral thins northward with 100 ft present in the Regina quadrangle and up to 180 ft present in the Jarosa quadrangle.

Kurtz and Anderson (1980) interpret the Salitral to be a lacustrine deposit formed by transgression of a lake over the Agua Zarca. They think the Agua Zarca and Salitral compose a fluvial—lacustrine sedimentary cycle.

Poleo Sandstone Lentil–According to Renick (1931), von Huene (1911) was the first to use the name Poleo Sandstone. Wood and Northrop (1946) redefined the Poleo as a lentil. This lentil is present in the northern part of the Sierra Nacimiento but pinches out southward in the vicinity of San Miguel Canyon. The ridge-forming Poleo consists of greenish, very fine to coarsegrained, thick to very thick bedded, micaceous sand-

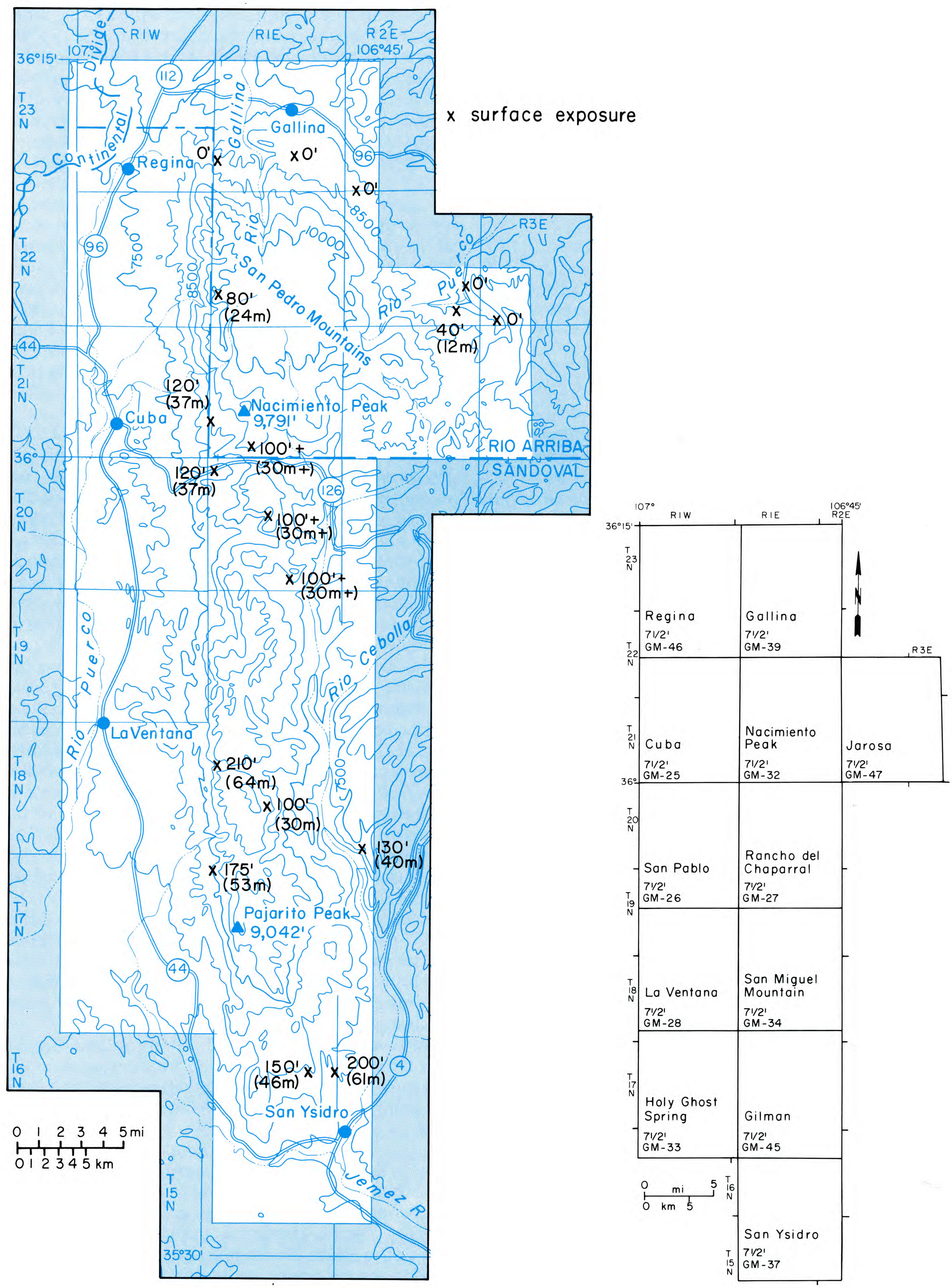


FIGURE 11—Thickness (in feet and meters) of Agua Zarca Sandstone Member of Chinle Formation at various localities in the Sierra Nacimiento area.

stone interstratified with lenticular, freshwater, channel deposits of limestone-pebble conglomerate. The limestone clasts average 0.5 inch in diameter. The gray to light-gray, locally very dense limestone clasts can be found at all horizons but are predominant at the base. Subordinate green and reddish-maroon shale and maroon, micaceous sandstone are present.

In the Gallina quadrangle (Gibson, 1975) the basal 5-40 ft of the Poleo is composed of crossbedded, fossiliferous (plant), chert-pebble conglomerate lenses. The clasts are well-rounded and well-sorted dark chert, quartz, and quartzite, plus minor amounts of sedimentary and granitic constituents. Maximum size of the chert, quartz, and quartzite clasts is 2.5 inches; the average is approximately 1 inch. Clasts of sedimentary rock range up to 10 inches in diameter. The matrix of the basal conglomerate is generally poorly indurated, dark-brown, silt-sized particles with subordinate sand. Conglomerate lenses occur rarely at the top of the unit but, where present, contain rounded clasts of coarsely crystalline limestone. Directional indicators such as crossbeds, elongate clay galls, and fossil plant remains are common in the conglomerate lenses. Above the basal conglomerate zone, the Poleo consists of dark yellowish-brown to light olive-gray, medium- to fine-grained, micaceous quartzose sandstone. The sandstone is thick to thin bedded and crossbedded.

The Poleo Sandstone Lentil ranges in thickness from a wedge edge at San Miguel Canyon in the San Pablo quadrangle to 135 ft near Señorito Canyon in the northern part of San Pablo quadrangle. In the Gallina quadrangle it is 90-130 ft thick, and in the Jarosa quadrangle it is 80-120 ft thick.

The Poleo lies disconformably on the underlying Salitral Shale and, locally, in the Gallina quadrangle the Poleo rests unconformably on the Yeso Formation (Permian) . The upper contact is gradational with the upper shale member. The Poleo is interpreted to be a high-energy fluvial deposit derived from the southeast (Gibson, 1975). Kurtz and Anderson (1980), however, indicated that the lower part of the Poleo had a source to the north, whereas the upper Poleo was derived from the south.

Upper shale member–The upper shale member of the Chinle Formation is an informal designation used by Wood and Northrop (1946). This member is a valley and slope former consisting mostly of reddish-brown shale with minor amounts of green and maroon shale and red siltstone and sandstone. The upper shale member lithologically resembles the Salitral Shale Tongue, and color is the major distinguishing feature.

The lower 100-150 ft of the upper shale member is mainly reddish-brown to maroon-brown, very thin to medium-bedded, fine- to coarse-grained, argillaceous and feldspathic quartzose sandstone interbedded with siltstone and silty claystone. The siltstone and silty claystone are dark maroon-brown, thin to very thin bedded, and make up approximately 30% of the interval. This interval grades upward into interbedded claystone and sandstone lentils that comprise most of the member. The sandstone in the upper three quarters of the member is predominantly fine grained, subangular, thin bedded, and moderately hard. Some of the sandstone is light gray but is commonly stained dusky red. The claystone is dark red, massively bedded, and has a conchoidal fracture.

This member ranges in thickness from 400 to 600 ft. The basal contact is gradational with the Poleo Sandstone Lentil, and the upper contact is disconformable with the Entrada Sandstone (Jurassic) .

Kurtz and Anderson (1980) interpret the upper shale member to have been deposited in swamps and sluggish streams on a broad lowland.

Petrified Forest Member–The Petrified Forest Member of the Chinle Formation was named by Gregory (1950) for exposures in the Petrified Forest National Park in eastern Arizona. This member is equivalent to the Salitral Shale Tongue and the upper shale member; it was mapped in the southern part of the Sierra Nacimiento where the Poleo Sandstone is absent. The lower part of the Petrified Forest Member tends to be purplish and similar to the Salitral, whereas the brownish-red and orange-red upper part resembles the upper shale member.

Ruetschilling (1973) described three units within the Petrified Forest Member in the San Ysidro quadrangle. A condensation of his description follows.

Unit 1, at the base of the member, is 30 ft thick and consists of interbedded sandstone, mudstone, and siltstone. Calcareous, ripple-laminated, well-indurated, yellowish-gray, silty, fine-grained feldspathic sandstone beds are 15-35 inches thick, these beds make up 40% of the unit and have abundant ripple marks, load casts, and biogenic structures. Bluish-gray mudstone and siltstone occur in beds 2.5-10 ft thick and comprise the rest of the unit. This unit marks the transition from the sandstone of the Agua Zarca Sandstone Member to the mudstones of the Petrified Forest Member of the Chinle. The contact with the Agua Zarca is conformable and is placed at the top of the highest high-angle crossbedded sandstone bed of the Agua Zarca.

Unit 2 was not measured because of the lack of a complete section, but, based on drill-hole data reported in Stewart and others (1972, p. 206), it is estimated to be approximately 1,000 ft thick. It consists of grayish-red mudstone with subordinate amounts of sandstone and limestone-pebble conglomerate beds.

Unit 3 is 40 ft thick. The lower part is 25 ft thick and is yellowish-gray to brown, ledge-forming, medium- to coarse-grained, moderately sorted, friable, crossbedded feldspathic sandstone occurring in beds 10-40 inches thick that locally contain lenses of calcareous, conglomeratic feldspathic litharenite with rounded clasts of sandstone and limestone up to 3 inches long and wood fragments up to 14 inches long.

The upper part of unit 3 is approximately 16 ft thick and consists of slope-forming, intercalated mudstone and crossbedded, ripple-marked, fine-grained sandstone in beds 2-24 inches thick. The upper part of unit 3 sharply truncates the crossbed sets of the lower part. Upsection the sandstone beds become finer grained with increasingly more clay- and silt-sized matrix. Unit 3 may correlate with a lithologically similar, ledge-forming sandstone and conglomerate bed at the top of the Petrified Forest Member in the Laguna area that was named the Correo Sandstone Member of the Chinle by Kelley and Wood (1946).

The Petrified Forest Member is approximately 1,070 ft thick in the southern Sierra Nacimiento.

Jurassic

In the Nacimiento area are three formations of Jurassic age. In ascending order, they are the Entrada Sandstone, the Todilto Formation, and the Morrison Formation. These units are extensively exposed on the north, west, and south margins of the range. Sometimes the Entrada and Todilto were mapped as one unit because of narrow outcrop width, but both are recognized readily in the field.

Entrada Sandstone

The Entrada Sandstone was named by Gilluly and Reeside (1928) for exposures on Entrada Point in the northern part of San Rafael Swell, Utah. Wood and Northrop (1946) mapped the Entrada of the Nacimiento area as the Wingate Sandstone. Baker and others (1947) later correlated the Wingate Sandstone of New Mexico and Arizona with the Entrada Formation of Utah and extended the name Entrada to include those rocks previously called Wingate in Arizona and New Mexico.

Harshbarger and others (1957) divided the Entrada into three members, a lower sandy member, a medial silty member, and an upper sandy (or "slickrim") member. In the Nacimiento area only the upper sandy member is found, except in the southern part of the area (San Ysidro quadrangle) where Ruetschilling (1973) recognized approximately 40 ft of the medial silty member at the base of the Entrada.

The Entrada in the Sierra Nacimiento area consists of light orange-tan to pale-yellow or white, very fine to medium-grained, subrounded to subangular, friable, quartz sandstone with massive bedding and common crossbed sets. The lower part is orange tan, and the upper is pale yellow to white.

The Entrada Sandstone thickens northward from approximately 100 ft in the San Ysidro quadrangle to approximately 300 ft in the Gallina quadrangle. The Entrada lies disconformably on the underlying Chinle Formation (Triassic) and is conformably overlain by the Todilto Formation. The Entrada is the uppermost unit of McKee and others' (1956) Interval B, which is the upper part of the Callovian (late Middle Jurassic) .

Harshbarger and others (1957) considered the Entrada to be an enlian sandstone that was deposited in arid lands marginal to the south shores of Late Jurassic seas. Poole (1962, fig. 163.1D) indicates a westerly to southwesterly direction of material transport for the Entrada Formation in northwest New Mexico. The Entrada Formation has been correlated with the Exeter Sandstone of eastern New Mexico (Smith, C. T., 1961).

Todilto Formation

The Todilto Formation was named by Gregory (1917) for exposures at Todilto Park, McKinley County. Rank and stratigraphic assignment of the Todilto have shifted considerably. It was first assigned to the Glen Canyon Group as a formation. Later it was given a member rank and assigned to the Morrison Formation and still later assigned to the Wanakah Formation in the San Rafael Group (Harshbarger and others, 1957). Wood and Northrop (1946) mapped the Todilto in the Sierra Nacimiento as a member of the Morrison Formation, but the Todilto is now considered a separate formation.

The Todilto Formation in this area consists of two members, a lower limestone and an upper gypsum. The lower unit is 4-20 ft thick and consists of light-gray, laminated, fetid limestone. The upper unit consists of 0-150 ft of mottled, light-gray to white gypsum. Limestone laminations persist into the overlying gypsum in a transition zone marked by nodules of gypsum in limestone matrix.

In the Gallina quadrangle the laminated limestone is locally overlain by mounds of massive limestone breccia up to 14 ft thick that are laterally discontinuous and occur where the overlying gypsum is thin or absent (Gibson, 1975). This limestone has a massive appearance in outcrop but is composed of angular clasts of tannish-gray calcilutite within a light-gray micrite matrix. Clasts are material broken from the underlying laminated limestone. These clasts appear either in random orientation or as crudely bedded to well-bedded layers. Both the lower contact with the Entrada Sandstone and the upper contact with the Morrison Formation are sharp but conformable. The upper contact is placed at the highest occurrence of gypsum.

Harshbarger and others (1957) suggested that the limestone and gypsum were concentrated by evaporation of marine water entering an embayment through a restricted channel. Anderson and Kirkland (1960), however, stated that the presence of freshwater fishes and lack of marine fossils in the limestone indicate that the basin of deposition was closed, and the salts were derived mainly from weathering of Triassic and Permian strata in the surrounding drainage basin.

Morrison Formation

The Morrison Formation was described by Cross (1894) but was named by Eldridge and others (1896) from the type section near Morrison, Colorado. Problems of nomenclature and different horizons chosen for the upper and lower contacts of the Morrison Formation (Fig. 12) have resulted in confusion, and, therefore, the following brief discussion of these problems is provided by Woodward and Schumacher (1973b).

> In a reconnaissance report concerning the area between San Ysidro and Gallina, Renick (1931) included in the Morrison all the strata above the Todilto Formation and below the Dakota Formation (Cretaceous) [Fig. 12] . He reported a measured section near Cuchillo Arroyo, where Freeman and Hilpert (1956) later measured the formation, and noted two informal members, a lower maroon shalt' unit and an upper sandstone and variegated shale unit.
>
> The basic references on Jurassic stratigraphy in northwestern New Mexico are two reports by Baker and others (1936, 1947). They placed the top of the Morrison at the contact with overlying Cretaceous beds and originally included

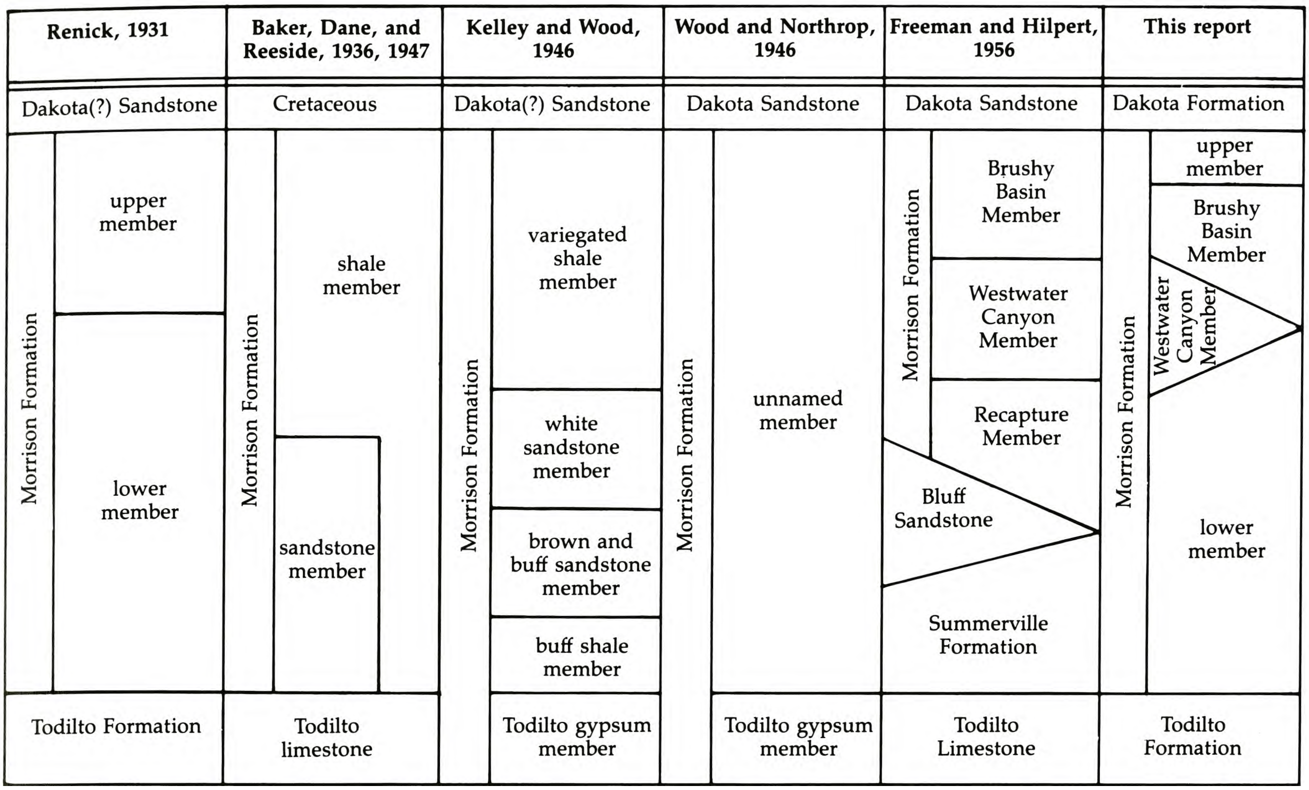


FIGURE 12—Correlation chart showing chronologic development of nomenclature used for rock units in the Morrison Formation in the Sierra Nacimiento area (Woodward and Schumacher, 1973b).

the Todilto as a member within the Morrison (1936), but later (1947) placed the base of the Morrison directly above the Todilto [Fig. 12].

Wood and Northrop (1946), on their reconnaissance map of the Nacimiento uplift and adjacent areas, considered the Todilto a member of the Morrison Formation, but showed the Todilto as a separate unit, and did not indicate any subdivisions within that part of the Morrison above the Todilto Member [Fig. 12].

In the area of the Lucero uplift, Kelley and Wood (1946) considered the Morrison to include the Todilto as a member and to extend upward to the base of the Dakota(?) Formation [Fig. 12]. In addition to the Todilto, they also recognized several informal members in the Morrison.

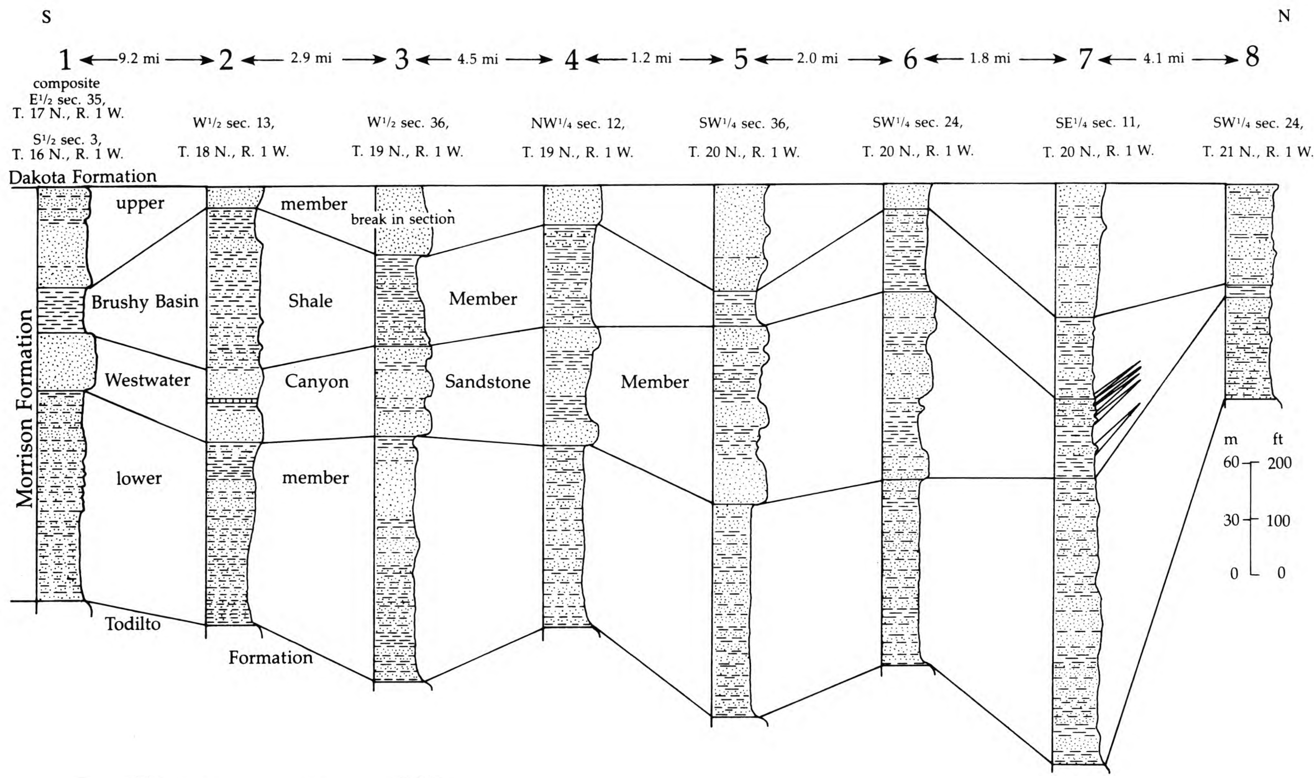
Harshbarger and others (1951), in discussing the Jurassic rocks near Thoreau, placed the base of the Morrison higher than Baker and others (1947), noting the Summerville Formation above the Todilto and below the Morrison. The Summerville has its type section in southeastern Utah (Gilluly and Reeside, 1928; Baker and others, 1936), and this unit as described near Thoreau appears to correlate with the buff shale member of the Morrison reported by Kelley and Wood (1946) in the Lucero uplift. Harshbarger and others (1951) divided their restricted Morrison Formation into four members: in ascending order, the Bluff, the Recapture, Westwater Canyon, and Brushy Basin. These members also have their type sections in southeastern Utah (Baker and others, 1936; Gregory, 1938).

In the Grants area, Craig and others (1955) used the same nomenclature as used by Harshbarger and others near Thoreau, but considered the Bluff to be a separate formation. Freeman and Hilpert (1956) then extended the nomenclature [Fig. 12] used by Craig and others eastward to Laguna and northeastward to Cuchillo Arroyo [Fig. 13, locality 1]. At the latter locality, however, the Bluff Sandstone is missing and the Recapture Member of the Morrison Formation rests directly on the Summerville Formation (Freeman and Hilpert, 1956).

Saucier (1974) considered the upper part of Woodward and Schumacher's (1973b) upper member of the Morrison Formation in the northern part of the Sierra Nacimiento to be equivalent to the Burro Canyon Formation of Early Cretaceous age. Saucier's (1974) Burro Canyon, however, is neither a mappable nor readily recognizable unit, because it is lithologically identical to the underlying rocks and without a prominent stratigraphic break.

In the southern part of the Nacimiento area, I recognized four members of the Morrison Formation. They are, in ascending order, the lower member, the Westwater Canyon Sandstone Member, the Brushy Basin Shale Member, and the upper member. To the north near Cuba, only three members are recognized (Fig. 13, locality 8) because of a facies change within the Westwater Canyon Member.

The lower member consists of reddish-brown and maroon-brown mudstones interbedded with gray, very fine grained sandstone. Above the lower member is the Westwater Canyon Sandstone Member, which is mostly a cliff-forming sandstone in the southern part of the area; toward the north, this member changes to brick-red mudstone with subordinate sandstone interbeds. Near Cuba the Westwater Canyon cannot be recognized. The Brushy Basin Shale Member is composed mostly of green and brick-red mudstone intercalated with subordinate amounts of sandstone. It overlies the Westwater Canyon Member in the southern part of the area and overlies the lower member in the northern part of the area. The upper member consists mainly of sandstone with subordinate amounts of green shale. Locally, green shale occurs at the top of the unit, just below the overlying Dakota Formation (Cretaceous).



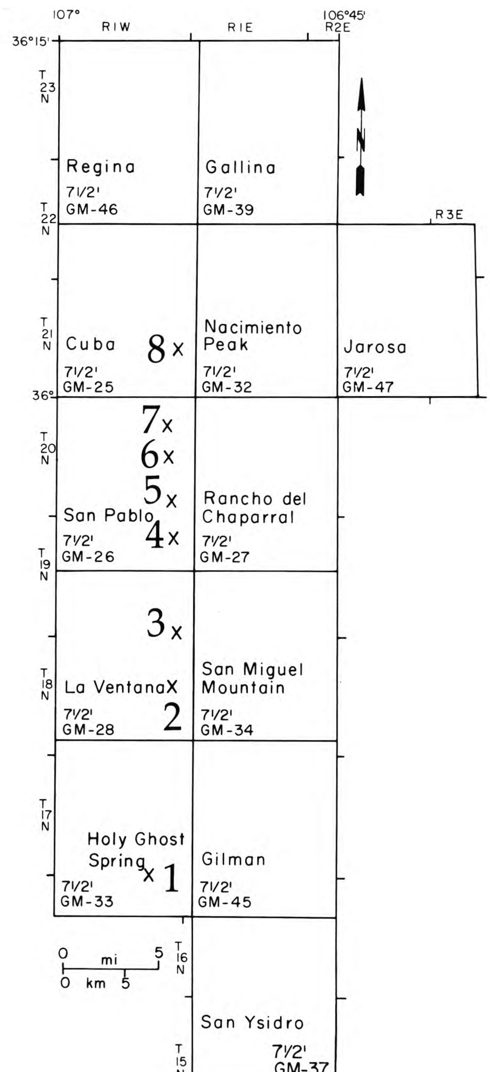


FIGURE 13—Columnar sections and inferred correlations of Morrison Formation along the western margin of the Sierra Nacimiento. Numbers above sections are locations described in text and are keyed to index map to $7^1/_2$-min quadrangles that cover the area (modified from Woodward and Schumacher, 1973b).

The age of the Morrison Formation is Late Jurassic, Kimmeridgian—Portlandian (McKee and others, 1956) .

The following discussion of the four members of the Morrison Formation is provided by Woodward and Schumacher (1973b).

Lower member—The lower member of the Morrison Formation is composed of 325 to 440 feet of approximately equal amounts of reddish-brown and maroon-brown mudstone and gray, very fine to fine-grained sandstone, with minor amounts of green mudstone. Locally thin beds of gray, clastic limestone are present. This member forms a saddle or slope beneath the cliff-forming sandstone of the overlying Westwater Canyon Member.

Bedding is rarely seen within the mudstone or sandstone intervals. These intervals mostly range from 1 to 6 feet thick, but locally the sandstone intervals may be up to 10 feet thick. The mudstone is easily eroded and the sandstones are friable, forming slopes or low, rounded ledges.

The lower member rests concordantly on the Todilto Formation (Jurassic) and interfingers with the overlying Westwater Canyon [Sandstone] Member. At most localities the lower member is poorly exposed, being covered by soil in a strike valley bounded by resistant ridges of gypsum and sandstone.

Near Cuchillo Arroyo [Fig. 13, locality 1] the mudstone in the lower part of this member is pale reddish-brown and probably correlates with the Summerville Formation (Freeman and Hilpert, 1956); to the north, however, the mudstones in this member are more uniformly darker, being maroon brown. Separating the Summerville and the Recapture is made difficult by this northward change in color in combination with poor exposures at most localities; therefore, they are both included in the lower member of the Morrison Formation of this report.

Westwater Canyon [Sandstone] Member—This unit consists principally of cliff-forming sandstone in the southern part of the area; these sandstone beds grade into brick-red and green mudstone toward the north. This facies change takes place by thinning of the sandstone intervals and thickening of the intercalated mudstone intervals northward [Fig. 13] .

The sandstone is mostly thick-bedded, slightly feldspathic to arkosic, fine to very coarse grained and locally conglomeratic, and yellowish to tan or pink. Within the sandstones in the southern part of the area are discontinuous mudstone layers and lenses. Scour and fill structure is characteristic of most of the sandstone beds, and, to the north, the beds become noticeably lenticular. Conglomeratic lenses up to 1 foot thick contain [lithic and quartz] pebbles up to 1 inch in diameter, and are found throughout this member. Thin beds of gray, clastic limestone [pebble conglomerate] occur locally in the mudstone intervals.

The Westwater Canyon [Sandstone] Member interfingers with the underlying member. In the southern part of the area the top of the Westwater Canyon Member is readily placed at the top of the highest, thick, cliff-forming sandstone. Northward, though, the top of the Westwater Canyon Member is difficult to locate because the overlying Recapture [Brushy Basin Shale] Member is very similar to the red and green mudstone, with subordinate sandstone interbeds characteristic of the northern facies of the Westwater Canyon Member.

This unit ranges in thickness from about 100 feet in the south [Fig. 13, locality 1] to about 320 feet toward the north [Fig. 13, localities 5 and 6] and appears to be absent at the northernmost measured section [Fig. 13, locality 8] .

Brushy Basin [Shale] Member—This unit consists of brickred and green mudstone with subordinate sandstone interbeds and minor amounts of gray, clastic limestone.

The mudstone mostly forms slopes or a saddle although, locally, this unit may be siliceous, hard, and resistant to erosion. Sandstone interbeds are generally 1 to 2 feet thick and range from very fine to coarse grained. Local conglomeratic lenses up to 1 foot thick contain [chert and limestone] pebbles up to $^{1}/_{2}$ inch in diameter. Most of the very fine grained sandstone is red or green and quartzose, whereas the coarser grained sandstone is yellowish, tan, or gray and is slightly feldspathic. The sandstone beds tend to form cliffs or ledges.

The Brushy Basin [Shale] Member ranges from 60 to 220 feet in thickness except at the northernmost measured section [Fig. 13, locality 8] where it is 25 feet thick. Possibly the Morrison at this latter locality has been tectonically thinned; therefore, the measured thickness should be used with caution.

Upper member—This unit consists mostly of sandstone with subordinate green or rarely red mudstone interbeds. The sandstone is fine to coarse grained or conglomeratic, thick bedded, and forms ledges or rounded cliffs. Sandstones near the base are mostly yellowish, tan, or rarely pink, and become whitish near the top because of small disseminated kaolinitic specks. Locally, slope- or saddle-forming green mudstone occurs at the top of this unit.

Thickness varies from 75 to 245 feet. The unit is conformable with the underlying Brushy Basin [Shale] Member and is dis-conformably overlain along a sharp contact by the carbonaceous sandstone and carbonaceous shale of the Dakota Formation (Cretaceous).

Sandstone beds in the unit are lithologically similar to the Jackpile sandstone (Jackpile ore-bearing bed) of the Laguna area (Moench and Schlee, 1967) and occur at the same stratigraphic position. Thus, the upper member of the Morrison Formation of the present report appears to correlate with the Jackpile.

Depositional environments

Flesch (1974) suggested the following interpretations for the depositional environments of the members of the Morrison Formation in the southeast San Juan Basin; his interpretations appear to be valid for the Nacimiento region as well. The lower member probably was deposited by a braided stream and(or) a low-sinuosity meandering stream with associated floodplains. The Westwater Canyon Sandstone Member is interpreted to have been deposited in an eastward-flowing braided-stream complex with interbedded and intertongued overbank deposits. The area that is now the northern part of the Sierra Nacimiento probably was the distal part of the complex. The Brushy Basin Shale Member appears to be best explained by strongly meandering streams with extensive floodplain deposits and temporary freshwater lakes. The upper member of the Morrison was probably deposited by an eastward-flowing braided-stream complex with minor floodplain and overbank deposits.

Cretaceous

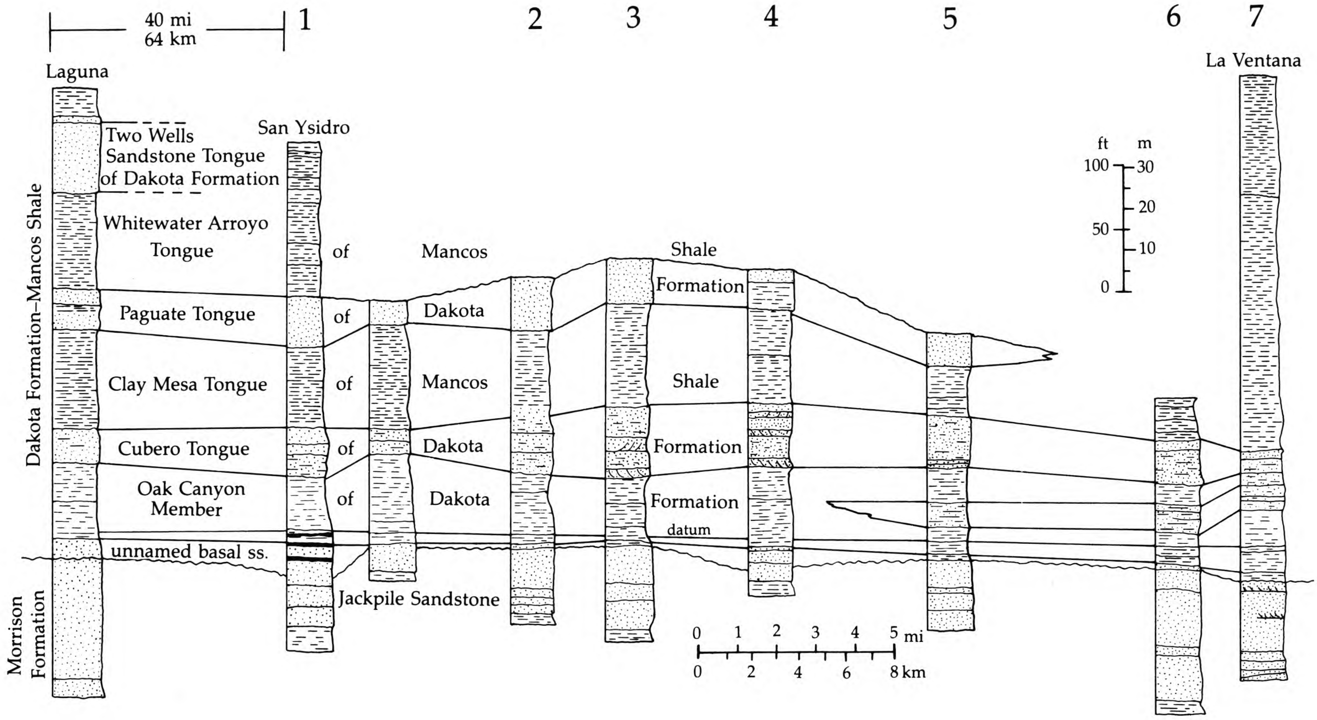
Cretaceous strata are exposed extensively west of the Sierra Nacimiento and are less extensive at the north and south ends of the range. Maximum composite thickness of the Cretaceous System in the Sierra Nacimiento area is approximately 6,600 ft. Six major units were mapped in this area and are, in ascending order, the Dakota Formation, the Mancos Shale, the Mesaverde Group, the Lewis Shale, the Pictured Cliffs Sandstone, and the Kirtland Shale and Fruitland Formation undivided. The Mesaverde Group was mapped as one unit where it is relatively thin, approximately 500 ft thick, and is steeply dipping; in the San Pablo and La Ventana quadrangles, however, the Mesa-verde is thicker, as much as 1,875 ft thick, and gently dipping. This thickness allowed mapping of three units within the Mesaverde, and, in ascending order, they are the Point Lookout Sandstone, the Menefee Formation, and La Ventana Tongue of the Cliff House Sandstone.

A very large amount of literature deals with the Cretaceous in this region because coal, oil, and gas occur in some of the Cretaceous units. References to these works are made in the appropriate places. Nomenclature is somewhat complex because of lateral discontinuity of some sandstone units in a predominantly shale sequence. This lack of continuity stems largely from episodic pulses of uplift in the source area for the elastics, as well as from transgressions, regressions, and stillstands of the epeirogenic Cretaceous sea.

Dakota Formation

The Dakota Formation was named by Meek and Hayden (1862) for exposures near Dakota, Nebraska. Since then, the term Dakota has been used extensively in the Rocky Mountains and Colorado Plateau, although exact correlation of the strata of the Colorado Plateau and that of the type area has not been demonstrated (Young, 1960). In the eastern San Juan Basin the Dakota consists of intertonguing sandstones and shales that generally show a northward pinching out of the upper sandstone beds (Siemers, 1975) . Generally the top of the Dakota is placed at the top of the stratigraphically highest sandstone bed in this sequence. Because of the northward pinchout of the upper sandstone beds, the top of the Dakota is placed at successively lower stratigraphic horizons in the area of this report (Fig. 14).

In the San Ysidro quadrangle at the southern end of the Sierra Nacimiento (Fig. 14, locality 1) Ruet-



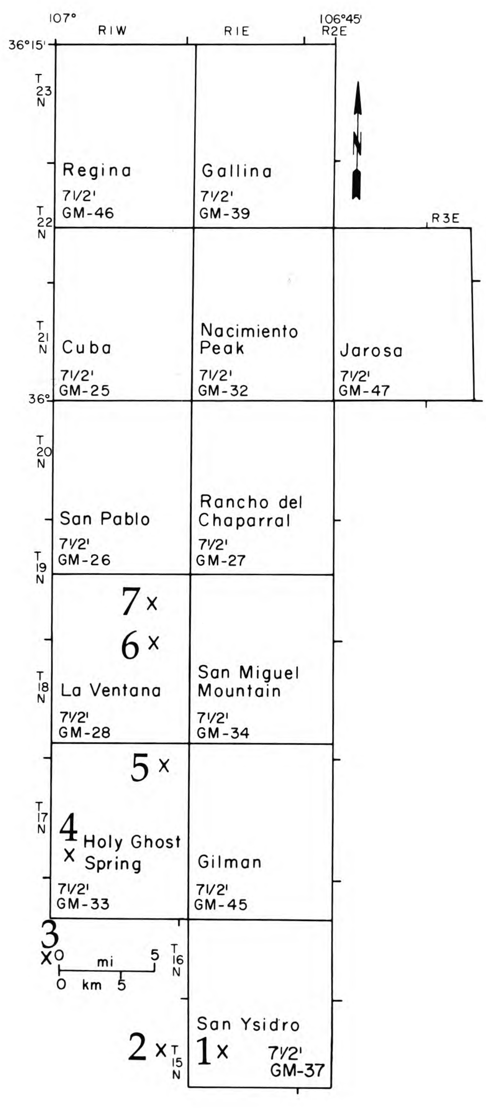


FIGURE 14—Intertonguing of sandstones and shales of upper Dakota Formation and lower Mancos Shale along the eastern side of the San Juan Basin. Numbers above sections are keyed to index map to 7½-min quadrangles that cover the area (after Siemers, 1975).

schilling (1973) described the Dakota as follows. The formation is approximately 175 ft thick and consists of three sandstone and two shale units. Siemers (1975) correlated these units with the Dakota section at Laguna (Fig. 14) described by Landis and others (1973). From oldest to youngest these units are an unnamed carbonaceous basal sandstone, the Oak Canyon Member of the Dakota Formation, the Cubero Tongue of the Dakota Formation, the Clay Mesa Tongue of the Mancos Shale, and the Paguate Tongue of the Dakota Formation. The sandstones of the Dakota form a steep hogback along most of the west side of the Sierra Nacimiento.

Unnamed basal sandstone—The unnamed basal sandstone, 0-25 ft thick, is lenticular, ledge-forming, coarse-grained to conglomeratic, crossbedded, well-indurated feldspathic arenite that contains abundant biogenic structures, plant impressions, and carbonaceous material. Coal beds, 4-17 inches thick, are locally abundant. The contact with the Oak Canyon Member is marked by an abrupt change from sandstone to carbonaceous shale.

Oak Canyon Member of Dakota Formation–This member is approximately 50 ft thick, nonresistant, and consists of dark-gray, carbonaceous shale that increases in silt and fine-grained sand content upward. Abundant bentonite beds and oyster-bearing septarian concretions are present. The Oak Canyon Member has a gradational contact with the Cubero Tongue.

Cubero Tongue of Dakota Formation–This unit is 36 ft thick, forms ledges, and is composed of biotur-bated, calcareous, moderately well to poorly indurated, fine-grained feldspathic arenite that is intercalated with thin shale and siltstone beds. Locally, it is crossbedded. The contact with the Clay Mesa Tongue is marked by an abrupt upward change from sandstone to shale.

Clay Mesa Tongue of Mancos Shale—This unit is approximately 60 ft thick and is lithologically similar to the Oak Canyon Member except that, in the San Ysidro quadrangle, it is less carbonaceous, is sandier, and contains no bentonite beds. The Clay Mesa Tongue has a gradational contact with the Paguate Tongue.

Paguate Tongue of Dakota Formation—This tongue is approximately 33 ft thick, is similar in lithology to the Cubero Tongue, but differs inasmuch as it contains concretions. The contact with the overlying Mancos Shale is marked by an abrupt upward change from sandstone to shale.

In the Holy Ghost Spring quadrangle (Fig. 14, localities 4 and 5) Martinez (1974) provided the following description of the Dakota Formation. The formation is 80-100 ft thick and consists of a very thin to locally absent basal sandstone, a middle shale interval, and an upper sandstone. The basal Dakota consists of 1 ft of tan to gray, poorly to well indurated, slope-forming, carbonaceous sandstone with numerous trace fossils. Above this unit is 29 ft of black, slope-forming, carbonaceous, fissile shale (Oak Canyon Member) with numerous yellow-tan bentomte beds up to 6 inches thick with abundant selenite. The upper part (Cubero Tongue) consists of 50 ft of intercalated fine- to medium-grained sandstone having thin black shale partings; fine- to medium-grained, gray, carbonaceous sandstone; and gray to black, sandy shale. Locally, an oyster bed up to 1 ft thick is found near the middle. Brown-weathering, calcareous concretions up to 2 ft in diameter are common in the upper third of the formation. The shale forms slopes, and the sandstones form cliffs.

Schumacher (1972) described the Dakota Formation in La Ventana quadrangle (Fig. 14, localities 6 and 7) as consisting of three informal members, a basal sandstone member, a medial shale member, and an upper sandstone member that correspond to the unnamed basal sandstone, the Oak Canyon Member, and the Cubero Tongue, respectively. The lower sandstone member is light-gray to pale-yellow or whitish, medium- to thick-bedded, medium-grained sandstone that is conglomeratic in places and has flecks and streaks of carbonaceous material throughout. In places the base of the lower member is extremely carbonaceous with associated uranium mineralization. The medial member forms a valley between the upper and lower members and primarily consists of black, fissile shale. The upper member consists of yellowish to buff, medium- to thick-bedded, fine-grained sandstone with flecks or streaks of carbonaceous material. Worm borings are common in many of the sandstone beds.

In a section south of Arroyo de Dos Gordos the Dakota is 210 ft thick; the lower, medial, and upper members are 106 ft, 35 ft, and 69 ft thick, respectively.

To the north in the San Pablo, Cuba, Regina, and Gallina quadrangles the Dakota consists of the three members noted by Schumacher (1972). The thickness of the formation ranges from 190 ft in the San Pablo quadrangle to 110 ft in the Gallina quadrangle. The Dakota lies disconformably on the Morrison Formation (Jurassic) and intertongues with the overlying Mancos Shale.

According to Landis and others (1973, pp. 1-2), the Dakota of the San Juan Basin region is latest Early Cretaceous to earliest Late Cretaceous. Lithofacies and biofacies relationships of the Cretaceous units in northwest New Mexico and adjacent areas indicate a transgressing shoreline and a subsequent deepening marine basin in the area during the early Late Cretaceous (Kauffman, 1969, p. 235). The basal clastic sequence that represents the beginning of the transgression is the Dakota Formation. The Dakota clastics were deposited under floodplain, swamp, and lagoonal conditions along the margins of the advancing Mancos sea (Pike, 1947; Dane, 1960). Young (1960) noted that transgression of the sea was probably intermittent, and deposition probably occurred during brief periods of quiescence or during minor regressions.

Mancos Shale

The Mancos Shale was named by Cross and others (1899) for outcrops in southwest Colorado. The formation is probably 2,000-2,200 ft thick in the Sierra Nacimiento area and consists mostly of dark-gray to black shale with minor amounts of thin-bedded, light-gray sandstone, yellowish limy concretions, and calcareous shale or thin-bedded limestone. This unit is present to the west of the Sierra Nacimiento and, where it dips steeply, forms a strike valley with poor exposures. The Mancos was mapped as one formation because of its poor exposures, but where it is well exposed several units within the Mancos can be recognized (Fig. 15). In ascending order these units are

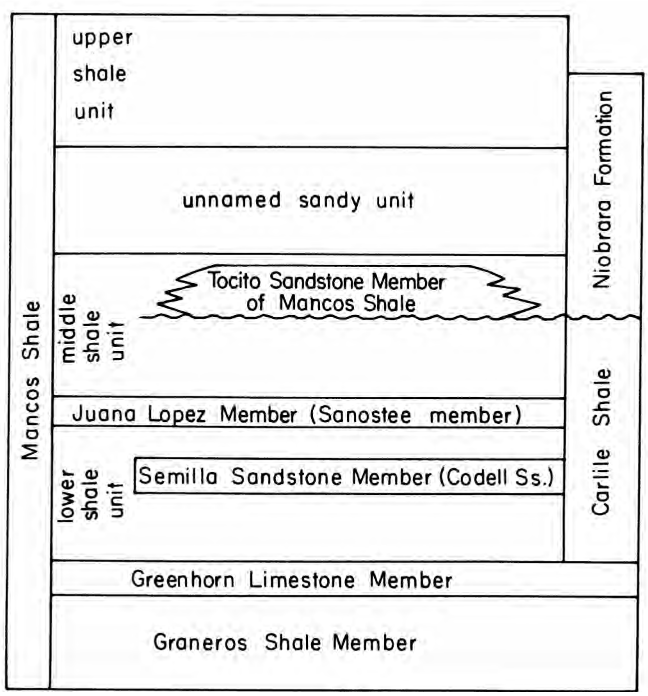


FIGURE 15—Nomenclature and stratigraphic relations of units in Mancos Shale.

the Graneros Shale Member, the Greenhorn Limestone Member, the lower shale unit that encloses the Semilla Sandstone Member, the Juana Lopez (San-ostee) Member, the middle shale unit, an unnamed sandy interval, and the upper shale unit (Fassett, 1974; Molenaar, 1977) . Due to intertonguing, unconf ormities, and problems in correlations from one area to another, a complex and confusing nomenclature has developed for the units in the Mancos and related formations in the San Juan Basin; for a thorough discussion of this topic, the reader is referred to a paper by Molenaar (1977) .

Lamb (1968) described the stratigraphy and paleontology of the lower part of the Mancos Shale along the eastern side of the San Juan Basin, and his findings are summarized briefly.

Graneros Shale Member–This unit is dark-gray marine shale with local, thin sandstone beds, which may be equivalent to tongues of Dakota Sandstone to the southwest, bentonite beds, and zones with limy concretions. Lamb (1968) reported that the Graneros is 219 ft thick in La Ventana quadrangle but thins northward to approximately 150 ft in the San Pablo quadrangle, accompanied by a northward decrease in the sand content, an increase in the amount of limy shale, and a darkening in color. The Graneros generally forms valleys and is poorly exposed.

Greenhorn Limestone Member–This member thins southward and is only locally present south of La Ventana quadrangle. At many localities it appears to be marked by a zone of calcareous concretions. Lamb (1968) described the Greenhorn in La Ventana quadrangle as consisting of approximately 17 ft of dark-gray calcareous shale with three minor limestone beds up to 1 ft thick near the top. Northward the limestone beds become more prominent, and the unit thickens to 30 ft north of the area of this report. Where the beds are gently dipping, the Greenhorn underlies low hills.

Lower shale unit and Semilla Sandstone Member–The lower shale unit of the Mancos consists of dark-gray shale that is interbedded with minor amounts of sandstone, bentonite, and calcareous beds. This interval has been called the lower Carlile Shale by Lamb (1968). It is approximately 320 ft thick. Within this shale unit approximately 200 ft above the base is the Semilla Sandstone Member; at the type section in the southeast corner of La Ventana quadrangle, the Semilla is 70 ft thick. It is composed of very fine to medium-grained sandstone that was deposited as a discontinuous offshore bar (Molenaar, 1977) . Lamb (1968) correlated this sandstone with the Codell Sandstone of Colorado. The Semilla thins both to the north and south of La Ventana quadrangle, pinching out in the southern part of the San Pablo quadrangle. Above the Semilla is 85 ft of dark-gray shale that makes up the remainder of the lower shale unit of the Mancos Shale.

Juana Lopez Member–Also called the Sanostee member, the Juana Lopez Member rests conformably on the lower shale member of the Mancos and consists of thinly interbedded calcarenite and calcareous shale. Broken shell fragments and shark teeth in carbonate cement form the calcarenite . This unit is reported to be 50-100 ft thick by Molenaar (1977), but Lamb (1968) noted that only 7 ft of the Juana Lopez Member is present in La Ventana quadrangle. This difference stems from differing definitions of the base of the unit. Molenaar (1977) apparently follows the usage of Dane and others (1966) who included all the shale above the Semilla Sandstone Member in the Juana Lopez. In view of the absence of the Semilla in some areas and the widespread occurrence of the restricted Juana Lopez of Lamb (1968), I prefer to use Lamb's definition.

Middle shale unit–This unit is approximately 400 ft thick and contains a regional unconformity that separates the upper Carlile Shale from the overlying Niobrara Shale (Lamb, 1968). This unconformity is recognized by use of microfossil zones and by the local presence of a sandstone, the Tocito Member, above the unconformity. In La Ventana quadrangle the Carlile portion of the middle shale unit is approximately 300 ft thick and is overlain by sandy, glauconitic shale that Lamb (1968) correlated with the Tocito. Fassett (1974, p. 226) reported the thickness of the middle shale unit to be 390 ft in a well a few miles to the north of the Regina quadrangle (Magnolia Schmitz 1, sec. 34, T. 24 1., R. 1 W.).

Unnamed sandy unit–This unit rests conformably on the middle shale unit of the Mancos and occurs within the Niobrara Shale as used by Lamb (1968). This unit consists of thinly interbedded, very fine grained sandstone, siltstone, and gray marine shale. Fassett (1974) noted a thickness of 290 ft in the subsurface (sec. 34, T. 24 N., R. 1 W.) for this interval and suggested that, in part, it may be correlative with El Vado Sandstone Member of the Mancos Shale (Landis and Dane, 1967) . The amount of sand in this interval decreases southward in the Sierra Nacimiento area.

Upper shale unit–The upper shale unit of the Mancos is composed of dark-gray marine shale that is equivalent to the upper part of the Niobrara Formation and lithologically similar to shale above the Niobrara interval (Molenaar, 1977) . This upper shale unit of the Mancos is reported to be approximately 1,000 ft thick in the subsurface in sec. 34, T. 24 N., R. 1 W. by Fassett (1974). The upper shale is overlain conformably by strata of the Mesaverde Group.

The depositional setting of the Mancos Shale in this area has been discussed in detail by Lamb (1968) who interpreted a major transgression of the Cretaceous sea from Dakota to early Carlile (lower Mancos Shale) time, a middle Carlile regression that culminated in erosion of the Carlile, and transgression during early Niobrara time. Molenaar (1977) noted that the Dakota transgression advanced generally from east to west or perhaps east-southeast to west-northwest but that the Mancos transgressions were toward the southwest. These complex transgressions and regressions resulted in intertonguing of the upper part of the Dakota Formation with the lower part of the Mancos Shale.

Mesaverde Group

The Mesaverde Group of Late Cretaceous age was named by Holmes (1877) for a thick sequence of sandstone, shale, and coal at Mesa Verde in southwest

Colorado. In the eastern San Juan Basin there are three units in the Mesaverde, and they are, in ascending order, the Point Lookout Sandstone, the Menefee Formation, and La Ventana Tongue of the Cliff House Sandstone (Dane, 1936; Beaumont and others, 1956). The Mesaverde is exposed west of the Sierra Nacimiento and ranges in thickness from 320 ft in the central Cuba quadrangle to 1,875 ft in the southern San Pablo quadrangle. Where the group is thin and steeply dipping it was mapped as one unit. Elsewhere, the three units in the Mesaverde Group were mapped separately.

Point Lookout Sandstone—The ridge-forming Point Lookout Sandstone conformably overlies and regionally intertongues with the Mancos Shale and is in gradational contact with the overlying Menefee Formation. The Point Lookout Sandstone consists of very pale orange weathered, salt- and pepper-textured, fine- to medium-grained, thin- to thick-bedded, cross-bedded, light-gray sandstone interbedded with minor, thin beds of carbonaceous, gray to black shale. Sandstone concretions and fossil worm burrows are locally abundant in the sandstone.

The Point Lookout Sandstone ranges in thickness from 40 ft in the Cuba quadrangle to 275 ft in the San Pablo quadrangle (Woodward, Kaufman, and others, 1973) and then thins to 20 ft in La Ventana quadrangle to the south. The Point Lookout is interpreted to be a regressive coastal-barrier sandstone (Molenaar, 1977) .

Menefee Formation–The Menefee Formation is in gradational contact with the underlying Point Lookout Sandstone and the overlying La Ventana Tongue of the Cliff House Sandstone. The Menefee consists of light- to dark-gray, fissile, carbonaceous shale interbedded with coal and light-gray, fine- to medium-grained, thin- to thick-bedded, lenticular sandstone. Minor ironstone concretions are locally abundant. The formation is predominantly shale and coal and is a valley former in most places.

Along NM-126 near Señorito in the San Pablo quadrangle, the Menefee is 265 ft thick. At this location intense internal deformation can be seen, and in some places boudinage structures have formed in the coal, suggesting that the unit is tectonically thinned here. The thinning, however, was probably not more than a few tens of feet. The Menefee thickens southward and is approximately 700 ft thick in La Ventana quadrangle.

Between the underlying regressive Point Lookout and the overlying transgressive Cliff House Sandstones, the Menefee is interpreted to be of continental origin. The fact that coal beds tend to be concentrated in the upper and lower parts of the formation near the marine sandstone beds may indicate that the Menefee coals are of back-shore swamp origin (Woodward, Fassett, and Talbott, 1974, p. 6).

La Ventana Tongue of the Cliff House Sandstone—La Ventana Tongue consists of fine- to medium-grained, salt- and pepper-textured, thin- to thick-bedded, gray sandstone interbedded with minor amounts of gray shale in layers up to 2 inches thick. Crossbedding, cone-in-cone structures, ripple marks, sandstone concretions, and fossil worm burrows are abundant in this ridge-forming sandstone. La Ventana Tongue is conformable with the overlying Lewis Shale, so that, southward in the Sierra Nacimiento area, successively higher sandstone beds are included in La Ventana. This results in a southward thickening of La Ventana Tongue and a concomitant thinning of the Lewis Shale. Near Señorito in the northern San Pablo quadrangle, La Ventana Tongue is 15 ft thick, but in the southern part of this quadrangle, the unit is 900 ft thick. Where the uppermost bed of sandstone included in La Ventana pinches out northward (as in the San Pablo quadrangle), an arbitrary cutoff is necessary that allows the upper contact of La Ventana to drop stratigraphically lower to the north.

La Ventana Tongue of the Cliff House Sandstone was deposited during a transgression of the Cretaceous sea, but Molenaar (1977) pointed out that the thick buildups of sandstone occurred during still-stands or minor regressions before being overridden by the overlying Lewis transgression.

Lewis Shale

The Lewis Shale of Late Cretaceous age was named by Cross and others (1899) for exposures near Fort Lewis in southern Colorado. This formation is exposed as a strike valley along the eastern side of the San Juan Basin in the Regina, Cuba, and La Ventana quadrangles.

The Lewis Shale consists of light- to dark-gray shale that weathers pale yellowish brown and is interbedded with minor amounts of light-gray to buff, lenticular, calcareous siltstone, fine-grained sandstone layers up to 4.0 ft thick, and bentonite . The shale contains yellowish, nodular, limy concretions with enclosed pelecypods and ammonites. Baltz (1967, p. 16) reported a thin, concretionary, limestone marker bed containing numerous pelecypods, gastropods, and ammonites, which occurs approximately one third of the way up from the base of the formation. This marker bed is present only in the Regina quadrangle.

The thickness of the Lewis Shale was scaled from sections and appears to be 1,500-2,000 ft. It thins southward because of intertonguing with the underlying La Ventana Tongue of the Cliff House Sandstone. The Lewis Shale represents a major marine transgression toward the southwest.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone is of Late Cretaceous age and was named by Holmes (1877) for exposures of massive sandstone along the San Juan River in southwest Colorado. The formation was redefined by Reeside (1924) to include interbedded sandstone and shale beneath the massive sandstone. The Pictured Cliffs Sandstone is present only in the Cuba and San Pablo quadrangles. In this area it has been studied in detail by Baltz (1967), and much of the following discussion is based on his work.

The Pictured Cliffs Sandstone is composed of thin-to thick-bedded sandstone, siltstone, and shale. There is a change in facies in Pictured Cliffs from mostly sandstone in the western part of the San Pablo quadrangle to sandy shale in the southern part of the Cuba quadrangle; in sec. 23, T. 21 N., R. 1 W., the Pictured

Cliffs can no longer be distinguished from the underlying Lewis Shale for mapping. For this report the Pictured Cliffs was not mapped north of that locality. Baltz (1967), however, noted that the sandy shale continues to the north. The thickness of the formation ranges from the wedge out noted above to a maximum of 65 ft in the western part of the San Pablo quadrangle.

The Pictured Cliffs Sandstone intertongues with the underlying Lewis Shale and is concordant with the overlying undivided Fruitland Formation and Kirtland Shale. The Pictured Cliffs Sandstone is interpreted to be a regressive coastal-barrier sandstone that marks the final retreat of the Cretaceous sea from the area of the San Juan Basin (Molenaar, 1977) .

Fruitland Formation and Kirtland Shale undivided

The Fruitland Formation was named by Bauer (1916) for exposures of coal, shale, and sandstone resting on the Pictured Cliffs Sandstone near Fruitland in northwest New Mexico. The Kirtland Shale was named by Bauer (1916) for sandstone and shale resting on the Fruitland Formation between Kirtland and Farmington in northwest New Mexico. Dane (1936) mapped these units in the southern part of the San Juan Basin but was unable to distinguish them east of sec. 7, T. 19 N., R. 2 W. and proceeded to map them as one unit, the Kirtland Shale. Baltz (1967), however, recognized equivalents of both the Fruitland and Kirtland along the eastern edge of the San Juan Basin and mapped them as undivided Fruitland Formation and Kirtland Shale.

The lower part of this unit consists of up" to 60 ft of carbonaceous shale, sandy to silty, gray shale, and thin beds of sandstone. This lower interval thins and is locally absent. It is overlain by coarse-grained, yellowish or gray sandstone that locally contains granules and pebbles. Silicified fossil wood is common in this sandstone. Above the sandstone is mostly gray and olive shale with interbeds of white, yellow, and buff, fine- to coarse-grained sandstone. The total thickness of the undivided Fruitland Formation and Kirtland Shale ranges from 85 ft in the Cuba quadrangle to approximately 240 ft in the western part of the San Pablo quadrangle.

The undivided Fruitland Formation and Kirtland Shale rests conformably on the Pictured Cliffs Sandstone and Lewis Shale and is unconformably overlain by the Ojo Alamo Sandstone along a channeled erosional contact.

Baltz (1967) interpreted the lower part of the undivided Fruitland—Kirtland to have been deposited in mixed marine, lagoonal, and paludal environments and interpreted the upper part of the unit to have been deposited in stream channels, floodplains, and swamps or lakes.

Tertiary

Seven bedrock units of Tertiary age in the Sierra Nacimiento area are covered by this report. In ascending order, they are the Ojo Alamo Sandstone, the Nacimiento Formation, the San Jose Formation, the Abiquiu Formation, the Zia Sand, unnamed volcaniclastic rocks (found only in the Gilman quadrangle), and the Paliza Canyon Formation. Surficial deposits, including travertine, terrace and pediment deposits, lag deposits, gravel of unknown origin, and alluvium that may be of Tertiary and(or) Quaternary age are discussed in a later section.

The Ojo Alamo, Nacimiento, and San Jose Formations are of early Tertiary age (Paleocene and Eocene) and occur in the San Juan Basin; they are found only in the Regina, Cuba, and San Pablo quadrangles. Baltz (1967) presented a detailed and thorough study of these units and much of this discussion of them is based on his work. The Abiquiu Formation, Zia Sand, and the unnamed volcaniclastic rocks are related to the mid-Tertiary (Miocene) development of the Rio Grande rift and, therefore, are found mainly along the eastern side of the Sierra Nacimiento. The Paliza Canyon Formation consists of mafic volcanic rocks of the Jerez volcanic field; this unit is present at only a few localities in the eastern part of the area covered by this report.

Ojo Alamo Sandstone

In the area of this report, these beds were first mapped by Gardner (1909, 1910) and later by Renick (1931) as the lower part of the Puerco Formation. Dane (1936), however, mapped the Ojo Alamo Sandstone along the south side of the San Juan Basin and, upon extending this formation into the area covered by the present report, discovered that the lower part of the Puerco Formation as mapped by Gardner (1909, 1910) and Renick (1931) was equivalent to his Ojo Alamo. Baltz and others (1966) restudied the type section of the Ojo Alamo, which had originally been named by B. Brown (1910) for beds along Ojo Alamo Arroyo in the San Juan Basin, and restricted the term Ojo Alamo Sandstone to a conglomeratic sandstone that forms the upper part of Brown's (1910) original Ojo Alamo. Baltz and others (1966) also assigned the restricted Ojo Alamo Sandstone to the Tertiary, because it intertongues with the overlying Nacimiento Formation of Paleocene age. This report follows the usage of Baltz and others (1966) .

The Ojo Alamo Sandstone consists of tan and brown, medium to very coarse grained quartzose sandstone containing local lenses of gray and olive-green shale. Red, pink, and green lithic and feldspar sand grains are common, and pebbles and cobbles of quartz, chert, and quartzite are found scattered throughout the sandstone beds. Locally, the pebbles and cobbles form conglomerate in the basal few feet of the formation. Fossil logs replaced by silica and limonite are common in the Ojo Alamo. Crossbeds are abundant, particularly in the upper part of the formation.

The Ojo Alamo Sandstone ranges in thickness from 70 ft in the San Pablo quadrangle to a maximum of 125 ft in the Regina quadrangle. This northeastward increase in thickness, along with an eastward increase in grain size (Dane, 1936), led Baltz (1967) to infer that the Ojo Alamo was derived from a highland to the northeast, probably the Brazos uplift of central-northern New Mexico. Silver (1950) suggested that the formation was deposited asa pediment gravel. As noted by Baltz (1967), the sandstone and conglomerate of the Ojo Alamo represent overlapping stream-channel deposits.

The Ojo Alamo is unconformable on the undivided Fruitland Formation and Kirtland Shale and inter-tongues with the overlying Nacimiento Formation. Baltz and others (1966) assigned the Ojo Alamo to the Paleocene because of the intertonguing with the Nacimiento Formation and because of the presence of pollen and spores of probable Paleocene age.

Nacimiento Formation

Gardner (1910) named the Nacimiento Group for Tertiary strata in the western part of the Cuba quadrangle that included the Puerco and Torreon Formations. Dane (1936) mapped the lower part of Gardner's (1909) Puerco Formation as the Ojo Alamo Sandstone. The upper part of Gardner's Puerco and lower part of the Torreon Dane (1936) mapped as the Puerco(?) and Torreon Formations, and the upper part of Gardner's Torreon he mapped as the Wasatch Formation. Wood and Northrop (1946) followed Dane's (1936) usage, mapping the Puerco and Torreon as an undivided unit, while Dane (1946) used the name Nacimiento Formation for what he had earlier mapped as the Puerco(?) and Torreon. Simpson (1948) proposed that Puerco and Torreon be used only for faunal zones, in accordance with the earlier paleontological work of Matthew (1897), who, in turn, had divided the Puerco Marls named by Cope (1875) into two faunal zones of different ages, the Puerco and the Torreon. The most thorough and detailed work on the Nacimiento Formation was done by Baltz (1967), and his usage is followed in this report.

The Nacimiento Formation consists of shale and interbedded sandstone with a facies change from mainly shale in the south to approximately half sandstone toward the north (Baltz, 1967). At the south end of Cuba Mesa, just west of the Cuba quadrangle, Baltz (1967, p. 39) reported the following section with four informal units. The lowest unit consists of approximately 130-150 ft of gray to light olive-gray shale with bands of purplish, lenticular siltstone and argillaceous, fine- to coarse-grained sandstone. This unit is overlain by approximately 120 ft of gray clay and lenticular interbeds of fine to very coarse grained, white-weathering sandstone with one or two thin beds of impure coal. Above this unit is approximately 115 ft of olive-green and gray clay and siltstone with a few interbeds of fine- to coarse-grained, argillaceous sandstone; near the top of this unit is a bed of brown to black lignite. The uppermost unit consists of approximately 425 ft of variegated light-purple, gray, and olive-green clay and siltstone with interbeds of yellow, white, and brown sandstone; two or three lignite beds occur in the upper part of this unit.

The Nacimiento Formation ranges from approximately 500 to 800 ft in thickness in the area of this report. Regionally, the formation thickens northward (Baltz, 1967). The contact with the underlying Ojo Alamo is conformable, but the contact with the overlying San Jose Formation is a slightly angular unconformity.

Baltz (1967) interprets two source areas for the Nacimiento. The sandstone facies in the north was part of a large fan of volcanic and orogenic debris derived from a highland to the north and northeast of the San Juan Basin; the shalt' facies to the south was derived largely from reworked Cretaceous sediments from the western and southern margins of the basin. The interbedded lenticular sandstones are probably stream-channel deposits, and the shales and siltstones represent floodplain, lake, and alluvial-fan deposits (Baltz, 1967).

Evidence supporting an early and middle Paleocene age for the Nacimiento Formation has been summarized by Baltz (1967).

San Jose Formation

Simpson (1948) proposed that the term San Jose Formation be used for strata in the San Juan Basin previously called Wasatch (Cope, 1875, 1877), and he designated a type locality along San Jose Creek in the badlands northwest of Regina in the Regina quadrangle. Renick (1931) mapped the base of the Wasatch at the stratigraphically lowest occurrence of variegated shales, which mostly characterize this formation, but Dane (1936) and Wood and Northrop (1946) placed the lower contact at the base of thick, arkosic sandstones beneath the variegated shales. Baltz (1967) mapped the lower contact where Dane (1936) and Wood and Northrop (1946) did, but he called the formation the San Jose and mapped several members. Some of Baltz's (1967) members are laterally equivalent facies of intertonguing sandstones and shales; where exposures are not good, they are difficult to map precisely at 1:24,000 scale. Therefore, the San Jose was mapped as an undivided formation in the Cuba and Regina quadrangles (Woodward, McLelland, and others, 1972; Merrick and Woodward, 1982). Three of the four facies described by Baltz (1967) are present in the area of this report and are described below.

Cuba Mesa Member–This unit lies unconformably on the Nacimiento Formation at Baltz's (1967, p. 46) type section at Cuba Mesa. Here the member consists of yellowish and buff, crossbedded, conglomeratic and arkosic, coarse-grained sandstone with minor thin lenses of purplish and gray shale. The Cuba Mesa Member is 782 ft thick here (Baltz, 1967, p. 46). It intertongues northward with the Regina Member, a shalt' unit; the upper tongues of sandstone pinch out northward, resulting in a thickness of the Cuba Mesa Member of less than 150 ft in the Regina quadrangle (Baltz, 1967).

Regina Member–This member both overlies and is laterally equivalent to the upper part of the Cuba Mesa Member. The Regina Member consists mostly of variegated light-gray, pale-maroon to purple, and green shale, siltstone, mudstone, and sandy shale with minor interbeds of white to brown, conglomeratic, arkosic sandstone. The sandstones tend to form cliffs, and the upper part of the unit forms extensive badlands. Baltz (1967, p. 50) reported this member to be 1, 640 ft thick in sec. 17, T. 24 N., R. 1 W., but in the Regina quadrangle it is probably thinner.

Llaves Member–Composed of massive beds of arkosic, conglomeratic sandstones, the Llaves Member grades laterally into the shales of the Regina Member to the south. Baltz (1967, p. 1) shows a tongue of the Llaves Member resting on the Regina Member in erosional outliers in the hills forming the Continental Divide in the northwest part of the Regina quadrangle.

The preserved thickness of the San Jose Formation in the area of this report probably ranges from approximately 800 to 1,400 ft. The San Jose contains early Eocene fossils (Granger, 1914) and is probably of early and middle Wasatch Age (Simpson, 1948). This formation was deposited under terrestrial conditions (Simpson, 1948); the coarse-grained sandstones were deposited in stream channels, and the shalt' rocks were deposited in swamps and savannahs (Van Houten, 1945) .

Abiquiu Formation

The Abiquiu Tuff was named by H. T. U. Smith, (1938) for a thick sequence of stream-laid tuff and volcanic conglomerate that rests unconformably upon the El Rito Formation and older rocks along the Chama Valley in northern New Mexico. H. T. U. Smith (1938, pp. 944-947) described the tuff as consisting of pure-white to light-gray, fine-grained material that is finely laminated to massively bedded and intercalated with lenticular volcanic conglomerate and lavas. The basal portion of the formation ranges in thickness from 0 to 300 ft, due in part to irregularities of the buried topography, and consists of arkosic gravels derived from Precambrian crystalline rocks. Light-buff limestone with pebbles and chips of granite and quartzite, approximately 4-6 ft thick, underlies the conglomerate in the western part of the Chama quadrangle. The thickness of the Abiquiu Tuff in the Abiquiu quadrangle reaches a maximum of 1,200 ft (Smith, H. T. U., 1938, p. 948).

Church and Hack (1939, pp. 618-622) extended the Abiquiu Tuff of H. T. U. Smith (1938) to the Sierra Nacimiento on the west and divided it into three members. The basal member consists of interbedded, coarse-grained, arkosic sand and gravel, which becomes finer grained westward and pinches out in the Sierra Nacimiento. The overlying Pedernal chert member is composed of white chert and white, siliceous limestone and extends westward from the southwest corner of the Abiquiu quadrangle to the western edge of the Sierra Nacimiento (Church and Hack, 1939) . The upper member of the Abiquiu Tuff is approximately 400-500 ft thick at Cerro Pedernal but is not present everywhere to the west; it is commonly tuffaceous.

Abiquiu Formation rather than Abiquiu Tuff is used in this report because of the diverse lithologies. Members of the Abiquiu are exposed in the Gallina, Nacimiento Peak, and Jarosa quadrangles.

Basal member–In the Nacimiento area the basal member of the Abiquiu is buff to orangish, poorly sorted, medium- to very coarse grained arkose, conglomeratic arkose, and arkosic conglomerate. Conglomerate clasts are angular to subrounded pebbles, cobbles, and boulders of granite and metamorphic rocks with lesser amounts of limestone, chert, and shale. Beds are commonly lenticular and may show crossbedding and graded bedding. This basal member ranges from a wedge edge to approximately 300 ft in thickness, generally thickening eastward. This member lies unconformably on rocks ranging in age from Precambrian to Permian. Timmer (1976) presented detailed petrographic descriptions of rocks from this member.

Pedernal chert member–Locally, the Pedernal chert member can be divided into upper and lower units having different lithologies (Timmer, 1976). The lower part consists of light-gray to whitish chert that is locally mottled yellow, orange, red, blue, and black. Locally, in the Jarosa quadrangle, cherty limestone occurs near the base of the member. The chert is resistant to weathering and forms lag deposits, thereby making it difficult to map. This chert unit is up to 20(?) ft thick in the Nacimiento Peak and Gallina quadrangles. It thickens eastward to a maximum of approximately 100 ft at Cerro Jarocito in the Jarosa quadrangle but thins again eastward from Cerro Jarocito to approximately 50 ft thick at the bench mark, VABM Brown, in the eastern part of the Jarosa quadrangle (Timmer, 1976) . This lower part of the member is missing at Mining Mountain, also in the Jarosa quadrangle, where the upper part of the Pedernal chert rests on the lower member of the Abiquiu Formation. In the western exposures along the crest of the Sierra Nacimiento, the Pedernal chert rests on Precambrian rocks, but, to the east of the crest, it rests on the lower member of the Abiquiu Formation.

The upper part of the Pedernal chert is exposed at Mining Mountain, Cerro Jarocito, and VARM Brown in the Jarosa quadrangle. The following description is summarized from the work of Timmer (1976). The upper part of the Pedernal chert member at Mining Mountain consists of generally thin-bedded, gray limestone with variable amounts of material derived from granitic and air-fall and erosional volcaniclastic sources. The basal contact (Fig. 16) is gradational with the underlying lower sandstone and conglomerate member of the Abiquiu Formation, which, at Mining Mountain, is 68 ft thick and rests on the Abo Formation (Permian). From this gradational contact the upper part of the Pedernal chert member consists of an upward-fining sequence and a corresponding decrease in clastic material and increase in calcite. Examination of thin sections from six of the seven limestone beds and from rubble collected near the top of the section indicates that the clastic components in the lower 13 ft of the unit are predominantly non-volcanic, and those in the upper 30 ft are predominantly volcanic.

At Cerro Jarocito the upper part of the Pedernal chert member is approximately 120 ft thick. Rubble of gray, fine-grained limestone, resembling the upper part of the Pedernal member at Mining Mountain, occurs along the north slope of Cerro Jarocito above

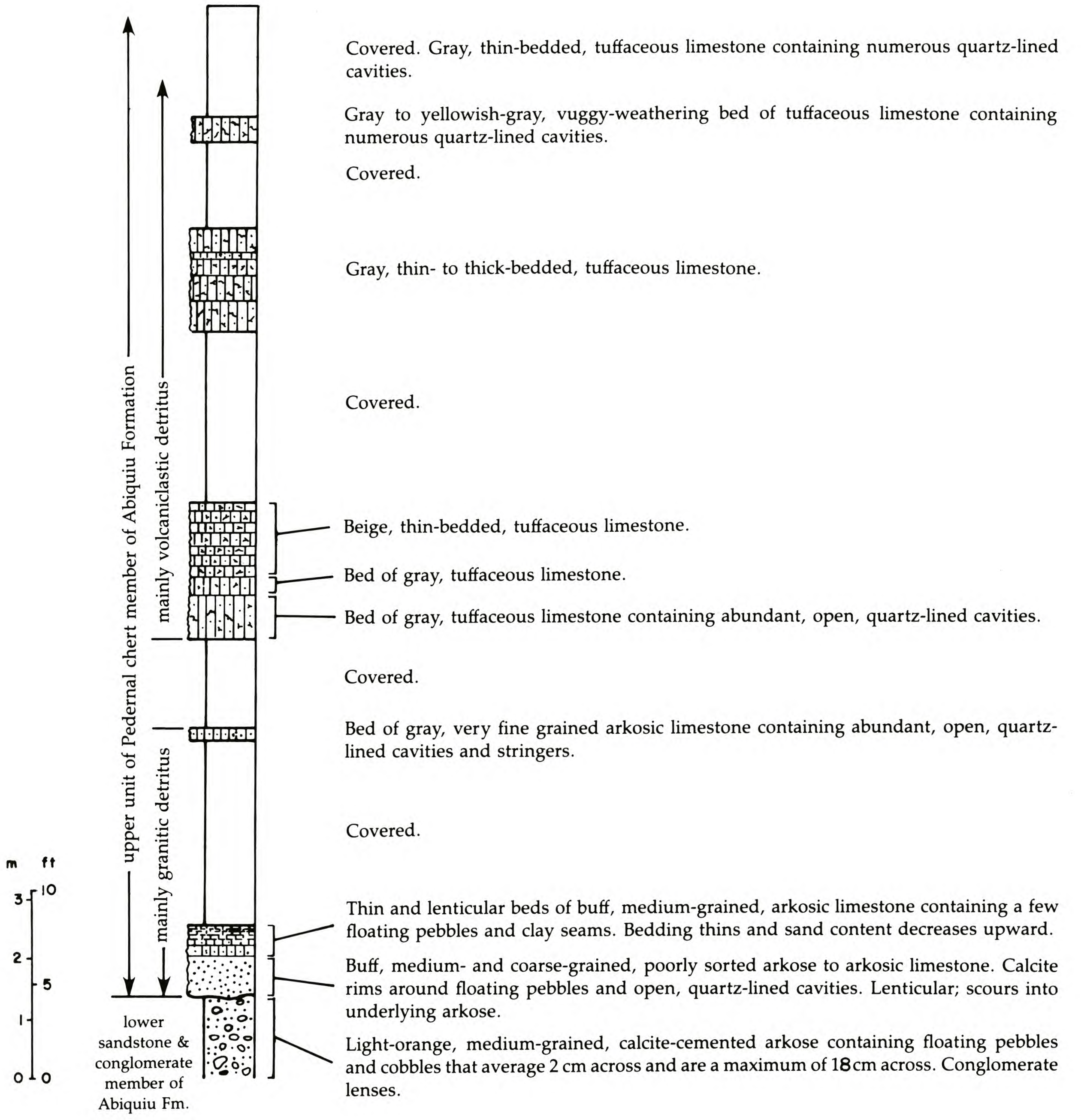


FIGURE 16—Measured section of upper unit of Pedernal chert member of Abiquiu Formation at the southwest end of Mining Mountain, Jarosa $7^1/_2$-min quadrangle (modified from Timmer, 1976).

the underlying lower chert unit. Complete exposures of this upper unit are rare; however, small exposures occur in a meadow adjacent to Cerro Jarocito Peak where this unit consists of gray-weathering, intercalated, erosional and air-fall volcaniclastics, limestone, and thin-bedded chert. At VARM Brown the upper part of the Pedernal chert is similar in thickness and lithology to that at Cerro Jarocito, but at VARM Brown this unit is overlain by white and tan chert almost identical to that in the underlying lower part of the Pedernal chert.

The Abiquiu Formation was assigned a Miocene age by H. T. U. Smith (1938) because of lithologic similarity to the Conejos Tuff in northern New Mexico and southern Colorado. Most workers have considered the Abiquiu to be Oligocene—Miocene based on regional correlations (Vazzana, 1980), but palynological evidence has been presented by DuChene and others (1981) suggesting that the unit is Miocene. The Abiquiu appears to be correlative with the Zia Sand at the south end of the Sierra Nacimiento. In the eastern part of the Jarosa quadrangle, the Abiquiu Formation is unconformably overlain by Bandelier Tuff.

Vazzana (1980) interpreted the basal arkosic to conglomeratic member to be a broad alluvial fan derived from the Brazos and Sangre de Cristo highlands to the northeast. The Pedernal chert member is interpreted to have been formed by silicification of carbonate horizons in soil profiles that developed during times of reduction in the rate of sedimentation.

Zia Sand

The Zia Sand was named and described by Galusha (1966) for exposures in the east fork of Cañada Piedra Parada, approximately 3 mi south of the San Ysidro quadrangle. The Zia Sand had been mapped previously as Santa Fe Formation by Renick (1931) and as the lower gray member of the Santa Fe Formation by Bryan and McCann (1937). Galusha (1966), however, recommended that the Zia (equivalent to lower gray member) be removed from the Santa Fe and be considered a separate formation inasmuch as the Zia is lithologically different from the Santa Fe Formation in the type area near the city of Santa Fe.

The Zia Sand is present in the San Ysidro and Gilman quadrangles east of the western boundary fault of the Rio Grande rift. This formation is composed of light-gray, medium- to coarse-grained, feldspathic sand and sandstone. A few siltstone and fine-grained sandstone interbeds are present. Locally, near faults, the beds are strongly cemented by calcite, but mostly the unit is very friable.

This unit rests unconformably on Eocene strata in the type area (Galusha, 1966), but, in the area of this report, the only exposures of the base of the formation have Zia resting on Permian strata. In the type area the Zia is overlain unconformably by the Santa Fe Formation and is approximately 1,000 ft thick (Galusha, 1966), but a complete section is not present in the area of this report, and, therefore, the stratigraphic thickness is not known. In this area the Zia Sand may range up to approximately 1,000 ft thick.

On the basis of distinctions in fossil vertebrate remains, Galusha (1966) recognized two membérs of the Zia Sand. In ascending order, they are the Piedra Parada and Chamisa Mesa Members. In the area of this report, the Zia was mapped as one unit, because the members described by Galusha (1966) are not lithologically different. The Zia Sand is of early and middle Miocene age, Arikareean and Hemingfordian (Galusha, 1966) .

DuChene and others (1981) have shown that the Abiquiu Formation of the type area, volcaniclastic rocks of this report, and the Zia Sand of the type area are of the same age. These units probably represent different facies of a depositional sequence that was once laterally continuous (Stearns, 1954) but has been disrupted by post-Miocene tectonism and erosion. A general southward decrease in grain size and orientations of primary sedimentary structures in the Abiquiu may indicate that the Abiquiu—Zia was derived from the north (Vazzana, 1980).

Volcaniclastic rocks

Unnamed volcaniclastic rocks that are of the same age as the Abiquiu Formation and Zia Sand (DuChene and others, 1981) are present in the northeast quarter of the Gilman quadrangle. These volcaniclastic rocks rest with angular unconformity on Permian strata and are unconformably overlain by Tertiary—Quaternary terrace and pediment deposits.

The volcaniclastic rocks comprise a cliff-forming, light-tan to beige unit. The lower part of this unit is conglomeratic, containing well-rounded volcanic cobbles up to 10 inches across. The unit becomes finer grained upward with sand- to silt-sized particles in the upper beds. Bedding ranges from 2 ft in the lower part of the unit to 2 inches toward the top of the unit.

A sample taken from the top of the lower conglomeratic portion of the unit consists of very fine grained, brown, carbonate matrix with rounded, floating grains of quartz, feldspar, chert, augite, opaque minerals, and rock fragments. DuChene (1973) reported the following composition for a thin section of the sample:

matrix	63%
rock fragments	16%
andesitic	15%
granitic	1%
quartz	16%
single crystals	6%
aggregates	10%
microcline	1 %
plagioclase	1%
chert	1%
augite	1%
opaque minerals	trace

Andesite rock fragments are well rounded, composed of mostly euhedral plagioclase with minor amounts of augite and opaque minerals, and range from 0.5 mm to 5.0 mm in diameter. Rock fragments consisting of quartz aggregates with minor amounts of microcline and plagioclase resemble similar aggregates in the Precambrian granite and gneiss exposed in the core of the Nacimiento uplift. These rock fragments are subrounded and are up to 5.0 mm in diameter. Quartz occurs as single, well-rounded grains and as moderately rounded aggregates of anhedral crystals. The single quartz grains are generally less than 0.5 mm in diameter. The crystal aggregates, which are up to 6.0 mm in diameter, consist of anhedral grains with sutured borders and undulatory extinction. Microcline occurs in subrounded to angular grains that range from 0.5 mm to more than 6.0 mm in diameter; larger grains are poikilitic with inclusions of plagioclase and minor quartz, similar to phenocrysts and porphyroblasts in nearby Precambrian rocks. Plagioclase occurs in subrounded, sericitized, and saussuritized grains up to 2.0 mm across. Chert occurs in well-rounded grains up to 4.0 mm across. Magnetite is commonly associated with the andesitic rock fragments.

This volcaniclastic unit is 350-450 ft thick. It was mapped as Abiquiu Tuff by R. L. Smith and others (1970), but, because it is somewhat different from the Abiquiu, I preferred not to assign it to that formation. The volcaniclastic rocks contain pollen of Miocene age, as do the Abiquiu Formation and Zia Sand in their type areas.

DuChene (1973) interpreted the volcaniclastic rocks of this unit to be water lain and to be derived from both granitic and andesitic source areas. He also noted the absence of relict structures, minerals, or rock fragments that might indicate an airborne or water-lain tuff origin. These beds may be lacustrine.

Paliza Canyon Formation

Bailey and others (1969) named the Paliza Canyon Formation for basaltic, andesitic, and dacitic flows, tuffs, and breccias in Paliza Canyon in the southeast part of the Jemez Springs 15-min quadrangle. They assigned the formation to the Keres Group of volcanic rocks, which forms the southern part of the Jemez Mountains.

The Paliza Canyon Formation is exposed along the cliffs east of Rio Guadalupe in the San Miguel Mountain quadrangle on the east side of the Sierra Nacimiento, where it rests unconformably on the Abo Formation and is unconformably overlain by the Bandelier Tuff. In Cebollita Canyon the Paliza Canyon Formation consists of 10-15 ft of coarse boulder conglomerate composed of basalt and basaltic-andesite boulders in a gray, fine-grained matrix. This layer is overlain by 20-30 ft of dark brownish-gray andesite (DuChene, 1973). The conglomerate beds erode readily and form slopes, whereas the more competent andesite beds above form dark cliffs beneath the lighter-colored Bandelier Tuff.

The basaltic andesite from the lower part of the formation consists of 5% pyroxene, 20% plagioclase (An_{50}), and traces of opaque minerals in a groundmass of glass and microlites. The pyroxene includes diopsidic augite and orthopyroxene in euhedra up to 0.5 mm long. The plagioclase is oscillatorily zoned and averages 0.2 mm in length, although a few grains up to 3.0 mm are present.

A thin section of the Paliza Canyon andesite was examined by DuChene (1973) and was found to have the following modal composition:

plagioclase (An_{39})	32%
sanidine	1%
augite	1%
hypersthene	1%
opaque minerals	1%
glassy matrix	65%

Plagioclase (An_{39}) crystals occur singly or in aggregates of corroded euhedra. Single grains range from 0.1 to 4.0 mm in length. Aggregates are up to 6.0 mm across and commonly include augite, hypersthene, and opaque minerals. Sanidine occurs as anhedral grains floating in matrix and ranges from 0.1 to 1.0 mm in diameter. Augite forms subhedral grains up to 0.5 mm in diameter, may have ragged edges, and is included in aggregates of plagioclase. Opaque minerals, probably magnetite, are metallic black. They are less than 0.1 mm across and are partly altered to limonite or hematite.

The Paliza Canyon Formation is of Miocene age (Smith, R. L., and others, 1970). Radiometric ages on this unit to the east of the area of this report range from 8.45 ± 0.38 my. to 9.5 ± 2.9 m. y. (Luedke and Smith, 1978).

Tertiary-Quaternary

Deposits of Tertiary and(or) Quaternary age include travertine, terrace and pediment deposits, gravel, lag deposits, and alluvium.

Travertine—Light-tan, thin- to thick-bedded travertine occurs in the Gilman, Holy Ghost Spring, and San Ysidro quadrangles. These deposits locally overlie or are overlain gradationally by terrace and pediment gravels; therefore, the travertine is locally conglomeratic with pebbles and cobbles mainly composed of Precambrian lithologies. Elsewhere, the travertine rests unconformably on rocks ranging in age from Permian to Tertiary. Locally, the travertine is as much as 50 ft thick, but mostly it is 20-30 ft thick.

The travertine was deposited by hot springs, some of which are still depositing travertine. These deposits define a potential geothermal resource area at the south end of the Sierra Nacimiento.

Terrace and pediment deposits—Terrace and pediment deposits are present along the flanks and base of the Sierra Nacimiento but are particularly abundant in the Cuba and Regina quadrangles. These deposits are composed of mostly Precambrian pebbles, cobbles, and boulders, although, locally, they are made up of coarse clasts of Paleozoic or Mesozoic lithologies. Rarely, they may be composed of sand-size fragments. The deposits are usually less than 30 ft thick but, locally, may attain a thickness of approximately 50 ft as they do in the Cuba quadrangle.

These deposits rest unconformably on Precambrian to Tertiary rocks and, in a few places, grade into underlying travertine. The terrace and pediment deposits are of fluvial origin and were deposited on a widespread pediment along the western foot of the Sierra Nacimiento and on terraces of more local extent.

Gravel—Gravel of stream or perhaps terrace and pediment origin occurs locally beneath the Bandelier Tuff (Quaternary) in the Rancho del Chaparral and San Miguel Mountain quadrangles. This gravel is composed mainly of boulders of Precambrian lithologies and is up to 30 ft thick. It rests unconformably on Permian strata. These deposits may be correlative, in part, with the terrace and pediment deposits described above.

Lag deposits—Lag deposits that have been let down by erosion of nonresistant underlying beds are found in the San Pablo and Rancho del Chaparral quadrangles. They consist of large blocks of Agua Zarca Sandstone up to 15 ft in diameter. These deposits range from scattered blocks resting on Permian strata to masses of jumbled blocks forming a unit up to 40 ft thick. Some of the blocks may have moved downslope as gravity-slide blocks.

Older alluvium—Older alluvium, at distinctly higher levels than Quaternary alluvium, is found at the heads of and along the sides of a few valleys in the Regina quadrangle and is found as old alluvial fans in the Gallina quadrangle. These fans are composed of pebble- to boulder-size gravel with clasts mainly of Madera Limestone. The fans appear to be too large for the present streams to have deposited and, therefore, are thought to have been deposited at a time when runoff was greater. The valley deposits in the Regina quadrangle are composed of clay, silt, and sand and have a maximum thickness of approximately 100 ft.

Quaternary

The only bedrock unit of Quaternary age in the Sierra Nacimiento region is the Bandelier Tuff. Younger surficial deposits include landslides, talus, sand dunes, and alluvium.

Bandelier Tuff

The Bandelier Rhyolite Tuff was named by H. T. U. Smith (1938) for exposures in the Abiquiu quadrangle, New Mexico. Griggs (1964), who studied the unit near the Los Alamos area, shortened the name to Bandelier Tuff and divided the formation into three members. Bailey and others (1969) assigned the Bandelier to the Tewa Group of felsic extrusive rocks derived from the Valles and Toledo calderas in the Jerez Mountains and divided it into the lower Otowi Member and the upper Tshirege Member based on mineralogy and lithic inclusions. Doell and others (1968), using paleomagnetic and potassium–argon methods, obtained approximate ages of 1.4 m.y. for the Otowi Member and 1.0 m.y. for the Tshirege Member. No attempt to distinguish the members was made in this study.

The Bandelier Tuff is exposed along the eastern side of the Sierra Nacimiento and is composed of non-welded to densely welded ash flows commonly containing bipyramidal quartz and chatoyant sanidine phenocrysts. Inclusions of hornblende-rich quartz-latite pumice and lithic fragments are sparse to abundant. Fresh surfaces of the tuff are light gray and light tan to whitish, and weathered surfaces range from white to beige or pale orange tan.

The Bandelier Tuff is up to 650 ft thick; it was extruded onto a surface of considerable relief, and, therefore, the thickness of the unit changes rapidly over short distances. The Bandelier Tuff lies unconformably on rocks ranging from the Madera Formation (Pennsylvanian) to the Paliza Canyon Formation (Pliocene).

Surficial deposits

Landslide deposits–Landslide deposits are found mainly along the flanks of the Sierra Nacimiento where stratified rocks of contrasting competences occur. The landslide deposits usually are seen where strong rocks are topographically higher than strata that are nonresistant and easily undercut. Gravitational sliding of the stronger, topographically higher rocks resulted. Units commonly involved in landslides include the Madera Formation (Pennsylvanian), the Entrada, Todilto, and Morrison Formations (Jurassic), the Dakota and Mesaverde rocks (Cretaceous), and the Bandelier Tuff (Quaternary). The landslide deposits are mostly small and rarely exceed 100 ft in thickness, most being less than 50 ft thick.

Talus–Most talus deposits in the area are found where Precambrian crystalline rocks are present. Many of the deposits are small and were not mapped, except where a bedrock contact is covered by the talus. Angular fragments up to boulder size make up the talus. The thickness of these deposits is generally less than 30 ft.

Sand dunes—Elongate dunes are present along the valley of Rio Salado in the San Ysidro quadrangle. These deposits consist of wind-blown sand, which is mostly fine grained. These dunes are mostly stabilized by a partial cover of vegetation and are estimated to be up to 10 ft high. The dunes are parallel to the trend of the valley and appear to have been formed of sand from the dry bed and banks of the Rio Salado by winds blowing toward the east.

Alluvium–Alluvial clay, silt, sand, and gravel is found along valleys in nearly all parts of the area. Maximum thickness is estimated to be 30 ft. Locally, minor colluvium has been included in the unit mapped as alluvium.

Paleotectonic setting

From Cambrian through Devonian time the Sierra Nacimiento region was relatively stable because of its location on the south flank of the Transcontinental arch, a mildly positive feature. No lower Paleozoic stratified rocks are in this region. The presence of intrusive syenite of possible Ordovician or Cambrian age suggests minor accompanying tectonism; the absence of lower Paleozoic strata, however, makes a precise tectonic determination difficult. The Mississippian was a time of quiescence and a thin sequence of shelf carbonates accumulated (Armstrong, 1967). Late Mississippian and Early Pennsylvanian uplift resulted in erosion of most of the Mississippian strata. During Pennsylvanian time the approximate sites of the Brazos and Nacimiento uplifts were positive areas shedding clastic debris into adjacent areas. These positive tendencies continued into Permian time.

Mesozoic strata were deposited throughout the region except in the Brazos area, which underwent several episodes of uplift (Muehlberger, 1967). Epeirogenic uplift resulted in regional unconformities between the Permian and Triassic, between the Triassic and Jurassic, and between the Jurassic and Cretaceous strata.

Structural development of the present-day Brazos and Nacimiento uplifts was initiated during the Lar-amide (Late Cretaceous–early Tertiary); further uplift of these areas occurred during the late Tertiary. Thus, the present tectonic features shown on the geologic map (in back pocket) are principally of Cenozoic age.

Regional tectonic setting

The Nacimiento uplift is located within the Rocky Mountain foreland tectonic province. The uplift is bounded on the west by the San Juan Basin, on the north by the Gallina—Archuleta arch, on the northeast by the Chama Basin, on the east by the Jerez volcanic field, and on the southeast by the Rio Grande rift (Fig. 2; map in back pocket) .

The Nacimiento uplift marks the southwest limit of the Rocky Mountains. The structure of the Nacimiento uplift is similar to that of many other basement-cored Rocky Mountain uplifts. The San Juan Basin, however, is part of the Colorado Plateau, a region that has been deformed much less than the Rocky Mountains. The Chama Basin is separated from the main part of the San Juan Basin by the structurally low Gallina—Archuleta arch; the Chama Basin has been considered to be an extension of the San Juan Basin. The structural outlines of the Nacimiento uplift, the San Juan Basin, and the Chama Basin were established during Laramide (Late Cretaceous—early Tertiary) deformation.

The Rio Grande rift and the associated Jerez volcanic field are late Cenozoic elements superimposed on the Laramide features. Some of the Laramide structures may have been rejuvenated during the late Cenozoic deformation; Slack and Campbell (1976) demonstrated such rejuvenation in the Rio Puerco fault zone immediately south of the Nacimiento area. Rejuvenation seems likely in the Sierra Nacimiento as well.

Preorogenic rocks range in age from Precambrian to Late Cretaceous. The Tertiary rocks of the San Juan Basin are synorogenic with respect to Laramide deformation. The crystalline, Precambrian basement rocks are brittle and tend to deform by fracturing; overlying sedimentary strata are more flexible, and the thick sequence of Mesozoic shale tends to behave plastically.

Late Cenozoic sediments (Zia Sand) and volcanic rocks that fill the Rio Grande depression are contemporaneous with rifting. Rocks of Precambrian to mid-Cenozoic age have fractured under the tensional stress field associated with rifting.

Structure

Each major tectonic element within the area covered by this report (Fig. 2; map in back pocket) is described separately, with the Laramide elements discussed first. Fig. 17 shows the structures under discussion; the reader who is interested in precise locations and the details of the geology is referred to the appropriate geologic quadrangle maps published by the New Mexico Bureau of Mines and Mineral Resources (Fig. 2, p. 8).

Nacimiento uplift

The Nacimiento uplift trends north and is approximately 50 mi long and 6-10 mi wide. In general, it consists of an uplifted block that is tilted eastward and is bounded on the west by faults. At least 10,000 ft of structural relief exist between the highest part of the uplift and the adjacent San Juan Basin.

An anticlinal bend occurs locally along the west margin of the uplift, east of the range-marginal faults. The Nacimiento fault, an upthrust that is steep at depth but flattens upward and has westward movement of the hanging-wall block over the San Juan Basin (Woodward, Kaufman, and Anderson, 1972), bounds the northern part of the uplift. Farther south, the Pajarito reverse fault dips steeply to the east and bounds the west side of the uplift.

The northern end of the uplift is a broad, faulted anticline that plunges 10°-20° northward and merges with the Gallina—Archuleta arch. The southern end of the uplift terminates in folds that plunge to the south beneath an unconf ormable cover of Tertiary rocks (Slack, 1973) .

Eastward-dipping Paleozoic rocks on the east side of the uplift are covered unconformably by extrusive rocks of the Jerez volcanic field. The southeast boundary of the uplift with the Rio Grande rift is defined by high-angle normal faults that are down-thrown to the east. The northeast part of the uplift merges with the Chama Basin through a broad slope dipping gently to the northeast.

Structures within the uplift include north-trending normal faults that bound second-order, tilted fault blocks at the north end of the uplift and a graben in the southern part of the uplift. High-angle faults trending east—west, northwest, and northeast also occur; these faults separate differentially uplifted segments within the Nacimiento uplift. A few northwest-trending folds are seen near the south end of the uplift (Ruetschilling, 1973) . Folds with similar trends may have been present elsewhere in the uplift, but stripping of sedimentary strata from most of the uplift would have removed evidence of them.

The western margin of the Nacimiento uplift is not bounded by one continuous fault as was supposed by Renick (1931) and Wood and Northrop (1946); rather, the northern and southern segments of the uplift are bounded on the west by faults that do not connect with each other (Fig. 17). The faults are here called the Nacimiento and Pajarito faults. The gap between

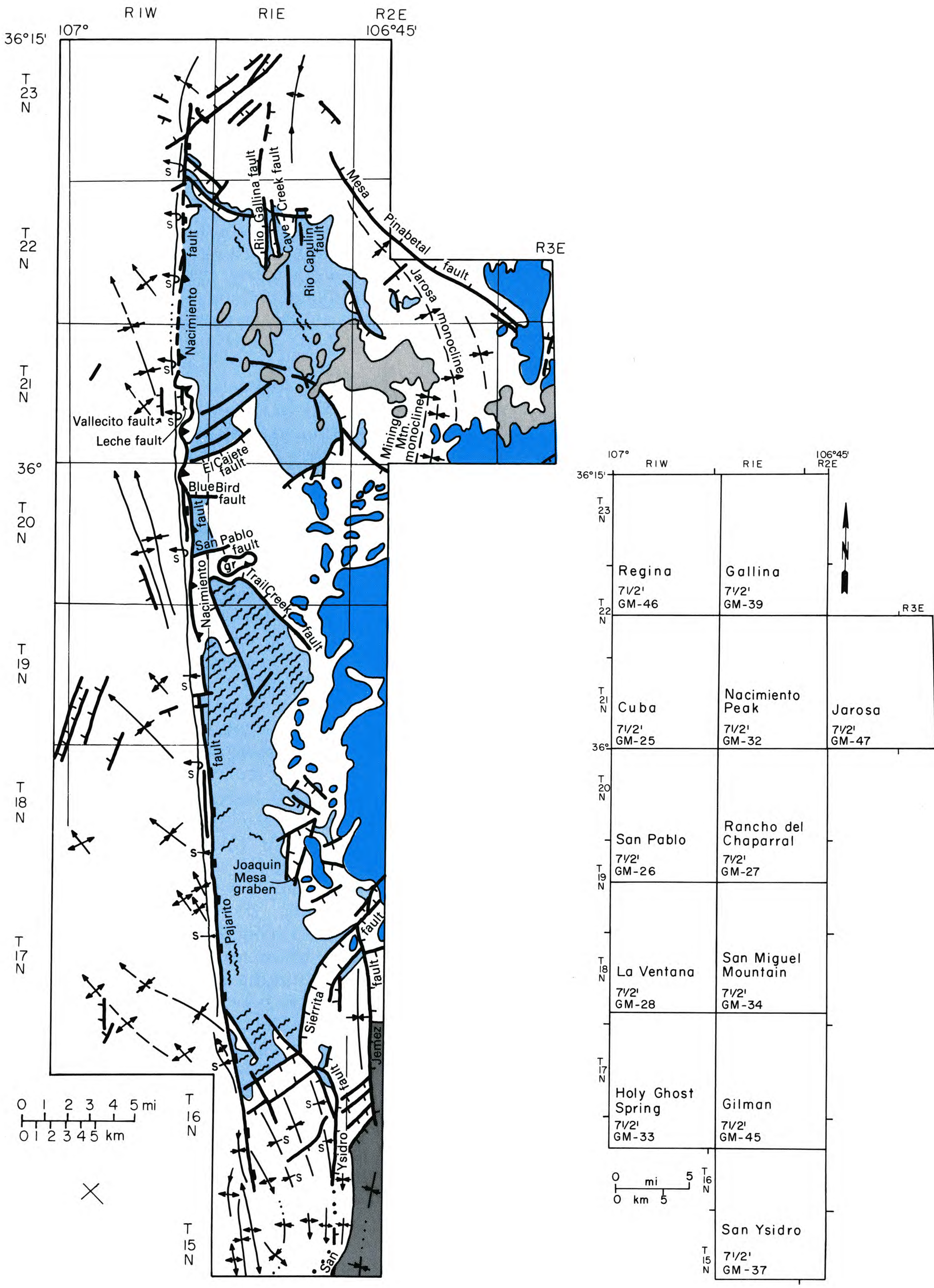


FIGURE 17—Tectonic map of Nacimiento uplift and adjacent areas.

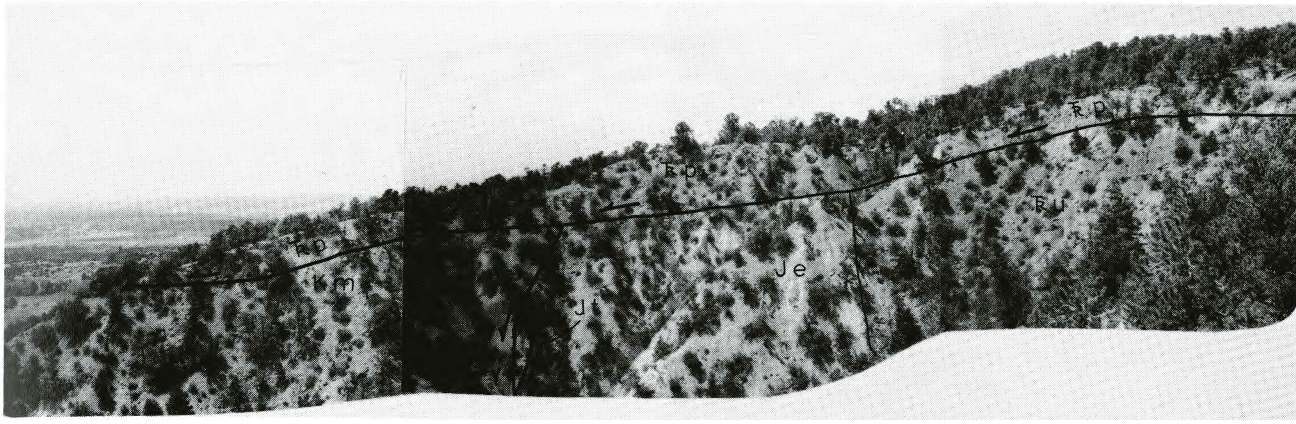
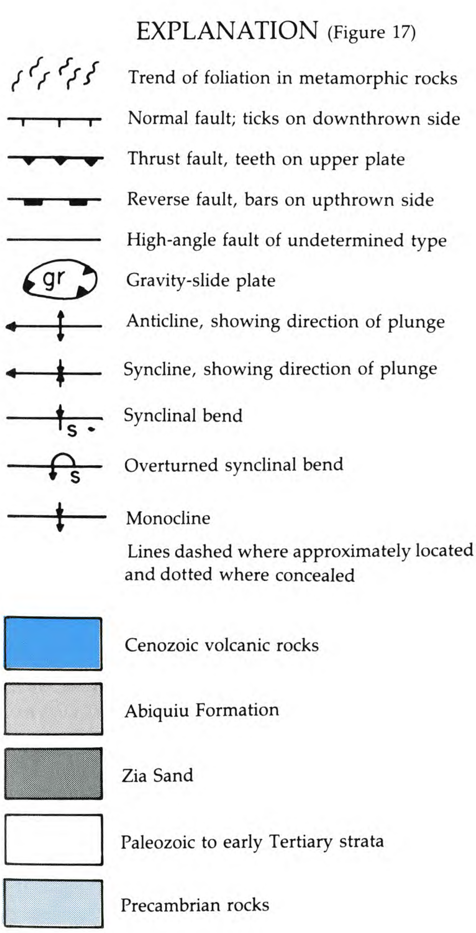


FIGURE 18—View north of flat-lying Nacimiento fault approximately 0.5 mi east of Vallecito del Rio Puerco. Steeply dipping Leche fault truncated by Nacimiento fault. Poleo Sandstone Member (Triassic) on vertical Triassic, Jurassic, and Cretaceous beds. Rock units are: **TRp** = Poleo Sandstone Lentil of Chinle Formation, **TRu** = upper shale member of Chinle Formation, **Je** = Entrada Sandstone, **Jt** = Todilto Formation, and **Km** = Mancos Shale.

these faults occurs near San Miguel Canyon (Fig. 17).

In addition to the Nacimiento and Pajarito faults are the following: 1) synthetic reverse faults adjacent ti the major faults, 2) east-trending faults that segment the uplift, 3) antithetic reverse faults that have movement in opposition to the general uplift, 4) normal faults that are older than the Nacimiento fault, 5) normal faults that are the same age as the Nacimiento fault, and 6) the Trail Creek fault that bounds a separate basement uplift.



Nacimiento fault

The Nacimiento fault extends northward from San Miguel Canyon to beyond the northern end of Sierra Nacimiento (north of Fig. 17) and appears to connect with the Gallina fault (Baltz, 1967). At deep stratigraphic and structural levels the Nacimiento fault is steep, but it flattens upward. The fault tends to be steep in areas of little stratigraphic separation but dips more gently where greater displacement is seen. Possibly, late Cenozoic gravitational gliding has occurred at some of the localities where the fault is flat lying, especially near San Miguel Canyon.

Erosion has removed the flat-lying or gently dipping part of the fault at most localities; however, three nearly horizontal segments of the fault are still preserved. One location is approximately 0.5 mi east of Vallecito del Rio Puerco (Figs. 18, 19); another is preserved south of Rito Leche; a third occurs immediately north of San Miguel Canyon. At each of these places the youngest rocks in the upthrown block are preserved. The area near Vallecito del Rio Puerco should be considered the type locality of the Nacimiento fault.

The transition from steep dip to a gentle dip can

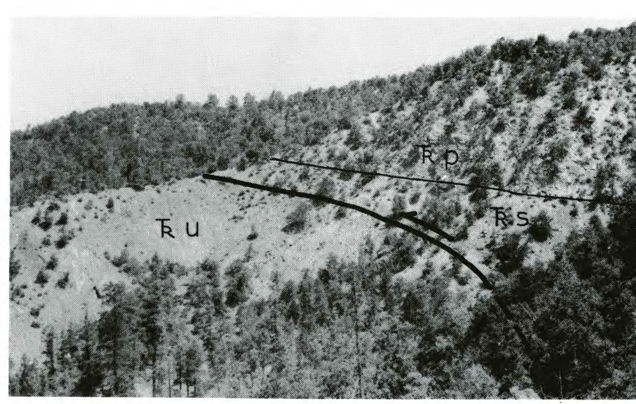


FIGURE 19—View northeast of Nacimiento fault 200 yds southeast of easternmost exposure of Fig. 18. Fault changes from flat lying on west to steeply dipping on the east. Members of the Chinle Formation are: **TRs** = Salitral Shale Tongue, **TRp** = Poleo Sandstone Lentil, and **TR u** = upper shale member (from Woodward, Kaufman, and Anderson, 1972).

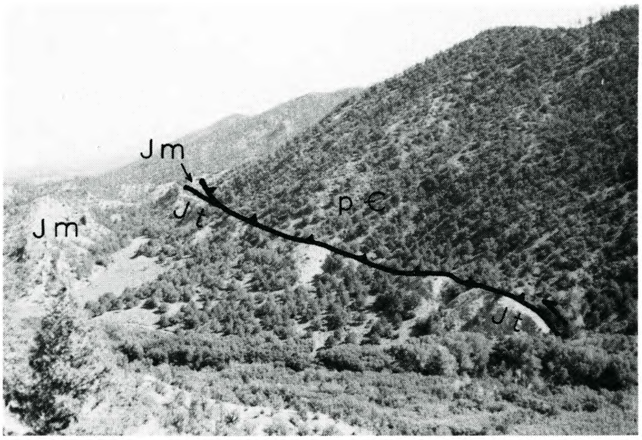


FIGURE 20—View north of Nacimiento fault across San Pablo Canyon. Fault dips approximately 60° E. and has Precambrian quartz monzonite on Todilto Formation (Jurassic). Wedge of Morrison Formation (Jurassic) along fault in middle foreground (from Woodward, Kaufman, and Anderson, 1972).

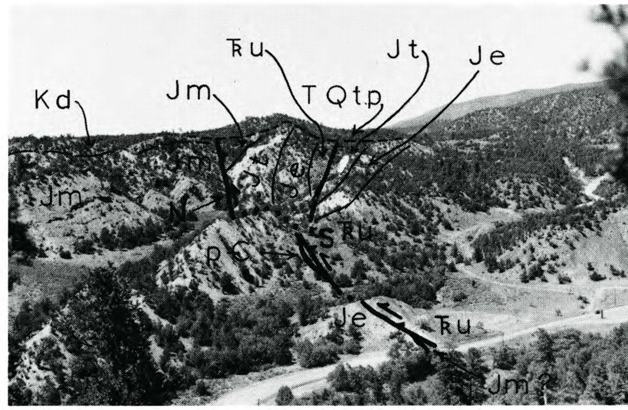


FIGURE 21—View north across Señorito Creek showing trace of Nacimiento (N) and Señorito (S) faults. Dip of Nacimiento fault ranges from nearly vertical at the roadcut to approximately 60° E. at north end of view. Rock units are: **p€** = Precambrian rocks, **T̄Ru** = upper shale member of Chinle Formation, **Je** = Entrada Sandstone, **Jt** = Todilto Formation, Jr = Morrison Formation, **Kd** = Dakota Formation, and **TQtp** = terrace and pediment deposits.

be seen approximately 0.25 mi south of the Rio Puerco and also approximately 0.25 mi north of Rito Leche.

At intermediate levels the fault dips approximately 45°, as can be seen immediately north of Nacimiento Creek. On the north side of San Pablo Canyon the fault dips approximately 60° and has Precambrian crystalline rocks in contact with Jurassic rocks (Fig. 20). A wedge of Morrison Formation (Jurassic) is present between the Precambrian and the Todilto Formation (Jurassic) . Small slices of Cretaceous rocks also are present in the fault zone at this locality. This presents a problem in the kinetics of faulting, because rocks younger than either the hanging wall or foot-wall are in the fault zone. This problem is discussed in the analysis of faulting (p. 61) .

Along Señorito Creek the fault is essentially vertical and has Triassic rocks in contact with Jurassic rocks (Fig. 21) . A small slice of strongly sheared Precambrian crystalline rock approximately 3 ft thick and 20 ft long is present in the fault zone approximately 0.25 mi north of Señorito Creek. This slice's emplacement is difficult to explain because it is older than the strata that tectonically bound it. The possibility of right-lateral strike-slip movement bringing this slice in from the large Precambrian outcrop area that is east of the Nacimiento fault and approximately 0.25 mi to the south seems unlikely. The strike-slip movement appears to have occurred before rise of the uplift brought the Precambrian crystalline rock into juxtaposition with the Mesozoic strata.

The Nacimiento fault trace curves slightly eastward at its southern termination. At the northern end of the uplift the fault trace also curves eastward, continues in a north-northeastward direction for at least 6 mi, and connects with the Gallina fault (Baltz, 1967).

Stratigraphic separation on the fault ranges from a maximum of 4,000 ft near Vallecito del Rio Puerco to approximately 100 ft near Señorito Creek. Maximum observed horizontal movement is 2,500 ft near Valle-cito del Rio Puerco. At this point, prior to erosion, the hanging-wall block may have extended even farther to the west.

The overturned eastern limb of the synclinal bend west of the Nacimiento fault dips as gently as 45° E. East of the fault the beds are not overturned and commonly dip 5°-15° W. but, locally, may be steeper.

Pajarito fault

The Pajarito fault is poorly exposed at most places, but, where it can be seen, it is a reverse to vertical fault dipping steeply (75°-90°) to the east. Its straight trace across varied topography also indicates that it is steep. The Pajarito fault extends 25 mi to the south, where its termination marks the southern end of the Nacimiento uplift.

The fault surface ranges from a knife edge to a 50ft-wide zone composed of sheared Precambrian rock stained with hematite. Maximum stratigraphic separation along the fault is approximately 3,600 ft. but the structural relief between the uplift and the San Juan Basin is at least 7,300 ft because of the synclinal bend west of the Pajarito fault.

Synthetic reverse faults

Because of inconsistency in usage of the term "synthetic fault," this paper follows the usage of Lowell (1970). The synthetic reverse faults described here have the same attitudes as the Nacimiento fault and have tended to increase the structural relief between the Nacimiento uplift and the San Juan Basin.

Between the Blue Bird and San Pablo faults (Fig. 17) are several synthetic reverse faults in a 0.25-miwide zone on the west side of the Nacimiento fault. These reverse faults trend north, dip steeply east, and have up to a few hundred feet of stratigraphic separation. Although slip cannot be determined precisely, I believe most of the movement was probably dip slip of no more than 1,000 ft, because these faults die out along strike and rarely can be traced for more than 1 mi.

In La Ventana quadrangle as many as three faults are synthetic with respect to the Pajarito fault. Moverent along these faults was probably dip slip, for the most part, with stratigraphic separation ranging from less than 100 ft to approximately 2,000 ft, depending, to a large extent, on orientation of bedding with respect to the fault surface. These faults are confined mainly to the mudstones of the Abo, Madera, and Chinle Formations and commonly are recognized only by the fact that bedding east of the fault may be overturned while bedding west of the fault is right-side up. Most of these faults die out along strike or are terminated by transverse faults.

Eastward-trending faults

The western part of the Nacimiento uplift is cut by the El Cajete, Blue Bird, and San Pablo faults, along which the various segments of the uplift have undergone different amounts of vertical movement. These vertical faults die out eastward and, thus, have maximum stratigraphic separation near their western ends. The amount of vertical movement is difficult to determine, because the datum used, the top of the Precambrian, was a surface of considerable relief at the time of deposition of the overlying Permian rocks. Estimated vertical movement at the west end of each fault is 800 ft on the El Cajete, 1,320 ft on the Blue Bird, and 1,420 ft on the San Pablo. The Blue Bird and San Pablo faults end against the Nacimiento fault, but the El Cajete may offset the Nacimiento fault.

Five, short, east-trending, vertical transverse faults offset the Pajarito fault in La Ventana quadrangle, and three offset the Nacimiento fault in the Regina quadrangle. Movement is predominantly rotational along these faults with displacement decreasing to the east. The lateral separation varies from fault to fault. Many of these faults are only a few tens of feet long, with separation amounting to only a few feet. The larger faults are from 500 ft to 2,000 ft long with strike separations up to 900 ft. These larger faults die out in shales at their west ends. Some of them extend into and die out in the Precambrian rocks at their east ends. Generally, little evidence has been found to suggest that these faults extend far into the Precambrian rocks to the east, except in those few instances where canyons developed in Precambrian rocks along strike of the faults. These faults apparently formed contemporaneously with the rise of the Nacimiento uplift and are the result of differential upward movement of basement blocks.

Trail Creek fault

The Trail Creek fault curves around the west and northeast sides of a block of Precambrian rock (Fig. 17) . It appears to be nearly vertical or possibly a steeply dipping normal fault. Vertical separation on this fault is at least 3, 000 ft on the west side of the uplifted block. The fault dies out as it is traced southeastward along the northeast side of the uplifted block.

Antithetic reverse faults

The term "antithetic" is used here for faults that have moved in opposition to the general uplift (King, P. B., 1948; Lowell, 1970). Therefore, the antithetic reverse faults described here dip steeply to the west. The two principal types are those faults that occur in the hanging-wall block of the Nacimiento fault and those faults that occur in the footwall or on the San Juan Basin side of the Nacimiento fault.

The Señorito reverse fault in the northeast part of the San Pablo quadrangle dips steeply to the west. It is restricted to the hanging-wall block of the Nacimiento fault and merges with the latter along strike. The Señorito fault has approximately 300 ft of stratigraphic separation, displacing the upper shale member of the Chinle Formation against the Todilto Formation. The slip is probably much greater than the stratigraphic separation because the beds dip very steeply. This fault appears to be a conjugate shear surface related to the Nacimiento fault.

A west-dipping antithetic reverse fault that occurs west of the Pajarito fault (Fig. 22) has approximately 150 ft of stratigraphic separation. Apparently, this fault is related to the development of the Pajarito fault, because both end at the same latitude, and this fault is interpreted as having formed by compression in the synclinal bend to the west of the Nacimiento uplift.

Normal faults

Normal faults occur in both the hanging-wall and footwall blocks of the Nacimiento fault, and all are subordinate in terms of stratigraphic separation. Of the two sets of normal faults, one is older than the Nacimiento fault and is related to early development of the uplift, and the other is essentially contemporaneous with the movement on the Nacimiento fault.

Many of the normal faults in the hanging-wall block of the Nacimiento fault appear to have moved nearly contemporaneously with the latter. North-trending normal faults north of San Miguel Canyon have created small fault blocks that are restricted to the hanging-wall block of the Nacimiento fault where it is nearly horizontal. These small faults have up to 100 ft of stratigraphic separation and appear to be tensional features formed by stretching of the hanging-wall block of the Nacimiento fault where it arches over the San

FIGURE 22—View north of antithetic, high-angle reverse fault west of Pajarito fault. Rock units are: **Py** = Yeso Formation and **TR**a = Agua Zarca Sandstone Member of the Chinle Formation (from Woodward, Kaufman, and Anderson, 1972).

Juan Basin to the west. They may be late Cenozoic gravity-slide blocks, although the exposures do not confirm this.

Joaquin Mesa graben in the San Miguel Mountain quadrangle is an elongate, north—northeast-trending block that is bounded on three sides by high-angle, normal faults (Fig. 17). The graben is 0.5-0.75 mi wide, 2 mi long, and is composed of rocks ranging in age from Pennsylvanian to Triassic. Structural relief between the graben and the adjacent crest of the Nacimiento uplift is estimated to be a minimum of 3,000 ft. The western fault has a curved trace, concave eastward, that is poorly exposed except in canyon bottoms. Along its northern reach this fault brings Pennsylvanian rocks into contact with Permian rocks of the graben. The southern part of the fault juxtaposes Precambrian rocks to the west and Pennsylvanian rocks to the east. Dips of rocks exposed near the fault zone range from 44° E. at a point southwest of Joaquin Mesa to vertical and slightly overturned (85° W.) at the northern end of the fault. Stratigraphic separation can only be estimated to be a minimum of 1,900 ft, because sedimentary units thin westward and exact thicknesses are unknown. To the north the fault is truncated against the normal fault bordering the north end of the graben. This northern border fault is downthrown to the south and has a trace that is poorly exposed but suggests it is a high-angle fault. This fault truncates the western boundary fault of the graben and is, in turn, truncated by the eastern marginal fault. Maximum stratigraphic separation is estimated to be 350 ft. The eastern side of the graben is bordered by a high-angle normal fault downthrown to the west. Stratigraphic separation east of the crest of Joaquin Mesa is approximately 175 ft, and displacement decreases southward. The fault appears to die out in Precambrian rocks near Deer Creek Canyon.

Three north-trending faults bound tilted blocks within the Nacimiento uplift in the southern part of the Gallina quadrangle (Fig. 17). Gibson (1975) referred to these faults from west to east as the Rio Gallina, Cave Creek, and Rio Capulin faults, respectively. The Rio Gallina fault has scissors motion with the point of rotation near the confluence of Rio Gallina and Cave Creek. South of the rotation point the fault plane dips to the west and the fault is normal with both hanging wall and footwall tilted eastward, although minor reverse drag is in the hanging wall. Maximum stratigraphic separation along this fault is 600 ft, but separation decreases to the south. North of the rotation point the fault is a west-dipping reverse fault with displacement of only a few tens of feet. Both displacement and degree of tilting of the hanging wall and footwall die out to the north. The Cave Creek fault is a steep, west-dipping normal fault with maximum displacement of approximately 600 ft. Rocks in the hanging wall, west of Cave Creek, dip 30°-50° to the east with the dip increasing toward the fault. Pennsylvanian strata east of Cave Creek are tilted to the northeast. The Rio Capulin fault also appears to be a west-dipping normal fault; maximum displacement is at least 400 ft.

In the southern part of the uplift, in the Gilman and San Ysidro quadrangles, are numerous northeast- and northwest-trending, high-angle faults that probably have normal separation. Maximum stratigraphic separation is approximately 1,000 ft on the larger of these faults; however, many of the faults have a few tens to a few hundreds of feet of stratigraphic separation.

Two northwest-trending, high-angle faults are present in the northwest part of the Nacimiento uplift in the Regina and Gallina quadrangles. These faults are antithetic with respect to the northward-plunging end of the Nacimiento uplift because they are down-thrown to the south. Maximum stratigraphic separation is approximately 400 ft. Wood and Northrop (1946) and Hutson (1958) mapped the San Pedro Mountain fault where these faults occur and described it as an east-trending, oblique-slip fault down-thrown to the north with 3,000-4,000 ft of displacement; I found no fault that fits their description.

Several other northwest-trending high-angle faults are in the Nacimiento Peak quadrangle; displacement is probably dip slip with only a few hundreds of feet of maximum separation. The two largest of these faults broadly define a graben trending northwest across the uplift.

Numerous other high-angle faults, having small amounts of stratigraphic separation and easterly, northwesterly, and northeasterly trends, occur in various parts of the uplift. They are observed readily where they offset stratified rocks, but they are obscure where present in Precambrian rocks, being marked generally by breccia or shear zones.

Folds

Where sedimentary strata are preserved high on the west side of the uplift, as in the northeast part of the San Pablo and Regina quadrangles, an anticlinal bend is seen. This bend is bounded on the west by the Nacimiento fault, and on the east it is truncated by erosion. The anticlinal bend trends north, paralleling the western margin of the uplift. Dips on the west limb of the bend near the Nacimiento fault are as steep as 60° W., and on the east limb strata dip gently to the west or, locally, may be nearly horizontal. The anticlinal bend adds several thousand feet to the structural relief between the Nacimiento uplift and the San Juan Basin. The synclinal bend that occurs west of the Nacimiento and Pajarito faults is described in the section on the San Juan Basin (p. 56) .

The south end of the Nacimiento uplift, in the San Ysidro quadrangle, is marked by several open, upright folds that plunge gently to the south. The uplift ends where these folds die out to the south. Amplitudes on these folds are a few hundred feet at the most.

The north end of the uplift is defined by a broad, open, anticlinal nose that plunges gently to the north toward a structural saddle that separates the Nacimiento uplift from the Gallina—Archuleta arch in the central part of the Gallina quadrangle.

A few northwest-trending, open, upright folds are truncated by the north-trending Pajarito fault on the west side of the uplift in the San Ysidro quadrangle. These folds have amplitudes of only a few hundred feet and are obscure where they abut the range-marginal Pajarito fault. The folds plunge to the southeast.

In the Jarosa quadrangle two arcuate monoclines and two broad, open synclines that have axial traces convex eastward are present. Timmer (1976) has referred to the westerly fold as the Mining Mountain monocline and the next easterly one as the Jarosa monocline. The following descriptions are modified from Timmer (1976) .

The Mining Mountain monocline is narrow and east facing. It is best exposed in the 1W$^{1}/_{4}$ sec. 22, T. 21 N., R. 2 E., where it has a width of less than 1,500 ft and a minimum structural relief of 300 ft. The Abiquiu Formation unconformably overlies the folded beds of the Abo Formation at Cerro Jarocito. North of Cerro Jarocito the trend of the monocline swings to the north—northwest, and, north of sec. 4, T. 21 N., R. 2 E., it cannot be distinguished as a separate structure. The monocline is poorly exposed to the south of sec.22 because of small gravity slides along the eastern slope. Dips along the monocline in the SW$^{1}/_{4}$ sec. 27 swing progressively southward up structure suggesting that the monocline plunges to the south.

The Jarosa monocline trends north—northwest and faces east. It is well exposed along the north side of Rio Puerco in sec. 33, T. 22 N., R. 2 E., where it is approximately 3, 000 ft wide and has at least 800 ft of structural relief. Dips reach a maximum of approximately 70° E . along the monocline. Structural relief appears to decrease southward along the monocline.

A gently east-dipping homocline, bounded on both ends by easterly trending faults, is located along the Jarosa monocline north of Rio Puerco. Structural relief across the monocline in this area is approximately 600 ft. Stratigraphic separation along the bounding faults near the western edge of the Jarosa quadrangle is at least 200 ft and appears to decrease to the east. Both of these faults are concealed beneath alluvium, but their presence is indicated by anomalous dips and juxtaposition of Madera and overlying Permian strata.

A broad, north—northwest-trending syncline is located along the eastern flank of the Jarosa monocline south of the Rio Puerco in the central part of the Jarosa quadrangle (Fig. 17) . This syncline is at least 10,000 ft wide and has a minimum of 200 ft of amplitude. The average dip of the limbs is approximately 7°, and the axial trace appears to plunge to the north. The western limb merges with the Jarosa monocline and the eastern limb probably is truncated by a fault.

A north-trending syncline lies along the eastern flank of the Mining Mountain monocline in sec. 27, T. 21 N., R. 2 E. in the southwest part of the Jarosa quadrangle. It is approximately 3,000 ft wide and has at least 100 ft of amplitude. It appears to plunge gently to the south.

San Juan Basin

Only the eastern part of the San Juan Basin is covered by geologic maps for this report (Fig. 17); however, in its entirety, it is nearly circular and approximately 100 mi in diameter. The basin is strongly asymmetrical with a steep northern limb and a gently dipping southern limb. The axial trace forms an arc that is convex northward and occurs near the northern edge of the basin; the axis is north and west of the area covered in this report.

The eastern boundary of the San Juan Basin is marked by a monocline along the west side of the Gallina—Archuleta arch and by range-marginal upthrust and reverse faults on the west side of the Nacimiento uplift. A sharp synclinal bend that locally is overturned occurs west of the upthrust and reverse faults. There is at least 10,000 ft of structural relief between the highest part of the Nacimiento uplift and the adjacent part of the San Juan Basin.

Several northwest-plunging, en echelon, open folds, as well as northeast- and north-trending, high-angle faults occur along the eastern margin of the San Juan Basin. Locally, small reverse faults that are antithetic with respect to the major Nacimiento fault are noted in the Dakota Formation in roadcuts in the northern part of the San Pablo quadrangle. Similar faults may be present elsewhere in the region but are not observed because of the lack of roadcuts.

En echelon folds

Northwest-plunging anticlinal and synclinal folds occur mainly along the eastern margin of the San Juan Basin (Fig. 17). A few of these folds also occur along the western edge of the Nacimiento uplift, but erosion of sedimentary strata from most of the uplift precludes observation of such folds.

These folds appear to predate development of the synclinal bend on the eastern side of the San Juan Basin and, thus, are steeply plunging where closest to the uplift. Plunges become shallower as the fold axes are followed into the basin. The folds are open and have amplitudes up to a few hundred feet; wave lengths between an adjacent anticline—syncline pair range from 0.5 mi to several miles. The folds are anticlines and synclines in the basin, but, as they are traced toward the eastern margin of the basin, many become anticlinal and synclinal bends and have no reversal of dip on the uplift side of the fold. This is because these folds have been refolded by the major synclinal bend on the east side of the basin.

Baltz (1967) studied the en echelon folds along the east side of the San Juan Basin and concluded that some of the folds began forming prior to deposition of the San Jose Formation and rejuvenated in post-San Jose time as a result of right shift between the uplift and basin before much structural relief existed across this boundary.

Northeast-trending faults

Northeast-trending, high-angle faults having up to approximately 100 ft of stratigraphic separation are present in the Holy Ghost Spring and La Ventana quadrangles (Fig. 17). These faults offset Jurassic and Cretaceous beds and are inferred to have formed as a result of right shift between the Nacimiento uplift and San Juan Basin.

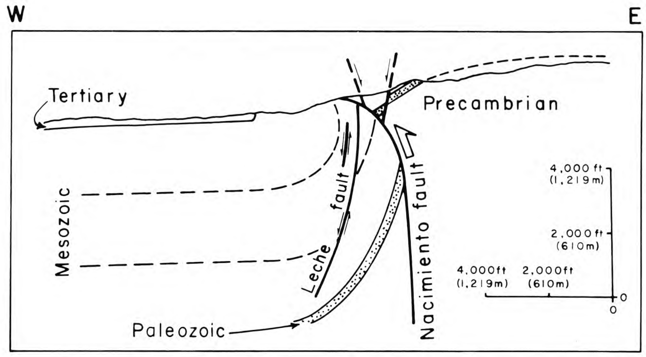


FIGURE 23—Structure section showing relation of Leche and Nacimiento faults in Cuba 7[1]/2-min quadrangle (from Woodward, Kaufman, and Anderson, 1972) .

Synclinal bend

This is the major structure of the eastern San Juan Basin, having an amplitude of approximately 8,000 ft in the Regina quadrangle and 5,000 ft in La Ventana quadrangle. Both limbs of the synclinal bend dip to the west in the northern and southern parts of the area. In the central part of the area, however, the eastern limb of the synclinal bend is inverted and dips eastward at angles as low as 55° (in the northern San Pablo and southern Cuba quadrangles). This overturning (Kelley, 1955; Baltz, 1967) occurs where the adjacent Nacimiento fault has a significant component of horizontal displacement.

The synclinal bend appears to have been part of a monocline separating the uplift from the basin prior to breaking of the monocline by the Nacimiento and Pajarito faults. Subsequent erosion has removed stratified rocks from much of the uplift, with the result that the anticlinal bend of the original monocline is no longer evident along much of the uplift.

Northerly trending normal faults

Both synthetic and antithetic normal faults occur west of and parallel to the Nacimiento fault. Some, and perhaps all, of these normal faults are older than the Nacimiento fault. For example, the Leche fault (sec. 24, T. 21 N., R. 1 W., Cuba quadrangle) is truncated by the Nacimiento fault (Fig. 23). The Vallecito fault (sec. 23, T. 21 N., R. 1 W., Cuba quadrangle) also is probably older than the Nacimiento fault, but the two are not in contact, and conclusive evidence is lacking.

The Leche fault strikes north and dips steeply to the west, displacing Cretaceous against Jurassic rocks. At least 1,000 ft of stratigraphic separation is present where this fault is truncated by the Nacimiento fault. Southward the Leche fault cuts upsection and dies out in Cretaceous shale or may grade into penetrative deformation, thinning the Mancos Shale. The Valle-cito fault trends north, and Lewis Shale (Cretaceous) is displaced against Kirtland—Fruitland Formation undivided. At least 200 ft of stratigraphic separation is present on this fault. The net tectonic effect of both faults, like the Nacimiento fault, is to eliminate strata along their traces and to increase the amount of structural relief between the uplift and the basin. They are, therefore, synthetic faults.

Antithetic faults, on the other hand, tend to oppose or decrease the amount of structural relief between the uplift and basin. Two such faults occur in secs. 11, 12, and 13, T. 20 N., R. 1 W. in the Entrada, Todilto, and Morrison Formations, and parts of the stratigraphic section are repeated. Maximum stratigraphic separation is approximately 200 ft.

The formation of these faults is inferred as the result of stretching of the limb between the anticlinal and synclinal bends of the early-formed monocline bounding the Nacimiento uplift.

Antithetic reverse faults

Several high-angle, west-dipping, reverse, strike faults are exposed in roadcuts in the Dakota Formation in the northern part of the San Pablo quadrangle. Separation is minor, amounting to only a few feet, and the faults are sigmoidal in cross section, becoming nearly parallel to bedding planes at their ends (Fig. 24). These faults are thought to be shears of the second order, related to bedding-plane slippage at the Morrison—Dakota contact and (or) as a result of flexure folding within the Dakota (Woodward, 1972).

Fig. 25 is a diagrammatic analysis of flexure folding and the resultant development of second-order shears. The fact that the bedding-plane slippage and the reverse faults are both left handed indicates that they cannot be conjugate shears and, therefore, are readily interpreted as related to the flexure folding.

Other small reverse faults with a similar origin may be present along major flexure folds elsewhere in the area, but most exposures are not good enough for recognition of such structures.

Gallina—Archuleta arch

The Gallina—Archuleta arch is a structurally lower, northward continuation of the Nacimiento uplift and separates the relatively deep San Juan Basin from the shallower Chama Basin. Only the southern end of the arch is present in the area of this report, but, in its entirety, the arch is a north-trending, arcuate anticlinorium that is slightly convex eastward and extends northward approximately 90 mi, terminating in southern Colorado (Dane, 1948; Wood, Kelley, and MacAlpin, 1948) .

A maximum of approximately 6,000 ft of structural relief occurs between the Nacimiento uplift and the Gallina—Archuleta arch in the Gallina quadrangle. In a general way, the Gallina—Archuleta arch and Nacimiento uplift merge along a north-trending anticlinal axis that is doubly plunging toward a saddle or structural low near the village of Gallina in the Gallina quadrangle.

Approximately 4,000 ft of structural relief occurs between the Gallina—Archuleta arch and the adjacent part of the San Juan Basin in the area of this report. A steeply dipping monocline that is broken by high-angle, normal, strike faults separates the arch from the basin to the west. The strike faults have from a few hundred to approximately 1,000 ft of stratigraphic separation and are mainly down to the west, thereby acting to increase the structural relief between the

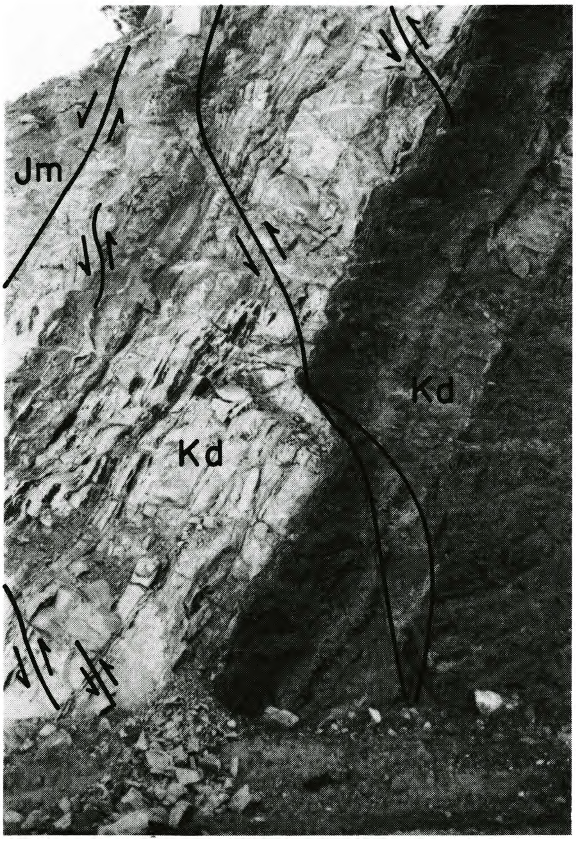


FIGURE 24—View south of high-angle reverse faults in overturned Dakota Formation **(Kd)** within inverted limb of synclinal bend, sec. 2, T. 20 N., R. 1 W., Cuba $7^{1}/_{2}$-min quadrangle. Morrison Formation **(Jm)** in upper left.

arch and the basin. One fault is down to the east, creating a small graben near the anticlinal bend of the monocline. This graben probably formed as a result of a local tensional stress field on the crest of the anticlinal bend during development of the monocline.

On the east the arch merges gradually with the Chama Basin through a broad gently dipping limb. Probably a maximum of 500 ft of structural relief exists between the highest part of the arch and the lowest part of the Chama Basin in the Gallina quadrangle.

Chama Basin

The southwest part of the Chama Basin, where it is bounded on the west by the Gallina—Archuleta arch and on the southwest by the Nacimiento uplift, is covered by this report. Mesa Pinnbetal fault (Fig. 17) is chosen arbitrarily as the boundary between the uplift and the basin. The fault surface is not exposed, but the straight trace suggests that it is dipping steeply. Structural relief across this fault near Rio Puerco is at least 690 ft; the northeast side is down. Stratigraphic separation is less than the structural relief, because beds are drag folded adjacent to the fault. Displacement appears to decrease to the southeast. Maximum structural relief between the Nacimiento uplift and the Chama Basin in the Gallina quadrangle is approximately 6, 000 ft.

In its entirety the Chama Basin trends north and is approximately 60 mi long and 20 mi wide at the south

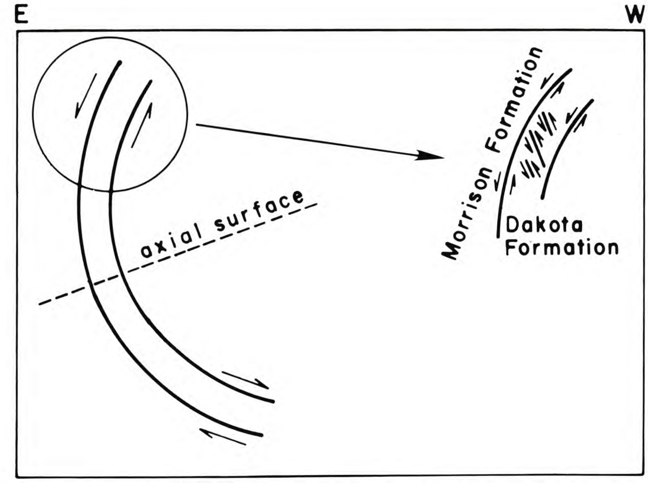


FIGURE 25—Diagrammatic cross section of flexure folding leading to second-order shears. View to south to facilitate correlation with Fig. 24.

end. Only the southwest corner of the basin is present in the area of this report; this western limb dips gently to the northeast. The homoclinal dip of the western limb of the basin is interrupted by only one small northeast-trending high-angle fault in the Gallina quadrangle (Woodward, Gibson, and McLelland, 1976) and a small gravity-slide plate of Poleo Sandstone (Triassic) near the deep canyon of the Rio Puerco in the Jarosa quadrangle (Woodward and Timmer, 1979) . At the south end the basin is unconformably covered by extrusive rocks of the Jerez volcanic field, as at Mesa Pinabetosa in the Jarosa quadrangle.

Rio Grande rift

The Rio Grande rift comprises a series of north-trending grabens that are arranged en echelon north—northeast in New Mexico and Colorado for a distance of at least 450 mi (Kelley, 1952) and perhaps as much as 600 mi (Chapin, 1971). Antithetic and synthetic faults occur within the major grabens forming step faults, as well as second-order grabens and horsts. The major grabens are usually referred to as basins; from north to south they are the Upper Arkansas, San Luis, Española, Albuquerque, San Marcial, Engle, and Palomas Basins (Fig. 26).

The Albuquerque Basin is approximately 90 mi long and 30 mi wide (Kelley, 1977) . It is an asymmetric graben in its northern part, with a maximum structural relief of approximately 28,000 ft between the deepest part of the basin and the adjacent Sandia uplift (Kelley and others, 1976). The northwest corner of the Albuquerque Basin is included in the area of this report. Along the northwest margin of the basin, the structural relief is much less, ranging from approximately 1,000 ft at White Mesa in the San Ysidro quadrangle (Woodward and Ruetschilling, 1976) to approximately 2,250 ft at Rio Guadalupe in the Gilman quadrangle (Woodward and DuChene, 1975) .

The boundary between the Albuquerque Basin and the Nacimiento uplift is a series of north—northeasttrending faults. This boundary is placed arbitrarily at those faults having Zia Sand or correlative volcani-

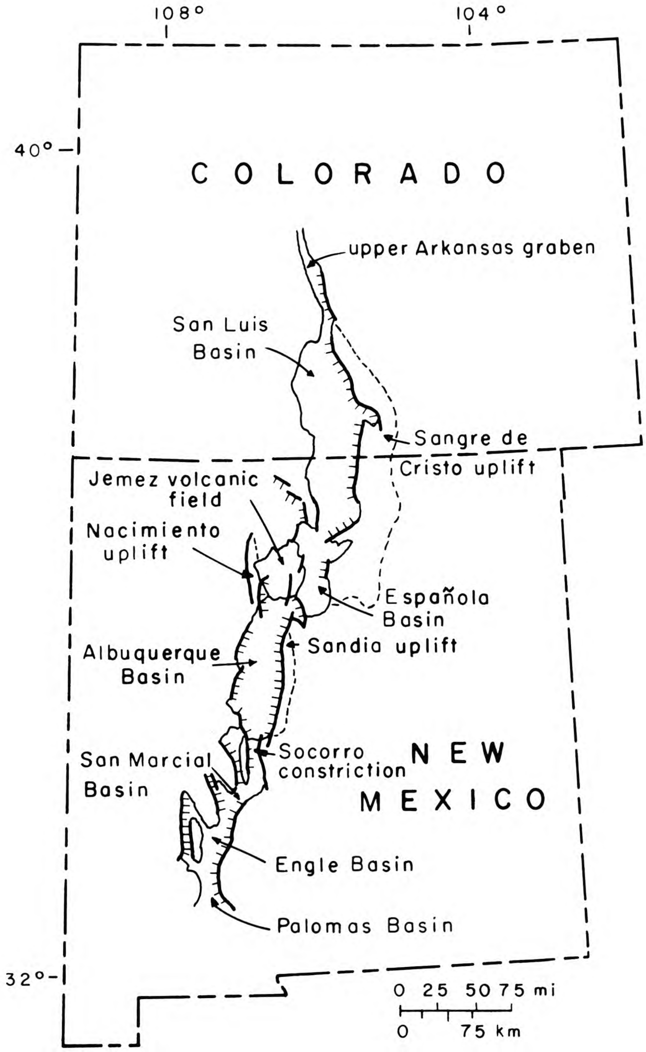


FIGURE 26—Index map showing major basins of Rio Grande rift (modified from Kelley and others, 1976).

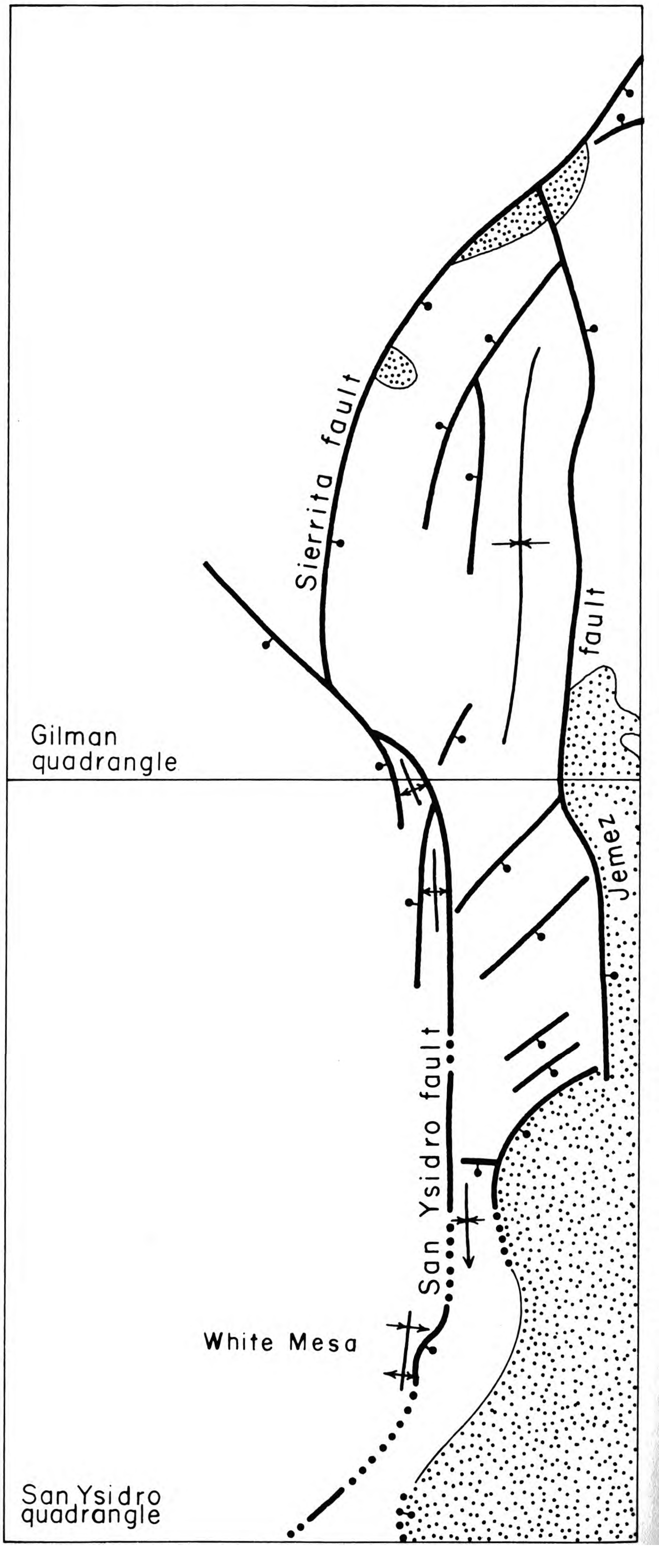


FIGURE 27—Diagrammatic map showing faults and Tertiary Zia Sand and correlative units (stippled) along the boundary between the Albuquerque Basin of the Rio Grande rift and the Nacimiento uplift.

clastic rocks (DuChene and others, 1981) preserved in the hanging-wall block. Some of the faults overlap (Fig. 27) with local preservation of Zia Sand and correlative strata on the downthrown sides of the faults, resulting in an irregular boundary. This pattern is described below from south to north.

An unnamed fault along the south edge of the San Ysidro quadrangle (Fig. 27) is poorly exposed but is probably steep; it has Mancos Shale (Cretaceous) on the west and Zia Sand (Tertiary) on the east. This fault may merge with the San Ysidro fault to the north, but its northern end is covered with alluvium, and a conclusive determination cannot be made.

The San Ysidro fault at White Mesa has Morrison and Todilto (Jurassic) beds on the west and Dakota Formation (Cretaceous) on the east. At this locality the fault is well exposed and dips steeply to the east. Drag on the west side of the fault here has produced the east limb of a minor monocline that grades southward into a small anticline. On the downthrown side is a small asymmetric syncline having a steep western limb and a gently dipping eastern limb (Fig. 28; Woodward and Ruetschilling, 1976). To the north this fault cuts stratigraphically lower until, near its northern end, Precambrian granite is on the west and Madera Formation (Pennsylvanian) is on the east side. A small, south-plunging syncline is preserved in Jurassic strata on the east side of the fault near the village of San Ysidro. Numerous small travertine deposits are present near the central segment of this fault. Maximum

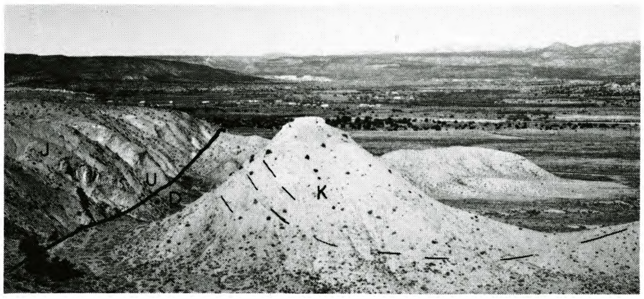


FIGURE 28—View north of San Ysidro fault at White Mesa, San Ysidro 7½-min quadrangle, showing monocline on west (left) and syncline on east (right) side of fault. **J** = Jurassic strata and **K** = Cretaceous strata (from Woodward, 1977).

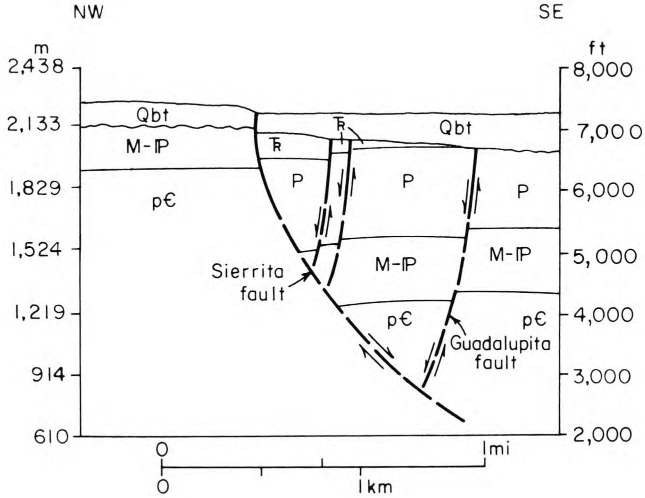


FIGURE 29—Diagrammatic northwest–southeast structure section through Sierrita and adjacent antithetic faults near Rio Guadalupe. **Qbt** = Bandelier Tuff, **TR** = Triassic strata, **P** = Permian strata, **MIP** = Mississippian and Pennsylvanian strata, and **p€** = Precambrian rocks (modified from Woodward and DuChene, 1975).

stratigraphic separation on this fault is approximately 1,500 ft near the village of San Ysidro.

Approximately 1 mi north of San Ysidro, a high-angle, northeast-trending fault has Triassic strata juxtaposed with Zia Sand, and it appears to be the principal bounding fault of the rift here. Total displacement on this fault is not known, but it is probably at least several hundred feet and could be several thousand feet. This fault is covered by alluvium at both ends. To the south it may continue a considerable distance, and this fault, rather than the San Ysidro fault, may be the main boundary fault. To the northeast the fault may abut or offset the Jerez fault, or it may be offset by the Jemez fault.

The north-trending, high-angle Jerez fault has Precambrian through Triassic rocks on the west side and Zia Sand (Tertiary) along the southern half of the east side. Stratigraphic separation is greatest along the central segment, at nearly 1,500 ft. Displacement appears to diminish to the north, where Abo Formation (Permian) occurs on both sides of the fault and to the south, where Triassic strata on the west are juxtaposed with Zia Sand. At its northern end the Jerez fault appears to abut the Sierrita fault.

Throughout most of its trace, the Sierrita fault has Precambrian rocks on the west side and Permian or Pennsylvanian beds on the east. Locally, volcaniclastic strata that are correlative with the Zia Sand (DuChene and others, 1981) are found adjacent to the fault on the downthrown side (Fig. 27). The fault is poorly exposed along most of its length; however, where it is crossed by Rio Guadalupe in the northeast part of the Gilman quadrangle, the topographic relief is approximately 1,000 ft. In addition to a good cross sectional view of the fault, several good exposures of the fault trace occur here. The fault zone is 3-10 ft wide and mainly consists of brecciated Precambrian gneiss, except where it forms a sharp break cutting stratigraphically higher units.

Where the Sierrita fault cuts the Bandelier Tuff (Quaternary), the fault surface is nearly vertical, but at its deepest exposure, where Precambrian and Permian rocks are juxtaposed, it dips approximately 50° SE. Permian strata are offset approximately 2,250 ft, and the Bandelier is offset approximately 40 ft; thus, the fault surface appears to be curved, being nearly vertical at structurally high locations and more gently dipping at depth.

The Sierrita fault has undergone several episodes of movement, the latest occurring after deposition of the Bandelier Tuff (Quaternary). Post-Triassic (probably Miocene and/or Pliocene) offset of approximately 2,200 ft along the fault was followed by an episode of erosion, which bevelled Triassic and older rocks. Bandelier Tuff was extruded across the fault and later offset approximately 40 ft.

Several small, high-angle antithetic faults up to 1 mi away from the Sierrita fault have up to 150 ft of stratigraphic separation. These antithetic faults are interpreted as terminating against the Sierrita fault (Fig. 29), and they are thought to represent minor adjustments to major crustal extension along the listric Sierrita fault bounding the Rio Grande rift. Similarly, the dip of beds toward the San Ysidro fault at White Mesa (Fig. 28) may represent reverse drag caused by rotation of strata along a listric normal fault; minor normal drag occurs close to the fault.

Jemez volcanic field

Pliocene and Quaternary extrusive rocks of the Jerez volcanic field (Ross and others, 1961; Bailey and others, 1969; Doell and others, 1968; Smith, R. L., and others, 1970; Kudo, 1974) straddle the western margin of the Rio Grande rift and lap unconformably onto the eastern part of the Nacimiento uplift in the Jarosa, Rancho del Chaparral, San Miguel Mountain, and Gilman quadrangles (Fig. 17). Radiometric ages of rocks of the Jerez field range from 10.4 ± 0.5 my. to 0.434 ± 0.015 m.y. (Luedke and Smith, 1978). Volcanism began after initial development of the rift and continued contemporaneously with later stages of rifting.

The following generalized description of the development of the Jerez volcanic field is summarized from publications by Ross and others (1961), Bailey and others (1969), and R. L. Smith and others (1970). Volcanic activity was initiated in early Pliocene or late Miocene time with the eruption from several centers of predominantly mafic to intermediate lavas. The lavas formed low coalescing shields. These early rocks have been divided into two groups, the Polvadera Group exposed in the northern part of the Jemez field and the Keres Group exposed in the southern part. This volcanism culminated in the Pleistocene with explosive, caldera-forming eruptions of rhyolitic ash-flow tuffs (Bandelier Tuff) . Later eruptions were confined to the Valles caldera and resulted in doming and filling of the caldera. Rhyolite domes were emplaced along ring fractures between the caldera wall and the resurgent dome.

In the area of this report only a relatively thin and incomplete volcanic sequence is present, consisting of the Paliza Canyon Formation (part of the Keres Group) and the Bandelier Tuff. The Paliza Canyon Formation is found locally beneath the Bandelier Tuff and ranges in thickness from a zero edge to approximately 45 ft. A radiometric date on this unit approximately 6 mi east of the Gilman quadrangle is 9.0 ± 0.3 my. (Luedke and Smith, 1978) . The overlying Bandelier Tuff is up to 650 ft thick and was extruded on a surface of considerable relief; radiometric dates on the Bandelier from nearby localities range from 1.02 ± 0.04 m.y. to 1.48 ± 0.09 m.y. (Luedke and Smith, 1978) .

Both the Paliza Canyon Formation and the Bandelier Tuff in the area of this report were derived from the east and represent only the thin western part of the Jemez volcanic field. Since the eruption of the Bandelier Tuff, extensive erosion has isolated large erosional outliers of the tuff to the west of the deeply incised Rio Guadalupe and Rio de las Vacas.

Tectonic evolution

Three main episodes of Phanerozoic deformation influenced this region, late Paleozoic block uplift, the Laramide orogeny of Late Cretaceous and early Tertiary age, and development of the Rio Grande rift during the late Cenozoic. The Nacimiento uplift, San Juan Basin, Chama Basin, and Gallina—Archuleta arch attained their structural outlines during Laramide time. The Rio Grande rift was initiated during the Miocene (Chapin, 1971) and was superimposed on the southeast corner of the Nacimiento uplift. Some of the Lar-amide structures probably were rejuvenated or further developed during the time of rifting.

Northwest-plunging folds arranged en echelon along the east side of the San Juan Basin (Fig. 17) suggest right shift between the basin and the Nacimiento uplift (Kelley, 1955). These folds appear to have formed prior to the main episode of uplift. Several of the anticlines began to form prior to deposition of the San Jose Formation (Eocene), because the underlying Nacimiento Formation (Paleocene) is thin along the crests of these folds, and because, on some of the folds, a slight angular unconformity exists between Eocene and Paleocene strata (Baltz, 1967) . Continued development of the folds is indicated by the fact that the Eocene beds are also folded. Baltz (1967, p. 70) thought shift might be as much as 3 mi. This right shift appears to be due to northeastward yielding of the Colorado Plateau structural block as a result of east—west compression in the Nevada and Utah segment of the Cordilleran foldbelt and nearly north—south compression in the New Mexico portion of the foldbelt (Fig. 30).

Major rise of the Nacimiento uplift appears to have begun after deposition of the Nacimiento Formation (Paleocene) and before deposition of the San Jose Formation (Eocene), as indicated by the unconformity between these units, which becomes increasingly angular near the uplift (Fig. 31). A diagrammatic illustration of the sequence of events during uplift is shown in Fig. 32. Baltz (1967, p. 54) indicated three stages of folding, based on detailed study of the San Jose Formation and its members. He also suggested that early uplift may have occurred as a result of movement along closely spaced vertical fractures in the Precambrian rocks with resultant shear folding of them. Overlying sedimentary strata were draped and stretched over the resultant monocline in the basement rocks.

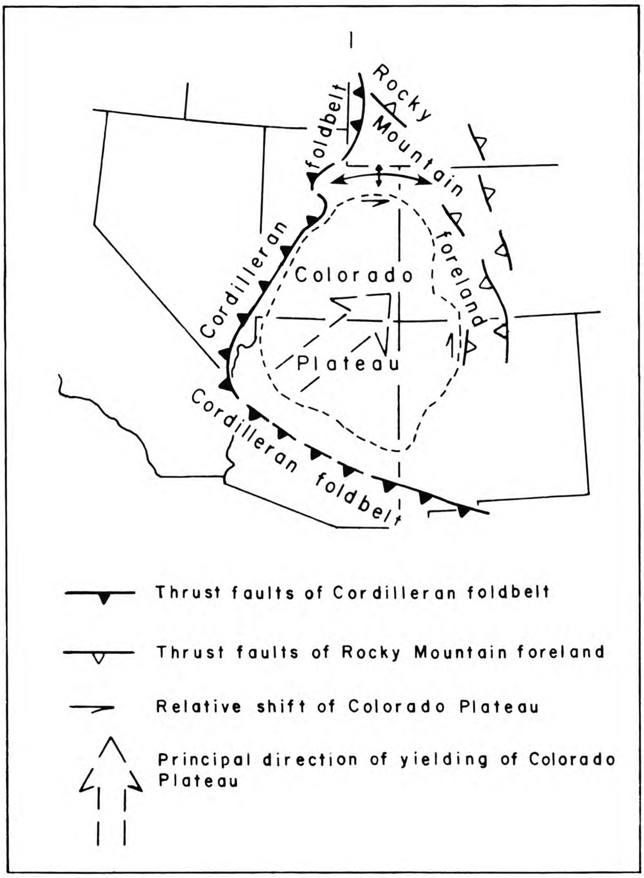


FIGURE 30—Regional tectonic sketch map showing the Cordilleran foldbelt, Colorado Plateau, and Rocky Mountain foreland.

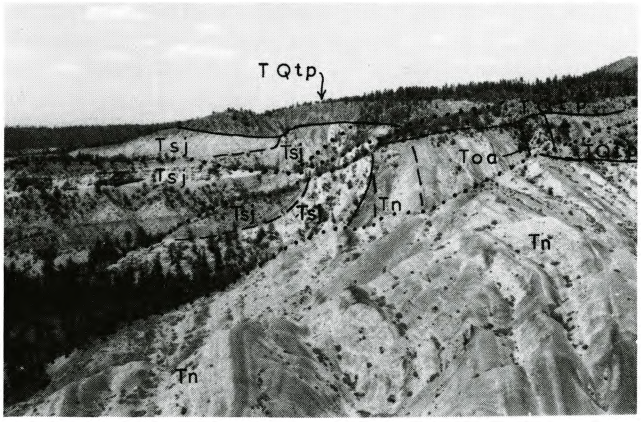


FIGURE 31—View north of synclinal bend along east side of San Juan Basin. Ridge lines dotted and bedding dashed. Rock units are: **Toa** = Ojo Alamo Formation, **Tn** = Nacimiento Formation, **Tsj** = San Jose Formation, **TQtp** = terrace and pediment deposits. Note angular unconformity between Nacimiento and San Jose Formations (from Woodward, Kaufman, and Anderson, 1972).

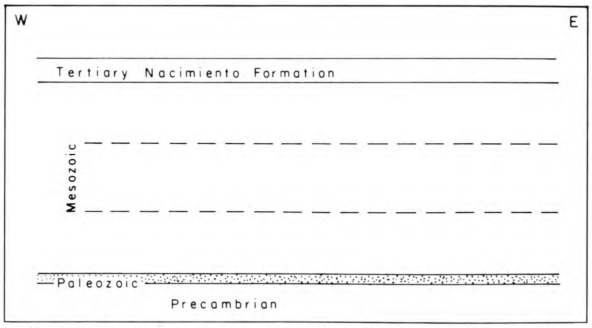
Normal faults, such as the Vallecito and Leche faults, developed in the stretched limb between the anticlinal bend and synclinal bend of the monocline (Fig. 32c) . As uplift continued the fold and normal faults were cut by the Nacimiento fault. The Nacimiento fault is an upthrust that is a steep reverse fault at deep structural and stratigraphic levels but flattens at higher levels with yielding over the adjacent basin.

Horizontal stretching of rocks in the upthrown block resulted in normal faults that are restricted to the hanging-wall block. Some of these occur adjacent to the Nacimiento fault where it is flat-lying, as in the San Pablo quadrangle (Fig. 32d). Larger normal faults occur near the crest of the uplift. Included are the Rio Gallina, Cave Creek, and Rio Capulin faults at the north end of the uplift and the faults bounding the Joaquin graben in the south-central part of the uplift (Fig. 17) .

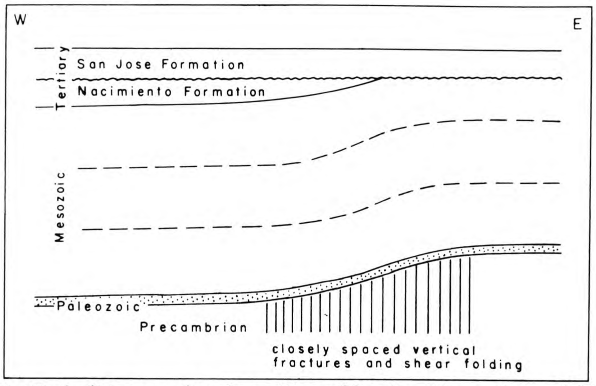
The east-trending San Pablo, El Cajete, and Blue Bird faults, which were formed synchronously with the Nacimiento fault, bound differentially uplifted segments of the uplift. Maximum displacements on these faults occur where they abut the Nacimiento fault; displacement dies out eastward on each fault.

A few east-dipping antithetic normal faults formed during the early phase of uplift as conjugate shears in relation to the west-dipping normal faults (Fig. 33) and as a result of stretching of monoclinal strata between the uplift and the basin. Where these antithetic normal faults occur near the Nacimiento fault, as they do approximately 0.25 mi north of San Pablo Canyon in the San Pablo quadrangle, a slice of younger rock is caught between the rocks of the uplift and the rocks of the San Juan Basin. Precambrian quartz monzonite is thrust onto Morrison Formation (Jurassic), which, in turn, is in fault contact and is structurally above the Todilto Formation (Jurassic). The Nacimiento fault truncates these antithetic normal faults.

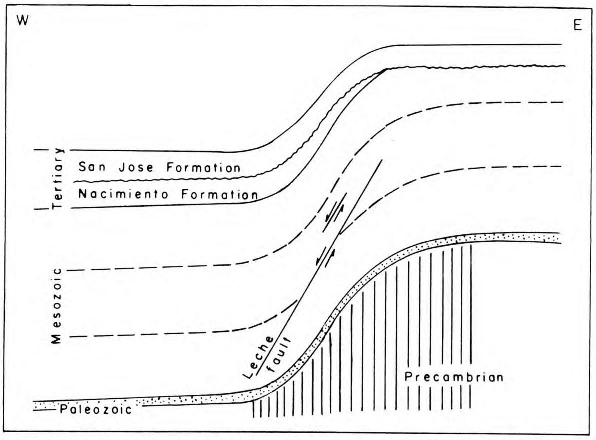
The Nacimiento fault appears to have formed as a curved fracture rather than as a folded planar fault. Beds in the upthrown blocks are right side up and dip gently to the west; had the fault been folded, these



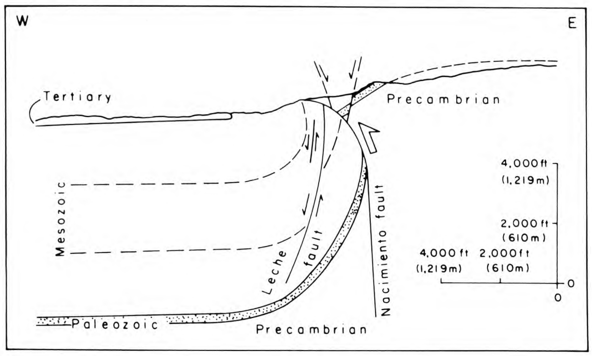
A—End of Paleocene immediately after deposition of Nacimiento Formation.



B—End of Eocene after deposition of San Jose Formation, which thickens to west.



C—Uplift by shear folding of basement with stretching and normal faulting in limb between anticlinal and synclinal bends.



D—Nacimiento fault cuts normal fault in limb and causes overturning of beds and folding of older normal fault. Normal faults develop in headwall as result of stretching as uplift yielded laterally over adjacent basin.

FIGURE 32—Diagrammatic structure sections showing development of range-marginal structures on west side of Nacimiento uplift (from Woodward, Kaufman, and Anderson, 1972).

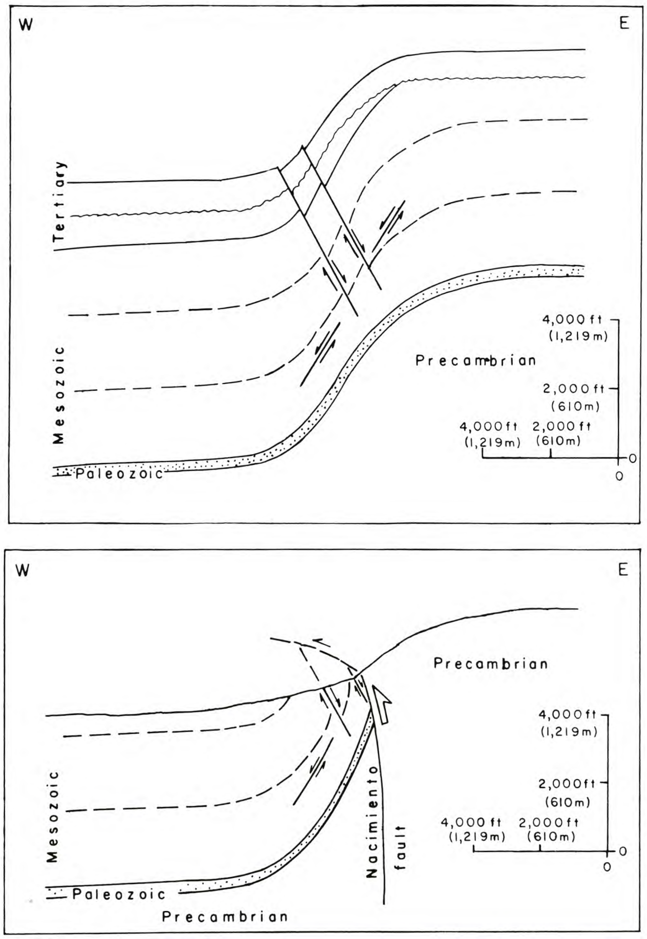


FIGURE 33—Diagrammatic structure sections showing strata younger than in footwall or hanging wall along Nacimiento fault as a result of antithetic normal faulting prior to development of Nacimiento fault (from Woodward, Kaufman, and Anderson, 1972).

beds should be very steeply dipping near the fault. This geometry of a steeply dipping reverse fault at depth that flattens upward conforms to theoretical and experimental fault surfaces as described by Hafner (1951) and Sanford (1959), respectively. The overturned limb of the synclinal bend, west of the Nacimiento fault, appears to have been caused by compression when the structurally higher upthrust yielded westward over the adjacent basin. Thus, the dominant movement along the Nacimiento fault has been vertical with subordinate horizontal movement.

The Nacimiento uplift and the San Juan Basin began their development during the Laramide, but Kelley (1950) suggested that the Laramide deformation consisted mostly of folding and that the Nacimiento fault formed later in the Tertiary when the Rio Grande rift began to develop. The distribution of the Pedernal chert member of the Abiquiu Formation along the highest part of the uplift suggests that some of the rise of the Nacimiento uplift is post-lower Miocene. The Pajarito fault is presumably the same age.

Small gravity-slide plates composed of competent Paleozoic and Mesozoic rocks are locally present near the foot of the uplift on its western and northern sides. Late gravitational gliding of the upper plate of the Nacimiento fault may have occurred where it is flat lying.

The Rio Grande rift is a late Cenozoic extensional feature that has been superimposed on the Laramide structures, apparently truncating the southeast corner of the Nacimiento uplift. The uplift may have undergone additional development during rifting with reverse faulting and upthrusting on the west side of the uplift. Stratigraphic and radiometric data indicate that the Rio Grande rift was initiated during the early Miocene or late Oligocene, perhaps about 26 m.y. ago (Woodward, 1977). Woodward (1977) calculated an annual rate of extension of approximately 0.3 mm per year, based on an interpretation that the normal faults bounding the rift flatten at a depth of approximately 6-10 mi with plastic deformation of the crust occurring below that depth. The listric Sierrita normal fault with its associated small antithetic normal faults is the strongest evidence for flattening of the faults at depth. The small syncline adjacent to the San Ysidro normal fault at White Mesa (Fig. 28; Woodward and Ruetschilling, 1976) also is interpreted to be the result of rotation along a listric normal fault. The eastern limb of the syncline represents reverse drag, which occurred when the hanging-wall block rotated to dip toward the fault and toward the narrow western limb, due to drag adjacent to the fault.

The Zia Sand and correlative units probably formed in a shallow basin that was a precursor to the present fault-bounded Rio Grande rift. Subsequently, these early basin-fill deposits were cut by the boundary faults (Sierrita, Jerez, and San Ysidro faults).

Volcanism in the Jerez volcanic field began after initial development of the rift and continued contemporaneously with later stages of rifting. The locus of eruption is the intersection of the western boundary of the rift and a northeast-trending chain of eruptive centers (Luedke and Smith, 1978) . Jerez volcanics grade through volcaniclastic rocks to sediments filling the rift, as well as unconformably overlying clastic basin-fill in the rift. The volcanic pile thickens eastward into the rift, indicating contemporaneity of volcanism and rifting.

Lipman (1969) proposed an area of high-heat flow and an associated upward bulge of the mantle beneath the rift based on the occurrence of tholeiitic basalts within the rift and the occurrence of partly contemporaneous alkalic basalts in adjacent areas. Subsequently, a heat-flow study by Reiter and others (1975) indicates a regional geothermal high along the western margin of the rift. Seismic studies by Keller and others (1978) show that the crust beneath the rift is 19-21 mi thick in contrast to a thickness of approximately 28 mi for the Colorado Plateau to the west and 31 mi for the Great Plains to the east. Chapin (1971) suggested that the crust west of the rift is drifting westward faster than the crust that is east of the rift, thus creating a tensional zone above the mantle bulge.

The uplift and associated compression seen along the west side of the Nacimiento uplift may be caused in part by westward and upward pushing of the mantle bulge. Thus, the extension across the rift and the contemporaneous (?) uplift and compression to the west may be manifestations of the same basic mechanism.

The following model for the tectonic evolution of the Nacimiento uplift and adjacent areas is proposed:

1) As the North American plate drifted westward over an eastward-dipping subduction zone in Laramide time, the Colorado Plateau structural block was pushed northeast into the Rocky Mountain foreland. This resulted in right shift between the plateau and the site of the present Nacimiento uplift and formation of the northwest-trending en echelon folds along the east side of the plateau. Immediately following the beginning of the right shift and, in part, contemporaneous with it, the San Juan Basin began to subside, and the Nacimiento uplift and Gallina—Archuleta arch began to rise.
2) Epeirogenic uplift of the entire region in Cenozoic time may have been a result of isostatic rise of a thickened sialic crust after the overridden subduction zone was dissipated.
3) The Rio Grande rift was initiated in later Cenozoic time with severe crustal extension above a mantle bulge. Upward and westward push by the mantle bulge may have caused additional rise of the Nacimiento uplift. Thus, the Nacimiento uplift has had a long and complex tectonic history related to Laramide deformation of the Colorado Plateau and Rocky Mountain foreland and to evolution of the Rio Grande rift of late Cenozoic age.

Mineral and energy resources

Production of natural gas, copper, coal, gypsum, and aggregate has been fairly large from this area, in addition to minor production of uranium. Large reserves of gypsum and travertine are currently sub-economic. Some potential for geothermal energy exists, but this has not been adequately evaluated.

Copper

This area produced over 7,500,000 lb of copper and approximately 75,000 oz of silver between 1881 and 1960 (Elston, 1967, p. 26), with most of the production coming from the San Miguel mine (Fig. 34, locality 3) prior to 1900 (Lindgren and others, 1910) . Between 1900 and about 1970, copper production was minor and sporadic and came mainly from the San Miguel and Eureka mines (Fig. 34, localities 3 and 1, respectively) . Earth Resources undertook an extensive exploration program in the late 1960's that was centered around the Nacimiento mine (Fig. 34, locality 2), formerly known as the Copper Glance—Cuprite mine. The Nacimiento mine went into production with reserves estimated to be 9.6 million tons at 0.71% copper (Mining Record, October 22, 1969) and produced until 1975 when the mine was closed.

The following discussion of the copper deposits of the Nacimiento area is taken mainly from reports by Kaufman and others (1972), Woodward, Kaufman, and Schumacher (1974), Woodward, Kaufman, and others (1974), Gibson (1975), Timmer (1976), Merrick (1980), and Talbott (1974). Previous reconnaissance reports by Newberry (1876), Cazin (1880), Jenks (1899), Lindgren and others (1910), and Fischer (1937) covered some of the deposits described here. A U.S. Bureau of Mines circular by Soule (1956) shows assay results and claim maps of these deposits. Elston (1967) summarized the mineral resources of several counties in central New Mexico, including the principal mines noted in this report.

Mineralization

Copper sulfides and copper—iron sulfides partly replaced or are associated closely with carbonaceous fossil-plant material in sandstones and arkoses ranging in age from Pennsylvanian to Triassic in the Nacimiento area. Mineralization probably occurred during Triassic time, shortly after deposition of the Agua Zarca Sandstone Member of the Chinle Formation. Chalcocite, covellite, bornite, chalcopyrite, and pyrite were probably deposited from low-temperature groundwater solutions, with mineralization occurring in a favorable reducing environment provided by fermentation of carbonaceous material. Small amounts of native silver occur with the sulfides. Minor amounts of cuprite, native copper, antlerite, and spangolite occur locally at the Nacimiento mine.

Partial oxidation of the sulfides occurred later, and copper, in the form of malachite, chrysocolla, and azurite, was disseminated in the adjacent host rock, forming irregular halos around the mineralized fossil-plant material. Carbonaceous fossil-plant material occurs as transported branches and trunks of trees, as rounded nodules of fossil wood up to 2 inches across, and as thin films of plant material along bedding surfaces. Branches and trunks are most abundant in the Agua Zarca Member of the Chinle Formation in paleochannels that are commonly filled with quartzite pebble to cobble conglomerate.

The most abundant ore minerals are chalcocite and malachite, with subordinate amounts of bornite and chrysocolla, and minor amounts of covellite, azurite, and chalcopyrite . Polished sections of mineralized fossil wood from the Eureka, San Miguel, and Nacimiento mines contain (by volume percent) an average of approximately 81% chalcocite, 11 % bornite, 2% covellite, 5% pyrite, and trace amounts of chalcopyrite. Pyrite is most abundant in nodules of fossil wood from the San Miguel mine (up to 10%) and is absent in some

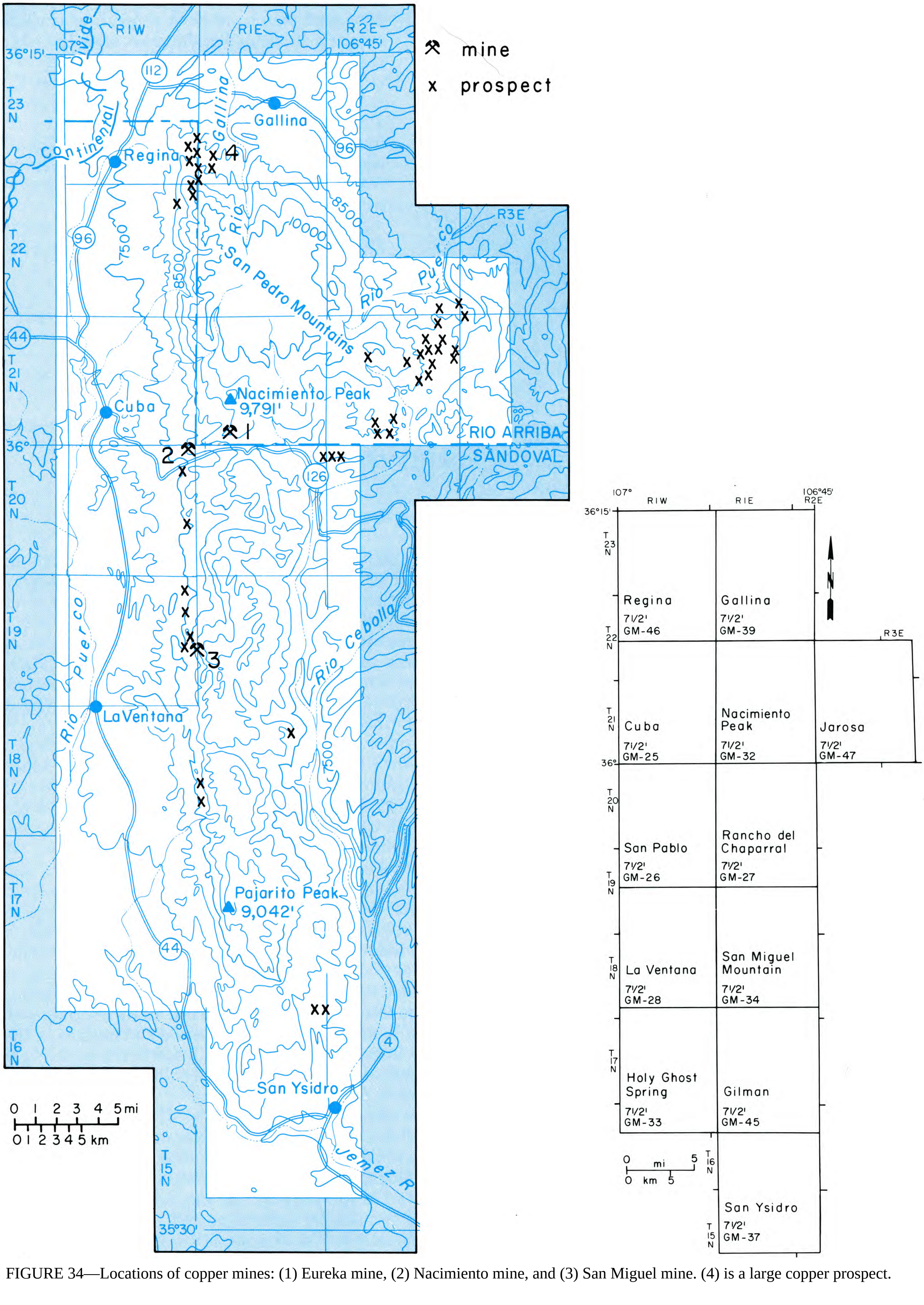


FIGURE 34—Locations of copper mines: (1) Eureka mine, (2) Nacimiento mine, and (3) San Miguel mine. (4) is a large copper prospect.

specimens from the Nacimiento and Eureka mines.

Bornite selectively replaced cell walls, and chalcocite replaced the centers of cells in the fossil wood (Fig. 35) . Pyrite, where present, also occurs in the centers of cells but, in part, has been replaced by chalcocite. The paragenetic sequence cannot be established firmly, but the suggested order of deposition (from oldest to youngest) is pyrite, bornite, chalcocite, and covellite . Any younger mineral may be seen to replace any older mineral in the sequence. The position of chalcopyrite in the sequence is not clear.

The mines and prospects in this report are sandstone-type deposits that have been called "red-bed" copper deposits (Emmons, 1905), but, actually, the host rocks are white to buff beds of Pennsylvanian to Triassic age. Strata above and below the host rocks, however, are typical red beds. The following descriptions of the mineralized areas are discussed in stratigraphic order from oldest to youngest (Table 1) and include those in the Madera Formation, the Abo Formation, and the Agua Zarca Sandstone Member of the Chinle Formation.

Madera Formation—Mineralization in the Madera occurs in siltstone and in coarse-grained arkose and consists of minor amounts of disseminated malachite. The observed areas of mineralization do not appear to be of commercial value. Malachite is usually the only copper mineral present in the Madera and is probably the result of leaching of copper minerals from the Abo Formation and(or) the Agua Zarca Sandstone Member of the Chinle Formation in the same general areas.

Abo Formation—Most of the mineralized beds at the numerous prospects in the Abo are tan, coarse-grained arkose or feldspathic sandstone, or rarely conglomerate. At most of the localities the mineralized areas are stratigraphically thin, laterally discontinuous zones. Carbonaceous material is sparse and so are sulfides; malachite, azurite, and chrysocolla are, by far, the most abundant cupriferous minerals and are present in the interstices of the host rocks.

One of the larger Abo prospects, which is in the Gallina quadrangle (Fig. 34, locality 4), differs from other Abo localities insofar as the mineralized horizon is conglomeratic with quartzite pebbles and cobbles exposed in lenticular channels that can be traced for several hundred feet along strike.

Exploration for copper in the Abo Formation should be directed along paleochannel trends for large accumulations of carbonaceous trash that may be mineralized. Host arkoses in the Abo, however, are lenticular and discontinuous, and, therefore, the chance of finding large copper deposits in this unit in the Nacimiento area is probably low.

Agua Zarca Sandstone Member of the Chinle Formation—The Agua Zarca Sandstone Member contains the largest of the known copper deposits in the region covered by this report. The mines and prospects in the Agua Zarca near Eureka Mesa (Fig. 34, localities 1 and 2) were called the Copper Cities group by Soule (1956) and include the Eureka mine, the Nacimiento mine, and one small prospect. The San Miguel mine (Fig. 34, locality 3) and several small prospects are located in the northeast part of La Ventana quadrangle and in the southeast part of the San Pablo quadrangle. The major deposits are described below.

The Eureka mine, on the south side of Eureka Mesa, where the Agua Zarca is approximately 140 ft thick and dips gently to the southwest, is in the basal part of the Agua Zarca. The ore has been mined by means of surface and underground workings (Fig. 36). Lindgren and others (1910) reported a 500-ft tunnel extending north through Eureka Mesa; the north end of this tunnel is now caved.

Mineralization is confined mainly to the lenticular channel approximately 280 ft wide and up to 40 ft thick, which is composed of intercalated, cross-bedded, quartz-pebble conglomerate and cross-bedded quartzose sandstone. High-angle, festoon and planar crossbed sets up to 5 ft thick and fossil-wood fragments up to 1 ft in diameter and 5 ft long are numerous within the channel. The conglomerate contains more carbonaceous material and is more porous and permeable than the adjacent sandstone, which is usually barren. Clay galls are common throughout the channel, and clay beds up to 2 ft thick are present as overbank deposits in the north part of the mine. Elston (1967) reported that crossbedding shows that the current direction was toward the southwest, and a detailed paleocurrent study confirms this trend (Kaufman, 1971).

The Nacimiento mine occurs east of the Nacimiento fault in steeply dipping Agua Zarca Sandstone along a faulted anticlinal bend (Fig. 37) in a structurally low segment of the Nacimiento uplift bounded by the east-trending El Cajete and Blue Bird faults on the north and south, respectively. This deposit was mined by open-pit methods to a depth of approximately 500 ft.

The orebody was approximately 2,400 ft long (north—south) and 300 ft wide (east—west). Large logs, up to tens of feet long and several feet in diameter, have been replaced mainly by chalcocite. Some remobili-

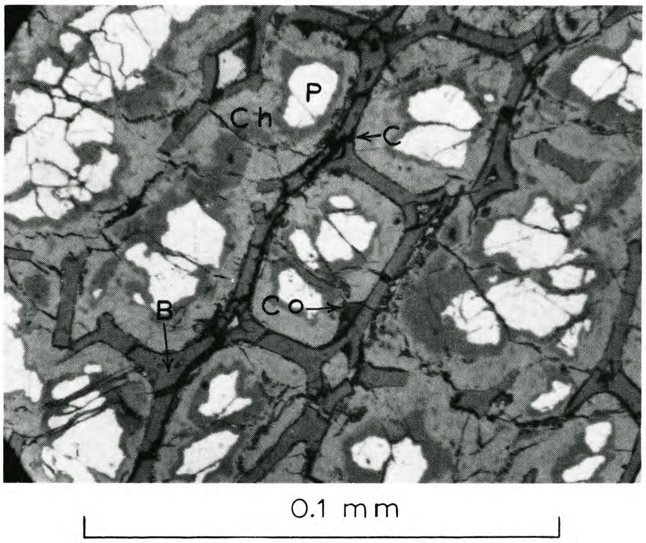


FIGURE 35—Photomicrograph of polished section of mineralized fossil wood from San Miguel mine showing chalcocite **(Ch)**, bornite **(B)**, pyrite **(P)**, covellite **(Co)**, and carbonaceous material **(C)** (from Woodward, Kaufman, and others, 1974).

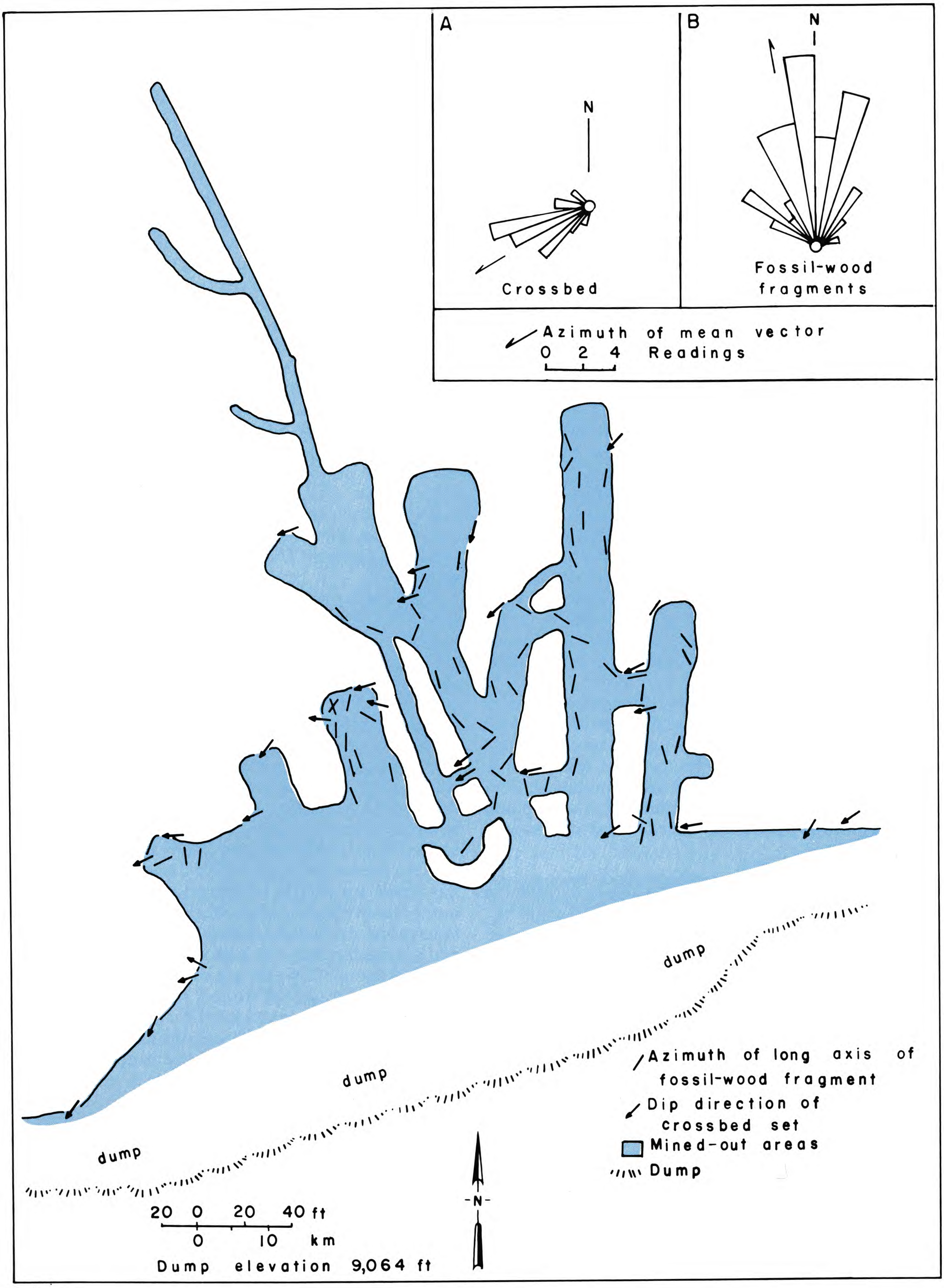


FIGURE 36—Map of Eureka mine and rose diagrams showing directions of dip of crossbeds (A) and azimuths of long axes of fossil-wood fragments (B) (after Woodward, Kaufman, and others, 1974).

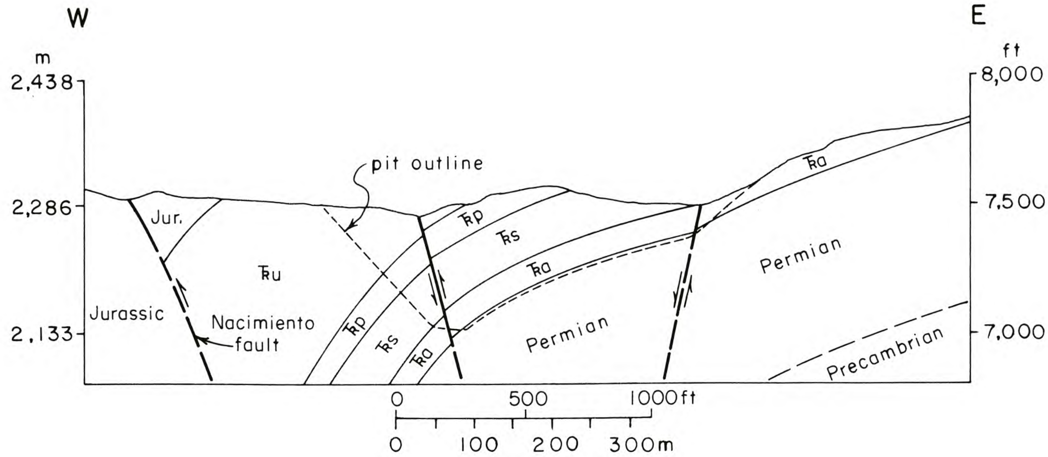


FIGURE 37—East-west cross section through Nacimiento open pit showing geology prior to excavation. Symbols for members of Chinle Formation are: **TRa** = Agua Zarca Sandstone Member, **TRs** = Salitral Shale Member, **TRp** = Poleo Sandstone Member, **TRu** = upper shale member (from Woodward, Kaufman, and others, 1974).

zation of chalcocite appears to have occurred below the water table, because the chalcocite occurs as discrete grains adhering to quartz grains (Talbott, 1974) . Minor native silver occurs along fractures in carbonaceous material near the water table.

The Agua Zarca is composed of fine- to coarse-grained, poorly cemented, crossbedded quartzose sandstone. The base of the unit is marked by cobbles and boulders of quartzite. Cut-and-fill channels containing conglomerate with quartzite clasts are common in the Agua Zarca here. These channels tend to be wide, shallow, and poorly sorted and lack graded bedding. Some smaller channels of crossbedded, laminated, fine-grained sandstone are well sorted and have graded bedding. Edgewise conglomerate of angular claystone fragments and clay galls in sandstone matrix occurs in many of the larger channels. These sedimentary textures and structures suggest that the Agua Zarca here was deposited in an environment of broad, shallow, high-energy, cyclic, cloudburst-type overbank flow channels. The logs that were later mineralized appear to have rolled along and to have been buried quickly by the poorly sorted bed and suspended load. Mud beds were ripped up and buried before they were strongly abraded.

The San Miguel mine occurs in a structural terrace in the Agua Zarca Sandstone west of the range-marginal Pajarito fault, which is nearly vertical here (Fig. 38) . The main part of the mineralized area occurs between two transverse faults approximately 800 ft apart. The southern fault is mostly covered by pediment gravel and is poorly exposed; this fault was reported to have offset the orebody (Lindgren and others, 1910) . Mineralized Agua Zarca Sandstone is present north of the northern transverse fault.

Prior to 1900 five or six underground drifts 300-800 ft long that trended north—northwest were reported (Lindgren and others, 1910), but these drifts are no longer accessible, and no mine maps are available. Most of the older workings are obscured by dozer trenches and dumps that developed later. The mineralized area appears to be approximately 1,000 ft long (east—west) and 800 ft wide (north—south).

The Agua Zarca in the San Miguel mine area is mainly fine- to coarse-grained sandstone with a channel complex in the lower part and minor lenses of shale in the upper part. Pebble and cobble conglomerate containing clay galls and fossil wood are present in the channel complex, which appears to trend nearly due west.

Ore minerals are chalcocite and bornite that replaced logs and round nodules of carbonaceous fossil wood. Chalcocite appears to have replaced bornite and pyrite. Halos of malachite, azurite, and chrysocolla surround the mineralized fossil wood. Lindgren and others (1910) reported that fossil logs up to 60 ft long and 2.5 ft in diameter were mined. A specimen of fossil wood from the San Miguel mine contains 43% copper and 6.8 oz of silver per ton. Some of the ore is reported to have contained 64-65% copper, much contained 48-50% copper, and a small amount contained 35-40% copper along with 2.5 oz of silver per ton (Lindgren and others, 1910) .

Origin

Carbonaceous fossil logs and plant material in fluvial paleochannels created the reducing environment necessary for precipitation of copper and copper—iron sulfides from solutions moving through the permeable channel sands and gravels. Some of the copper sulfides probably replaced pyrite that had been precipitated in the presence of carbonaceous material. Although some of the copper sulfides appear to have replaced pyrite, all of the copper, most likely, was not deposited in this manner, because pyrite is not present in many specimens. Regardless of whether pyrite was replaced by copper sulfides or the copper sulfides directly replaced the carbonaceous material, the presence of the carbonaceous material ultimately was essential in localizing deposition of the ore. Later, the sulfides were oxidized, resulting in disseminations of malachite, azurite, and chrysocolla in the adjacent sandstone and conglomerate.

Two principal hypotheses concerning the time and processes of mineralization have been considered by

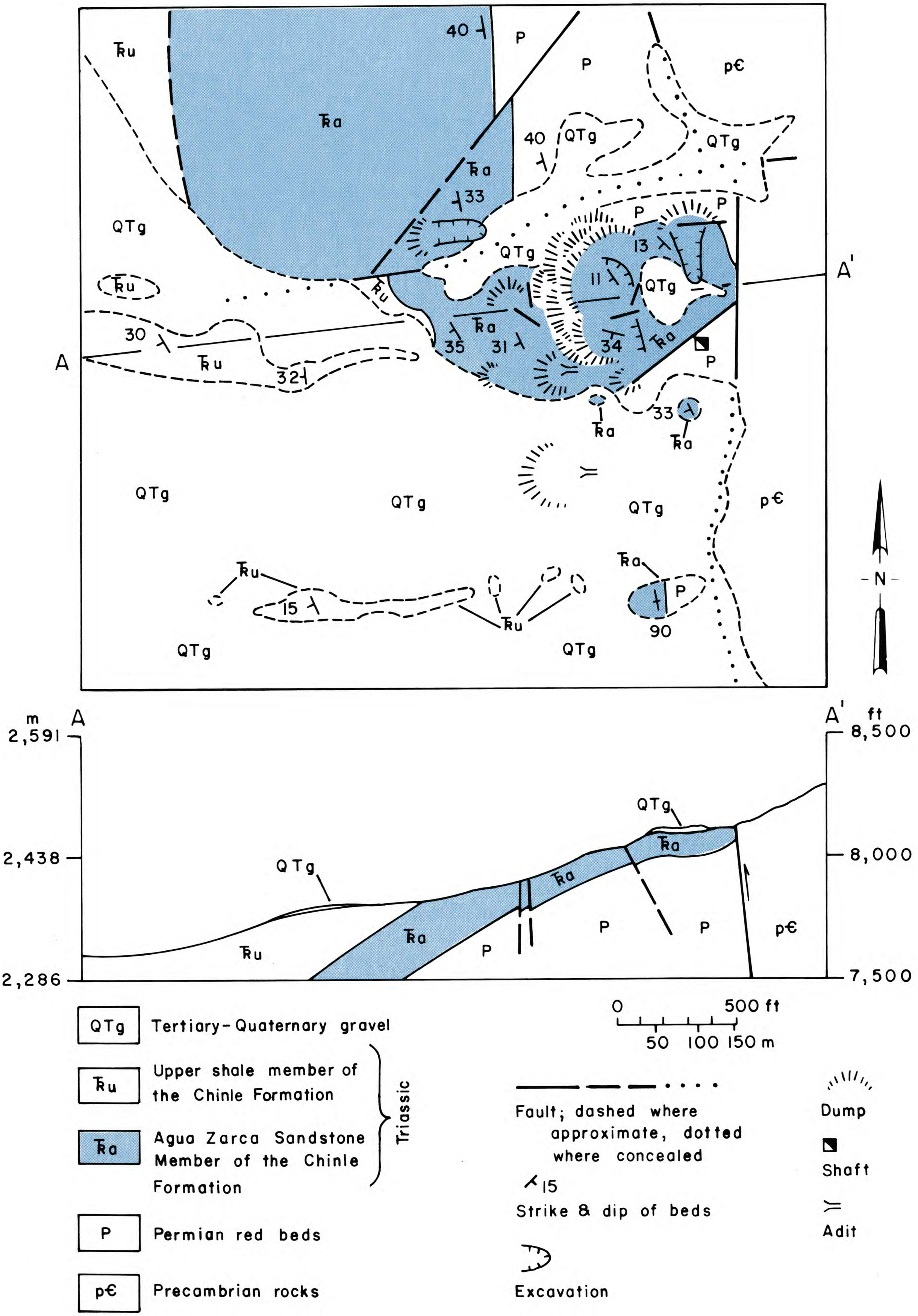


FIGURE 38—Generalized geologic map and structure section of San Miguel mine area (from Woodward, Kaufman, and others, 1974).

geologists working in this area: 1) sulfide ore minerals were deposited by ground water moving through permeable zones, either during, shortly after, or possibly long after deposition of the sediments; 2) hydro-thermal solutions passed upward along faults and mineralized favorable adjacent sedimentary rocks. These hypotheses have totally different and important implications for exploration; according to the first hypothesis, the mineralized areas need not be directly or even remotely associated with faults, whereas the second hypothesis implies that faults are critical in the localization of the ore deposits.

Lack of sulfide mineralization and of hydrothermal alteration along the faults or other conduits indicates that the copper-bearing solutions were not derived from nearby hydrothermal sources. No apparent relation exists between faults and mineralized zones as would be expected if the copper minerals were deposited by solutions moving through faults. The strata-bound nature of these deposits and their wide geographic distribution favor deposition from ground water.

Copper mineralization has not been observed in rocks younger than the Agua Zarca Sandstone Member of the Chinle Formation. The Poleo Sandstone Member of the Chinle commonly contains permeable carbonaceous zones, but no mineralization is reported. (Soule [1956] incorrectly reported that the host rock for some of the ore deposits discussed here was the Poleo Sandstone Member of the Chinle Formation.)

Primary sulfide ore deposition in the Agua Zarca Sandstone Member probably occurred after deposition of the host rock but prior to deep burial and probably prior to deposition of the Poleo Sandstone Member. Well preserved cellular structure in the mineralized fossil logs (Fig. 35) indicates that replacement by sulfides occurred prior to deep burial, which would have crushed the wood cells.

LaPoint (1974) discussed the possible source areas for these copper deposits and suggested that Precambrian metavolcanic terrane in northern New Mexico was the most likely source, with the copper coming from mafic rocks with low copper content, as well as from Precambrian sulfide deposits. General models to account for the ultimate source of the copper-bearing solutions include: 1) an older deposit leached by ground water, 2) hydrothermal solutions introduced into the paleohydrologic system from outside the study area, and 3) copper derived by leaching of large volumes of rock containing low abundances of the metal.

I favor a model that derives the copper from an older deposit, or deposits, located in the Uncompahgre highland to the north during the time of deposition of the Agua Zarca Sandstone Member. The highland supplied the clastic components of the Agua Zarca Sandstone Member of the Chinle Formation (Stewart and others, 1972, p. 94), and, in an area approximately 35 mi northeast of the Eureka mine, Gabelman and Brown (1955) reported detrital chalcocite in the Agua Zarca in a paleochannel. Precambrian copper sulfide deposits occur in the Brazos uplift of northern New Mexico (Bingler, 1968), an area that comprised part of the Uncompahgre highland in Triassic time. This model is similar to a tectonic—climatic model proposed by Strakhov (1970) to account for the genesis of sandstone copper deposits from copper sulfides that are leached from an actively dissected highland in a moist climatic zone where relatively low-pH hydrologic conditions exist. Copper is carried in solution by water draining into an arid intermontane basin where relatively high-pH hydrologic conditions occur. Deposition of copper minerals occurs as a result of either a local or a regional pH and(or) Eh change. The association of copper sulfide with coarse-grained clastic rocks appears to be related to changes in pH of water in streams moving from humid to arid environments (Strakhov, 1970, pp. 7181) . Mineralization in the Agua Zarca and Abo appears to be related to lowering of Eh conditions in and around accumulations of carbonaceous material as a result of fermentation, subsequent reduction of copper and iron in solution, and resultant precipitation of copper sulfides and copper—iron sulfides. In many cases the copper may have been deposited and later leached, perhaps several times, en route to its present location.

Other possibilities concerning the ultimate source of the copper are discussed below; however, they seem to have less in their favor than the model proposed above.

The possibility that copper was derived from Precambrian rocks in the Nacimiento area is unlikely, because these rocks were buried by the Abo Formation (Permian) during the time that the Agua Zarca Sandstone Member was being deposited. Also, the Precambrian rocks are low in metal content (Woodward, Kaufman, and others, 1974) .

The Mogollon highland to the south was the source area for the sediments composing the shale members of the Chinle Formation in the Nacimiento region (Stewart and others, 1972) . Much of the clay in these units is of volcanic origin, which suggests that leaching of copper from the shales is a possibility. Also, hydrothermal solutions may have entered the paleo-hydrologic system and moved northward from the Mogollon highland in the direction of sediment transport. The fact that the Poleo Sandstone Member contains permeable, carbonaceous zones and is enclosed by the Chinle shales but has not been mineralized detracts from this hypothesis.

No evidence exists of copper-bearing hydrothermal solutions being released into the groundwater system during Triassic time, although this may have happened. The Brazos uplift, the likely source area for the sediments of the Agua Zarca Sandstone and thus the likely source for the copper, is not reported to have had any igneous or hydrothermal activity during the Triassic.

Aggregate

Excellent gravel deposits, abundant near the base of the Sierra Nacimiento, are mainly terrace and pediment deposits composed of cobbles and boulders derived from Precambrian crystalline rocks. These deposits have been mapped in detail and are shown as Quaternary to Tertiary terrace and pediment deposits (QTtp) on the geologic quadrangle maps of this area.

Although most of these deposits consist of Precambrian rock clasts, a few contain a large proportion of Paleozoic and Mesozoic rock fragments. These Phanerozoic clasts are mostly limestone, sandstone, arkose, and orthoquartzite and are not as good for aggregate as the Precambrian clasts. Thicknesses up to 50 ft have been observed in the Cuba quadrangle, but most deposits are approximately 10 ft thick. Deposits near NM-44, on the west side of the Sierra Nacimiento, have been used extensively for highway aggregate.

Travertine

Light-tan, thin- to thick-bedded travertine up to 50 ft thick is exposed near the unsurveyed common corner of the Holy Ghost Spring, Gilman, and San Ysidro quadrangles on Zia Pueblo land. This exposure covers nearly 2 mi^2 and is readily accessible from NM-44. Locally, the travertine is gradational with overlying or underlying terrace or pediment gravel.

Another large exposure of travertine is present in secs. 16 and 21, T. 15 N., R. 1 E. in the San Ysidro quadrangle, but access is not as good here. Other smaller deposits occur in secs. 24, 25, and 36, T. 16 N., R. 1 E. in areas that have poor access.

Much of this travertine is suitable for building stone, but, at this time, a market has not been developed. Easton (1955) reported that several travertine deposits in T. 16 N., R. 1 E. are radioactive and assay 0.005 to 0. 006% U_3O_8.

Gypsum

The Todilto Formation, composed mainly of gypsum, is exposed in a nearly continuous outcrop band around the southern, western, and northern margins of the Nacimiento Mountains. The gypsum member of the Todilto is up to 150 ft thick, but averages approximately 100 ft in thickness. Large tonnages of gypsum amenable to surface mining are necessary for commercial deposits. Gypsum is mined at White Mesa from a dipslope in sec. 14, T. 15 N., R. 1 E. in the south-central part of the San Ysidro quadrangle. Other areas readily accessible from NM-44 are present in unsurveyed areas in the western part of the San Ysidro quadrangle and southeast Holy Ghost Spring quadrangle, all within the Zia Indian Reservation. Another area exposed on a dipslope over approximately 300 acres is present near NM-96 in secs. 4 and 9, T. 23 N., R. 1 E. in the Gallina quadrangle. Elsewhere, the Todilto Formation dips steeply and has a narrow outcrop, resulting in small tonnages that could be mined by surface methods.

Coal

Subbituminous coal is present in seams up to 6 ft thick in the Menefee Formation of the Mesaverde Group (Cretaceous) that crops out in La Ventana, San Pablo, Cuba, and Regina quadrangles. Major underground mining of coal occurred in the northern part of La Ventana quadrangle (Dane, 1936) where the Santa Fe, San Juan, and Northern Railway used to extend. This railroad, along with the coal mines, has been abandoned for many years. Dane (1936) gives detailed descriptions of the coal resources between La Ventana coal field and the area near Cuba. Surface mining near La Ventana is not economic because of the thinness of the coal beds and the large amount of overburden.

Another area that produced coal, but to a lesser degree than La Ventana, is near San Miguel Canyon in sec. 33, T. 20 N., R. 1 W. This coal was used for a smelter to treat copper ore from the San Miguel mine (Dane, 1936) .

Numerous adits are located elsewhere in the Menefee Formation along the outcrop belt, but most appear to be small mines that produced coal for local consumption. The steep dip and narrow seams at these localities preclude surface mining of the coal.

Humate

Humic acid-rich, carbonaceous shale or claystone has been mined from the Menefee Formation of the Mesaverde Group (Cretaceous) in sec. 9, T. 19 N., R. 1 W. of the San Pablo quadrangle. These rocks are crushed and sold as soil conditioners at relatively high prices compared to surface-mined coal (Shomaker and Hiss, 1974) . Large reserves are present.

Uranium

Uranium-bearing minerals and(or) radioactive anomalies have been reported for at least 87 localities in the Nacimiento area (Fig. 39; all localities in this section refer to Fig. 39), but only five of the localities are reported to have produced ore. Host rocks range in age from Pennsylvanian to Tertiary, with most of the occurrences found in the Abo (Permian) and Morrison (Jurassic) Formations. All the known deposits are subeconomic at this time. Most of the following material has been taken from the work of Chenoweth (1974); the reader is referred to his work for more detailed descriptions. Much of the information on production was provided by V. T. McLemore (personal communication 1983) . Inasmuch as the uranium deposits are stratabound, they are described according to the age of the host rocks, from oldest to youngest.

Anomalous radioactivity is reported for carbonaceous plant material with associated copper carbonates occurring in very coarse grained, light-gray, arkosic sandstone in the Madera Formation (localities 4 and 5) . No uranium minerals were noted at either locality.

Those deposits hosted by the Abo Formation (Permian) occur in gray, feldspathic sandstone and arkose containing carbonaceous plant material that commonly has associated copper minerals. Yellow, oxidized uranium minerals occur in many of the deposits. Deposits are clustered in the Gallina quadrangle (locality 6) and in the Jarosa quadrangle (locality 7), with scattered deposits near Blue Bird Mesa (locality 8) and in the northeast part of the San Ysidro quadrangle

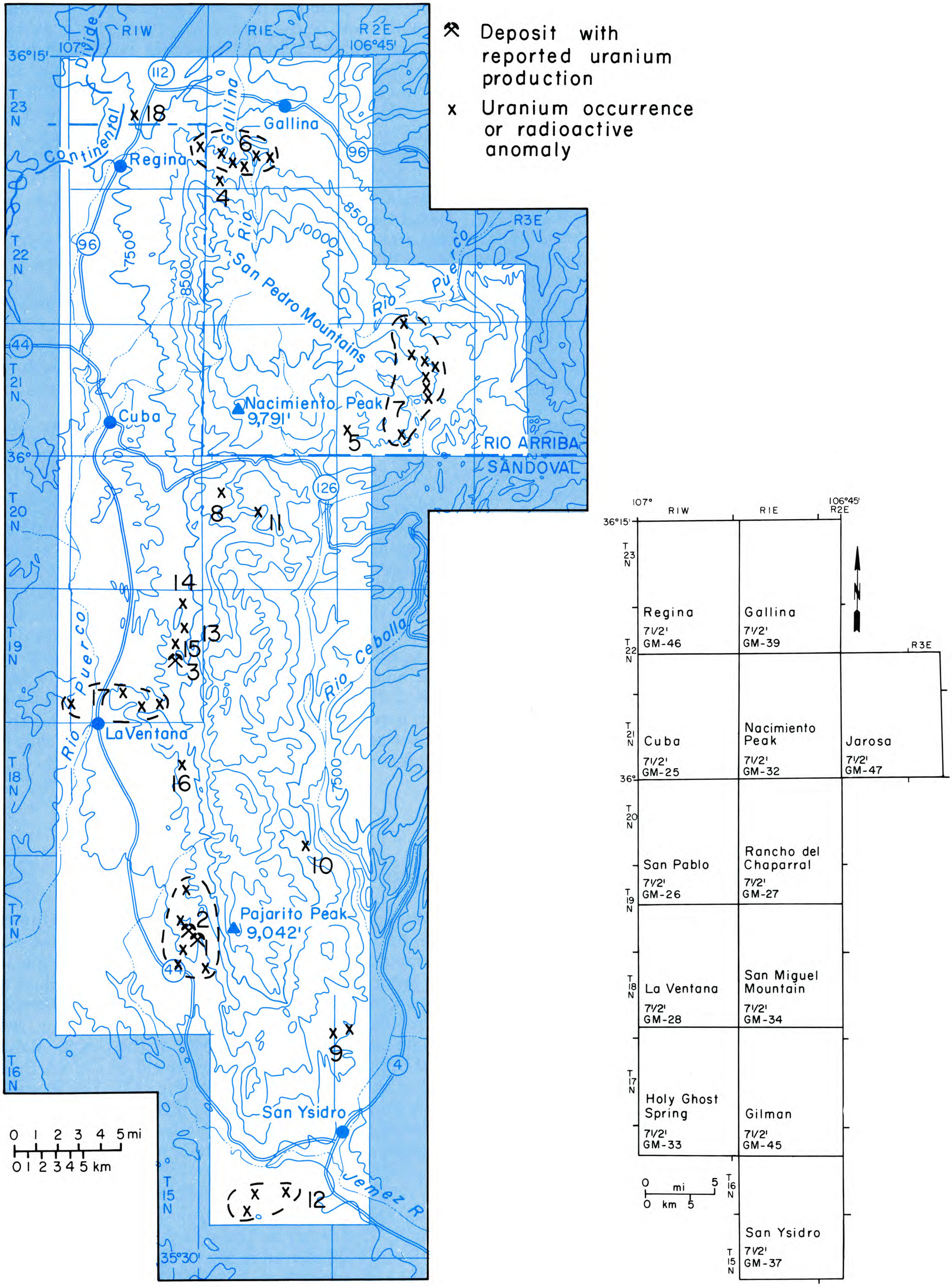


FIGURE 39—Occurrences of uranium-bearing minerals or radioactive anomalies (modified from Chenoweth, 1974).

(locality 9) . An unusual deposit in the Abo Formation occurs near Deer Creek in the Gilman quadrangle (locality 10), where the host rock is black, carbonaceous shale with associated copper sulfides. Production of uranium (locality 6) has been minor from the Corral #3 deposit (NE$^1/_4$ sec. 25, T. 23 N., R. 1 W.), which yielded 12 lb of U_3O_8 and 24 lb of V_2O_5 and from the Whiteflo #1 deposit (SW$^1/_4$ sec. 19, T. 23 N., R. 1 E.), which produced 7 lb of U_3O_8 and 43 lb of V_2O_5. The ore from the Corral #3 averaged 0.03% U_3O_8, and the Whiteflo #1 ore contained 0.08% U_3O_8. All of the other deposits in the Abo Formation are small and subeconomic.

The Agua Zarca Sandstone Member of the Chinle Formation (Triassic) hosts yellow uranium minerals associated with carbonaceous plant material and copper carbonates in medium- to coarse-grained, gray, quartzose sandstone at the Jewell claims in the Rancho del Chaparral quadrangle (locality 11) .

The Morrison Formation (Jurassic) is the host rock for uranium deposits in the eastern part of the Holy Ghost Spring quadrangle (clustered around localities 1 and 2) and in the southern part of the San Ysidro quadrangle (locality 12) . The Goodner and Collins leases (localities 1 and 2) produced 395 tons of ore containing 0.13% of U_3O_8 during 1957-1959 (Chenoweth, 1974) . The ore yielded 989 lb of U_3O_8 and 116 lb of V_2O_5. The ore came from fine- to medium-grained, lenticular, quartzose sandstone beds 10-30 ft thick in the Brushy Basin Shale Member. Near the ore the sandstone is red, but, elsewhere, it is light gray or tan. Some uranium in nearby localities occurs in the Westwater Canyon Sandstone Member as well. Chenoweth (1974) reported yellow and green uranium minerals along fractures and disseminated in sandstone, particularly near greenish clay galls and mudstone layers. In the San Ysidro quadrangle (locality 12) anomalous radioactivity is concentrated near mudstone galls, in limonite-stained sandstone lenses, and at sandstone-mudstone interfaces in the Brushy Basin Member. Visible uranium minerals are rare here (Chenoweth, 1974) . At locality 13 in the San Pablo quadrangle the Westwater Canyon Member contains bayleyite, a magnesium—uranium carbonate, and liebigite, a calcium—uranium carbonate (Chenoweth, 1974). Ridgley (1980) discussed the geology and uranium potential at the Dennison—Bunn claim (sec. 11, T. 19 N., R. 1 W.) and reported assays ranging from 0.002% to 0.07% U_3O_8. McLemore (personal communication 1983) collected a sample at this locality (locality 13) that assayed 0.082% U_3O_8. Green and others (1982) and Ridgley (1980) suggested that subsurface uranium deposits of low grade may be present in the Morrison Formation in the general vicinity of localities 1 and 2 northward to locality 13 (Fig. 39).

The Butler Brothers deposit in the northeast part of La Ventana quadrangle (locality 3) produced 23 tons of ore containing 0.63% of U_3O_8 from the Dakota Formation (Cretaceous) . The ore yielded 290 lb of U_3O_8 and 56 lb of V_2O_5. The host rock is carbonaceous shale approximately 1 ft thick. No uranium minerals are visible in the radioactive zone, which is approximately 100 ft along strike (Gabelman, 1956). Similar prospects occur north (localities 14 and 15) and south (locality 16) of the Butler deposit.

Several occurrences of uranium are reported in the Mesaverde Group in La Ventana quadrangle (locality 17) with most of the uranium occurring in coal, carbonaceous shale, and carbonaceous sandstone in the upper part of the Menefee Formation. Bachman and others (1959) identified coffinite, a uranium silicate, here, although no uranium minerals are visible to the naked eye. They (Bachman and others, 1959) reported 132,000 tons of coal and carbonaceous shale containing 0.10% uranium at this locality. Green and others (1982) also described the geology and uranium potential here. Potential uranium resources at La Ventana are estimated by the U.S. Department of Energy to be 35 tons of 0.10% U_3O_8 at $50 per pound and 1,539 tons of 0.07% U_3O_8 at $100 per pound.

At locality 18 in the Regina quadrangle the San Jose Formation (Tertiary) contains a yellow-green uranium mineral that coats fractures in gray-green mudstone. Limonite staining and black manganese minerals are associated with the uranium mineralization here.

Geothermal energy

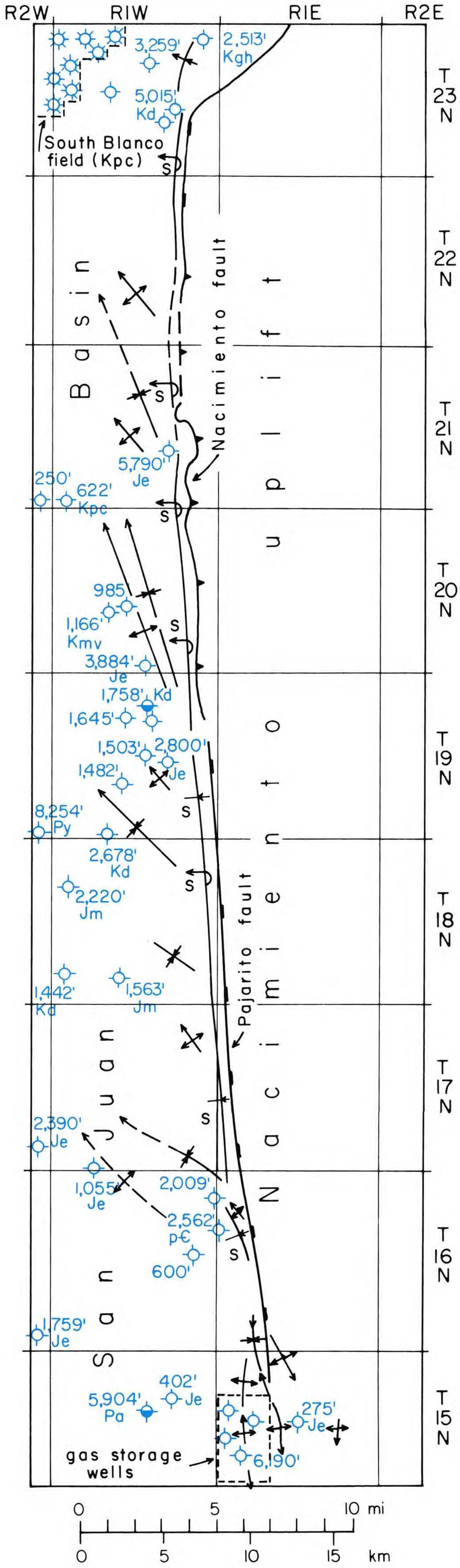
Near San Ysidro, secs. 9, 11, and 13, T. 15 N., R. 1 E. have been classified as a known geothermal resource area (KGRA) by the U.S. Geological Survey (Godwin and others, 1971) . The presence of warm springs and abundant travertine along the southern margin of the Nacimiento uplift indicate movement of thermal waters along and near the faults bounding the uplift. Callender (1982) reported that oxygen-isotope analyses indicate that the springs on the west side of the uplift probably have sources in reservoirs with temperatures of approximately 100°C. This suggests a potential for local use such as space heating, but generation of electricity is not feasible.

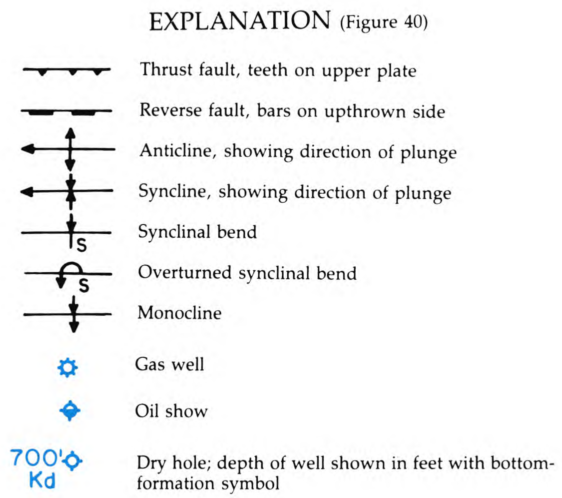
Oil and gas

Production and shows

Most of the oil and gas production in northwest New Mexico comes from Pennsylvanian, Jurassic, and Cretaceous rocks with the vast majority coming from the latter (Fassett and others, 1978). Within the Pictured Cliffs Sandstone (Cretaceous) gas is produced from a stratigraphic trap in northwest-trending, lenticular bar and beach deposits at the South Blanco field approximately 3 mi northwest of the northern end of the Nacimiento uplift (Fig. 40). The Pictured Cliffs thins to the southeast and is absent in outcrops at the eastern margin of the San Juan Basin. Estimated recovery of gas from this field is 1, 377, 618, 000 MCFG (Brown, C. F., 1973) .

A drill-stem test in the Dakota Formation (Cretaceous) recovered 400 ft of slightly gas- and oil-cut mud with 947 ft of water and mud in the Benn—McKay No. 2-3 Benn—McKay well in sec. 3, T. 19 N., R. 1 W. The Avila Oil Corporation's No. 1 Odlum well (sec. 15, T. 15 N., R. 1 W.) is reported to have encountered a slight oil show throughout the Entrada Sandstone (Jurassic).





Potential hydrocarbon source rocks and reservoirs

Potential hydrocarbon source rocks occur in the Madera Formation (Pennsylvanian), Todilto Formation (Jurassic), and in the dark, organic-rich beds of the Cretaceous System, including the Dakota Formation, Mancos Shale, Mesaverde Group, Lewis Shale, and Kirtland Shale and Fruitland Formation undivided. Clastic rocks are associated with or adjacent to these units and could be reservoirs for oil and(or) gas, particularly the sandstones in the Madera Formation, the Entrada Sandstone, and the sandstones in the Cretaceous System. The following descriptions of potential hydrocarbon source rocks and reservoir beds are presented in stratigraphic order from oldest to youngest.

The subsurface extent of the Arroyo Peñasco Formation (Mississippian) is not known. Its subsurface presence, in fact, may be very local, because, at the surface, it is present only at those localities where it has been preserved as down-faulted blocks that escaped widespread pre-Pennsylvanian erosion. Carbonate rocks of the Arroyo Peñasco Formation are dense and have little porosity except where fractured. Hydrocarbon source rocks are rare in this unit. This, in conjunction with the small, isolated patches of preserved Arroyo Peñasco, suggests that the Arroyo Peñasco Formation is not a primary hydrocarbon exploration target in the Nacimiento region. The nearest hydrocarbon production from Mississippian rocks is approximately 100 mi away in the northwest corner of New Mexico (Fassett and others, 1978) . Another unit of Mississippian age, the Log Springs Formation, consists of reddish, continental clastic rocks that are present only locally; the Log Springs, therefore, is not likely to be a principal exploration target.

Dark, organic-rich shales and limestones of the Madera Formation (Pennsylvanian) are potential source rocks; numerous associated beds of sandstone and limestone also could serve as reservoir rocks. Pennsylvanian rocks produce oil and(or) gas from the

FIGURE 40—Generalized tectonic map showing wells and oil and gas occurrences near the Nacimiento uplift with total depth (in feet) and bottom-hole formation symbols. Rock units are: **p€** = Precambrian rocks, **Pa** = Abo Formation, **Py** = Yeso Formation, **Je** = Entrada Sandstone, **Jm** = Morrison Formation, **Kd** = Dakota Formation, **Kmv** = Mesaverde Group, **Kpc** = Pictured Cliffs Sandstone, and **Kgh** = Greenhorn Limestone Member of Mancos Shale.

Rattlesnake, Barker Creek, Hogback, Table Mesa, To-cito Dome, Pajarito, Cone, Buena Suerte, and Ship-rock fields in the northwest part of New Mexico (Fassett and others, 1978) . Pennsylvanian rocks are absent locally along the Nacimiento uplift (Fig. 5). The subsurface distribution of the Madera must be taken into account prior to exploration for oil and gas in rocks of the Pennsylvanian System.

No production of oil or gas from Permian or Triassic rocks is reported in northwest New Mexico (Fassett and others, 1978) . These beds have no apparent source rocks in the Nacimiento area, suggesting that they are unlikely to contain major amounts of hydrocarbons despite the fact that sandstones with reservoir capabilities are abundant.

The Entrada Sandstone (Jurassic) is a reservoir for oil in several small fields in the nearby eastern part of the San Juan Basin (Vincelette and Chittum, 1981). The source of the oil is apparently the basal, laminated limestone member of the overlying Todilto Formation (Jurassic). The uppermost Jurassic unit, the Morrison Formation, is composed of continental sandstone and variegated mudstone; no production has come from the Morrison in northwest New Mexico, and it is unlikely to contain hydrocarbons in the Nacimiento area.

Six major units in the Cretaceous, the Dakota Formation, Mancos Shale, Mesaverde Group, Lewis Shale, Pictured Cliffs Sandstone, and Kirtland Shale and Fruitland Formation undivided, contain abundant black, organic-rich source rocks and associated clastic reservoir beds. Most of the oil and gas production in the San Juan Basin comes from the Cretaceous; these units are all primary exploration targets in the Nacimiento region, including the major shale units, which may have fracture reservoirs (Gorham and others, 1979) .

Tertiary units (Ojo Alamo Sandstone, Nacimiento Formation, and San Jose Formation) are not primary exploration targets, but, locally, they may contain small amounts of hydrocarbons derived from older rocks (Fassett and others, 1978).

Potential hydrocarbon traps

Four principal types of potential hydrocarbon traps are found in this region: 1) lenticular bar and beach deposits enclosed by tight rocks, 2) updip stratigraphic pinchouts on the eastern side of the San Juan Basin, 3) truncated beds in the footwall beneath the thrust and reverse faults bounding the west side of the Nacimiento uplift, and 4) fracture reservoirs in Cretaceous shales along the synclinal bend on the east side of the San Juan Basin.

The South Blanco field in the northwest corner of the area of the report (Fig. 40) belongs to the first type of trap. The northwest-trending bar and beach deposits of the Pictured Cliffs Sandstone (Brown, C. F., 1973) extend across the San Juan Basin. On the east side of the basin, however, the Pictured Cliffs is absent, thus limiting the southeast extension of the producing trend.

Updip pinchout of the Madera Formation probably occurs in the subsurface a short distance west of the Nacimiento uplift (Fig. 5) and could provide traps, especially along the northwest-trending, en echelon anticlines in the eastern part of the San Juan Basin.

Structural overhang of the Nacimiento uplift onto the eastern edge of the San Juan Basin may conceal traps beneath the thrust and reverse faults bounding the west side of the uplift. The most promising potential reservoir rocks, the Madera Formation (Pennsylvanian), the Entrada Sandstone (Jurassic), and the Dakota Formation (Cretaceous), are upturned or inverted on the eastern limb of the synclinal bend along the east side of the San Juan Basin and, locally, are truncated by the thrust and reverse faults with resultant overriding by older rocks of the Nacimiento uplift. This situation creates potential traps for hydrocarbons (Fig. 41) . Stratigraphically lower rocks are more commonly truncated by the uplift than are younger beds, and, therefore, they offer a greater number of localities for potential traps.

Potential traps in the Madera Formation (Pennsylvanian) occur in sec. 36, T. 23 N., R. 1 W., in unsurveyed secs. 30 and 31, T. 18 N., R. 1 E., and from sec. 20, T. 17 N., R. 1 E., to sec. 9, T. 15 N., R. 1 E., where overriding by the Nacimiento uplift occurs. The Madera Formation is absent locally (Fig. 5) where Permian beds rest directly on the Precambrian; therefore, the Madera is not necessarily present in the subsurface at all localities where the uplift has been thrust onto rocks younger than the Madera.

The Entrada Sandstone (Jurassic) may contain potential traps along the structural overhang from sec. 36, T. 23 N., R. 1 W. to sec. 14, T. 22 N., R. 1 W., from sec. 26, T. 22 N., R. 1 W. to sec. 14, T. 21 N., R. 1 W., and from sec. 25, T. 21 N., R. 1 W. to sec. 35, T. 20 N., R. 1 W.

The Dakota Formation (Cretaceous) has been overridden by the uplift at only a few localities (sec. 14, T. 22 N., R. 1 W., from sec. 26, T. 22 N., R. 1 W. to

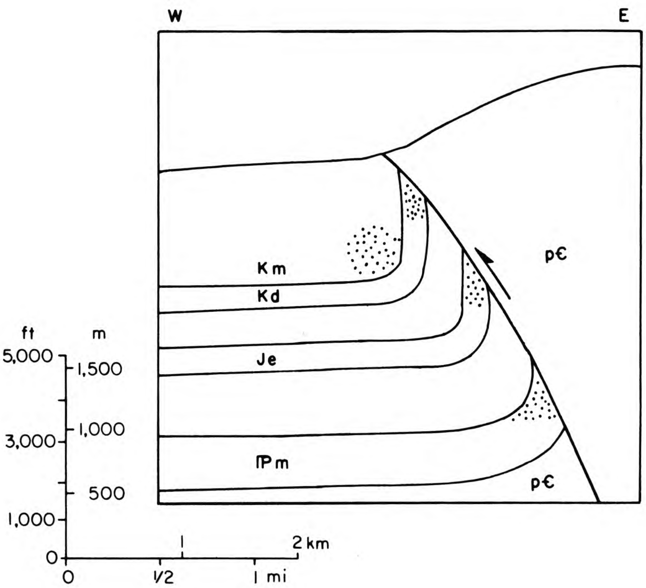


FIGURE 41—Potential hydrocarbon traps (stippled) in a diagrammatic east–west structure section through the western part of the Nacimiento uplift and eastern San Juan Basin. Formation symbols are: **€** = Precambrian rocks, **ℙm** = Madera Formation, **Je** = Entrada Sandstone, **Kd** = Dakota Formation, and **Km** = Mancos Shale.

sec. 14, T. 21 N., R. 1 W., and secs. 25 and 36, T. 21 N., R. 1 W.).

At least the lower part of the Mancos Shale is upturned and truncated by a thrust in sec. 35, T. 22 N., R. 1 W. and in sec. 2, T. 21 N., R. 1 W., where extensive pediment and terrace deposits of Quaternary and(or) late Tertiary age unconformably cover much of the range-marginal fault and the adjacent part of the basin. Some of the sandstone in the lower part of the Mancos could be prospective here.

The northwest-trending, en echelon anticlines noted earlier may form traps where they have been truncated by the uplift. Projection of the fold axes under the overhang provides initial targets that can be further refined with seismic studies.

No evidence exists of longitudinal anticlines that are parallel to the uplift and covered by the overhang; however, east—west seismic lines should be run to better interpret the subsurface relations along the front of the uplift. This might reveal potential traps that cannot be discerned from surface observations.

Fracture reservoirs may occur in brittle quartzose siltstone and carbonate-rich interbeds in the Mancos Shale where it is sharply folded along the synclinal bend on the east side of the San Juan Basin (Fig. 41). Gorham and others (1979) discussed oil and gas production from fracture reservoirs in Cretaceous rocks of the San Juan Basin. They suggested that exploration should focus on areas of maximum curvature of folds in the subsurface and that synclines are not necessarily unfavorable for the formation of fracture reservoirs.

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Index

(Page numbers in italics denote detailed discussions.)

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TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, μm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^3	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^1	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^3	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^1	grams, gr
troy ounces, oz	3.1103×10^1	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^1	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}

TO CONVERT	MULTIPLY BY	TO OBTAIN
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^3	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^2	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^6	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^1	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^5	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^2	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^3 (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

Contents of pocket

SHEET 1—Generalized bedrock geologic map and structure sections of Sierra Nacimiento and adjacent areas. Major tectonic and geologic provinces of Nacimiento Mountains and adjacent areas shown on inset map.