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Structure And Stratigraphy Of The San Ysidro Quadrangle, Sandoval County, New Mexico

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This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of The University of New Mexico in partial fulfillment of the requirements for the degree of

Master of Science

STRUCTURE AND STRATIGRAPHY OF THE SAN YSIDRO QUADRANGLE, SANDOVAL COUNTY, NEW MEXICO
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BY

Richard LuVerne Ruetschilling

B.S., Saint Joseph's College, 1968

THESIS

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ABSTRACT

The mapped area is in Sandoval County, New Mexico, and includes the San Ysidro 7-1/2 minute quadrangle. Precambrian rocks in the area consist mainly of quartz monzonite gneiss. Quartz diorite xenoliths and leucocratic dike rocks are less abundant.

Strata totaling 1300 meters, ranging from Morrow-age strata of Pennsylvanian age through the Zia Sand Formation of Miocene age, are exposed in the area (Fig. 3). Overlying the marine Pennsylvanian Morrow-age strata and Madera Formation is 900 meters of continental, marginal marine, and evaporite deposits consisting, in ascending order, of the Permian Abo, Yeso, Glorieta, San Andres and Bernal Formations, the Chinle Formation of Triassic age, and the Entrada, Todilto, Summerville, and Morrision Formations of Jurassic age. Cretaceous rocks are represented by the marginal-marine Dakota Formation and part of the marine Mancos Formation, totaling 200 meters. The Zia Sand Formation of Miocene age is approximately 100 m thick in the area and consists of continental deposits.

Five major structural elements each contribute over 300 m of structural relief: 1) the Pajarito fault, 2) the San Ysidro fault, 3) north- and northwest-trending folds, 4) the Jemez Pueblo fault zone, and 5) the Jack Rabbit Flats fault zone. The Pajarito fault is a steeply dipping reverse fault and has no strike-slip component in the area.

There were two main periods of deformation. The first occurred during Paleocene and Eocene time and resulted in the development of northwest-trending folds, northeast-trending tension fractures and possibly north-trending fractures along which later vertical uplift

occurred. Earliest deformation resulted from the right-shift of the Colorado Plateau. The second period of uplift occurred in post-middle Miocene time and is related to the formation of the Rio Grande depresion. This is the main period of vertical uplift in the area and resulted in the formation of north- and northeast-trending faults including the Pajarito fault. This uplift resulted from the arching of the rim of the Rio Grande depression.

Extensive gypsum deposits occur in the area and gypsum is currently being quarried on White Mesa, 1 mile south of San Ysidro. Minor copper mineralization occurs in carbonaceous channel-sandstones in the Abo Formation.

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INTRODUCTION

Location and Accessibility

The study area includes the entire San Ysidro 7-1/2 minute quadrangle in Sandoval County, New Mexico (Fig. 4). This area contains parts of the Zia Pueblo, the Zia Indian Reservation, the Ojo del Spiritu Santo Land Grant of the Zia Indians, the Jemez Pueblo, the Jemez Indian Reservation, the San Ysidro Land Grant, federal lands supervised by the Bureau of Land Management and private-ownership land. The non-Indian land is restricted to the southern third of the map-area.

Access to the area is excellent with New Mexico Highways 4 and 44, both paved roads, running through the center of the area. Several jeep trails branch from these roads.

Physiography

The mapped area includes the southern end of the Nacimiento Mountains and the western margin of the Rio Grande depression. There is 600 m of topographic relief, with the maximum elevation reaching 2260 m at Red Mesa. Mesas and broad flood plains dominate the physiography of the area. The mesas, with the exception of White Mesa, are associated with fault scarps. The Arroyo Peñasco, Cañada de las Milpas, Jemez River and Rio Salado form broad flood plains where they cross outcrop areas of the non-resistant Petrified Forest Member of the Chinle Formation, Mancos Shale and Zia Sand Formation. Hogbacks occur around the Tierra Amarillo anticline (Fig. 5) and the Cañada de las Milpas syncline. Mesa Cuchilla and the Sierra Nacimiento ridge are cuestas capped by resistant sandstone beds of the basal member of the Chinle Formation.

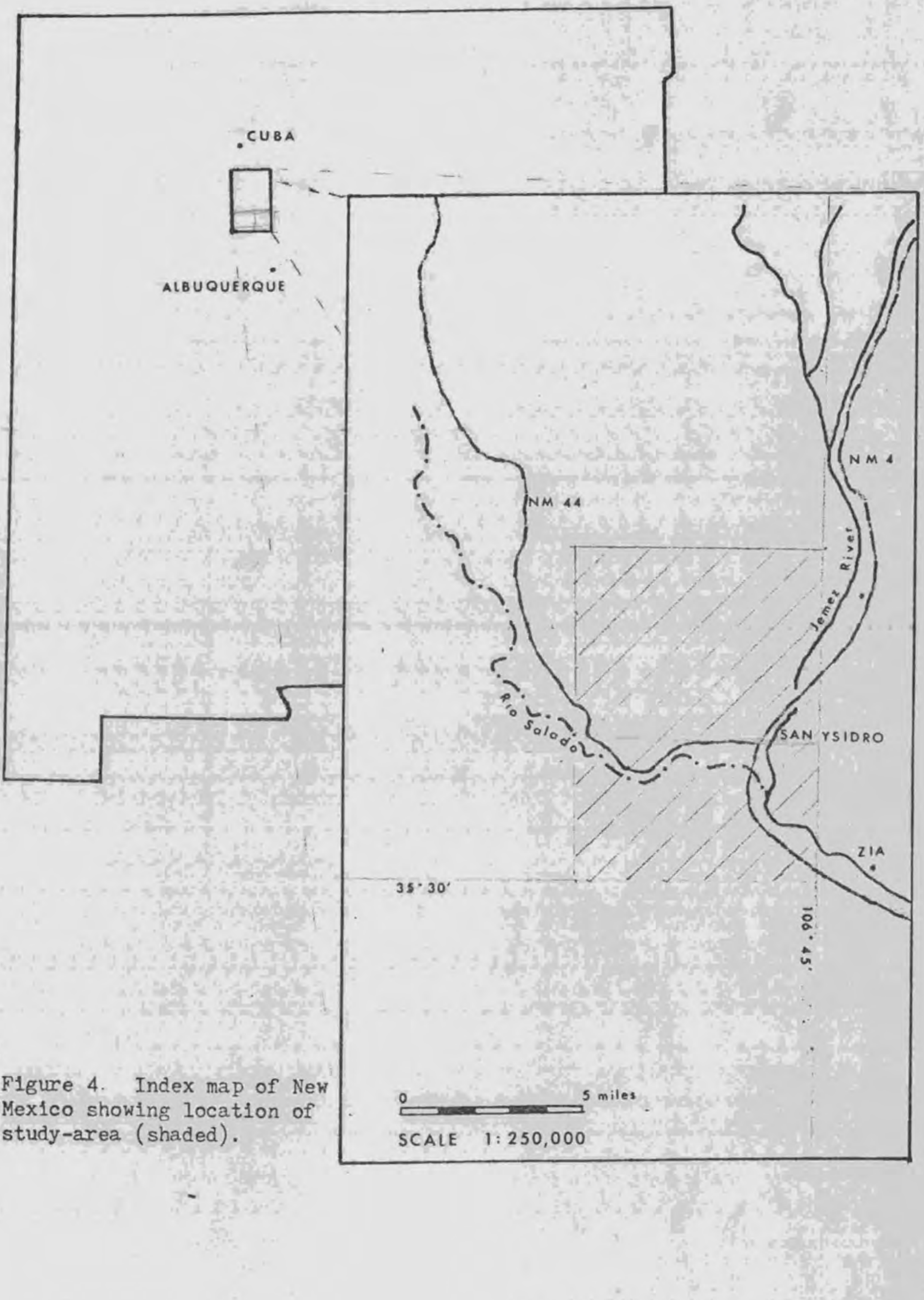


Figure 4. Index map of New Mexico showing location of study-area (shaded).

Figure 5. View north along the east limb of the Tierra Amarillo anticline. Flat irons are formed in the Brushy Basin Member of the Morrison Formation.

Purpose

The main purpose of this study was to map the geology of the San Ysidro 7-1/2 minute quadrangle at a scale of 1:24,000 and to describe the Precambrian rocks, the structure and the stratigraphic units of the area. Particular attention has been given to the interpretation of the age and development of deformation and the determination of the relationship between structures produced by the Laramide orogeny and the Rio Grande depression.

Methods

Mapping was carried out during the spring and fall of 1972 and the spring of 1973 using the San Ysidro 7-1/2 minute quadrangle map as base map. Stratigraphic sections were measured using a Jacob staff and Brunton compass. Thin sections of representative Precambrian rocks were examined microscopically and all modal analyses given are based on visual estimates of mineral percentages.

Previous Work

Previous geologic investigations carried out in this area include only the reconnaissance report by Renick (1931) at a scale of 1:250,000 and the map of Wood and Northrop (1946) at a scale of approximately 1:100,000.

Acknowledgments

I would like to thank Drs. Jonathan F. Callender, Albert M. Kudo, and Douglas G. Brookins, for reviewing the text, Ruben Martinez, Gary Flesch and George Forsythe for their encouragement and stimulating conversations, Drs. Charles T. Siemers and Lee A. Woodward for their great patience and advice and most of all, my wife, Rosemary, who shared with me a deep love of the beauty of this land.

ROCK UNITS

Precambrian igneous and metamorphic rocks and strata totaling 1300 meters (Fig. 3) ranging from Morrow-age strata of Pennsylvanian age through the Zia Sand Formation of Miocene age, are exposed in the area. Overlying the marine Morrow-age strata and Madera Formation of Pennsylvanian age is 900 m of continental, marginal marine, and evaporite deposits consisting, in ascending order, of the Abo, Yeso, Glorieta, San Andres and Bernal Formations of Permian age, the Chinle Formation of Triassic age, and the Entrada, Todilto, Summerville, and Morrison Formations of Jurassic age. Rocks of Cretaceous age are represented by the marginal marine, Dakota Formation and part of the marine Mancos Formation, totaling 200 meters. The Zia Sand Formation of Miocene age is approximately 100 m thick in the area and consists of continental deposits.

Precambrian Rocks

The Precambrian rocks in this area include the following units, from oldest to youngest:

1. Xenoliths of biotite quartz diorite.
2. Quartz monzonite gneiss, the dominant Precambrian rocks in the area.
3. Leucocratic dike rocks (aplite, pegmatite, and fine-grained granitic rocks) which intrude all the other Precambrian rocks.

No absolute ages have been determined for these rocks. They are assumed to be Precambrian in age because they are all overlain with an erosional unconformity by strata of Pennsylvanian age, and there are no known basement rocks of Paleozoic age in northwestern New Mexico.

A radiometric age of a quartz-feldspar-muscovite schist in the Tusas Mountains approximately 120 km north of the study area indicates an age of 1,425 m.y. for the time of metamorphism (Long, 1972, p. 3425). Radiometric dating of Precambrian rocks of the Sandia Mountains, 64 km to the southeast, gave an age of at least 1470 m.y. (Brookins, 1973, p. 467). Both dates are comparable to ages determined for other Precambrian rocks in northern New Mexico and southern Colorado (Long, 1972, p. 3430). Precambrian rocks of the southern Nacimiento Mountains may have generally similar ages.

The metamorphic rocks all have a plagioclase (An 25-40)-microcline-quartz-biotite-epidote- mineral assemblage. No muscovite or orthoclase was noted in the metamorphic rocks studied. Metamorphism reached the amphibolite facies which Turner (1968, p. 307-308) interpreted as covering the span of medium- to high-grade metamorphic facies in many areas of progressive regional metamorphism. Winkler (1965, p. 93) stated that the absence of muscovite is significant in metamorphic rocks with hydrous minerals and a high potassium, aluminum and quartz content; pressures of at least 4,000 bars and temperatures of the order of 680° to 690°C must be exceeded for the complete breakdown of muscovite to occur. Turner (1968, p. 354) reported that the quartz-muscovite mineral assemblage becomes unstable at 600°C at 2000 bars.

Xenoliths

Xenoliths ranging in size from a few centimeters to several hundreds of meters in diameter are present in Arroyo Peñasco. An east-trending shear zone separates the main body of mafic inclusions from quartz monzonite gneiss relatively free of inclusions. These rocks are generally dark grayish-green, fine-grained and slightly foliated. The contact of the xenoliths with the surrounding quartz monzonite gneiss ranges from sharp (Fig. 6) to gradational. The quartz monzonite gneiss increases in calcic plagioclase and sphene in the vicinity of the mafic bodies. Numerous unmetamorphosed pegmatites cut the xenoliths and the adjacent quartz monzonite gneiss.

Microscopically, the xenoliths are fine-grained and have hypidiomorphic-granular to schistose texture. Megacrysts of plagioclase, microcline, and quartz are abundant in samples collected adjacent to the quartz monzonite gneiss.

Modal composition of the rock is as follows:

50%	plagioclase (An_{25-40})
10%	microcline
13%	quartz
10%	biotite
5%	epidote
4%	chlorite
3%	opaques
2%	sphene
1%	apatite
1%	calcite
<1%	clinozoistite
<1%	myrmekite
tr	zircon, rutile, sericite and kaolinite

Plagioclase (An_{25-40}) occurs as zoned subhedral grains 0.5 to 3.25 mm in length, that have been altered to calcite, sericite, kaolinite and epidote. Some grains show reverse zoning. Biotite, epidote, microcline and quartz embay many plagioclase grains. Myrmekite commonly occurs along plagioclase-microcline grain contacts.

Figure 6. Sharp contact between quartz diorite xenolith and quartz monzonite gneiss. Symbols are the same as Figure 1. Lense cap 5 cm in diameter.

Microcline generally occurs as subhedral poikilitic megacrysts that are up to 11.0 mm in length. Much of the microcline is microperthitic. Quartz grains are predominantly grain aggregates composed of anhedral grains with undulatory extinction and sutured contacts. The average size of the quartz aggregates is 0.4 mm. Biotite is slightly altered to chlorite and is associated with epidote, clinozoisite, opaques, sphene, zircon, and apatite. Sphene occurs in euhedral grains up to 1.0 mm in length that generally have been altered to calcite and opaques.

Quartz Monzonite Gneiss

Quartz monzonite gneiss is the most abundant Precambrian rock in the area. It is moderate red to grayish-pink, medium- to coarse-grained with foliation striking N.30°-45°E. Foliation is due to the alignment of biotite and feldspar grains. Gneissic texture is generally poorly developed, but where present it is due to segregation of the minerals into quartz and feldspar-rich layers and biotite-rich layers. At the Mesa Cuchilla anticline the gneiss and leucocratic dike rocks are highly sheared and locally have undergone cataclastic deformation. The shearing appears to have resulted as the response of the basement rock to the development of the fold during the early Tertiary deformation of the area.

Modal composition of the rock is as follows:

16%	quartz
35%	microcline
30%	plagioclase (An_{25-30})
7%	biotite
1%	sphene
1%	opaques

<1%	myrmekite
<1%	apatite
tr	zircon, sericite, kaolinite, chlorite

Microscopically, this rock is hypidiomorphic-granular in texture. Megacrysts of plagioclase, quartz and microcline occur in a groundmass of quartz, microcline, plagioclase and biotite. Some of the feldspar grains have poikilitic textures. Microsheared zones up to 1.0 mm wide were present in most samples.

Plagioclase (An_{25-30}) occurs as subhedral grains, 0.3 to 2.0 mm long, in the groundmass and as subhedral megacrysts up to 6.0 mm. Most grains have been kaolinized and sericitized. Myrmekite occurs along plagioclase-microcline grain contacts. A few of the plagioclase grains have bent twin lamellae. The megacrysts are commonly poikilitic and contain inclusions of quartz and microcline.

Microcline is fresh and occurs as grains 0.5 to 1.5 mm long in the groundmass and as megacrysts up to 12.0 mm long. Many of the microcline megacrysts are poikilitic and microperthitic.

Quartz occurs as anhedral grains and aggregates of anhedral grains 0.5 to 10.0 mm in diameter. All grains show undulatory extinction and many have sutured contacts. Biotite occurs as individual grains or grain aggregates 0.2 to 2.0 mm long. Alignment of biotite grains is generally not strong. Sphene, apatite, opaques, and epidote are commonly associated with biotite.

The presence of slightly metamorphosed quartz diorite inclusions, its uniform composition in the southern Nacimiento Mountains and the consistent N.30-45°E. strike of the foliation throughout the area suggest that this rock represents a regionally metamorphosed igneous pluton.

Leucocratic Dike Rocks

The quartz monzonite gneiss is cut by dikes consisting of pegmatite, aplite, and fine-grained granite to quartz monzonite. Zoned pegmatite dikes also cut the quartz diorite inclusions (Fig. 7).

Aplites, pegmatites, and fine-grained granitic rocks all occur in dikes generally less than 1.0 m wide. Microcline, quartz, and plagioclase are the dominant minerals, with lesser amounts of biotite and muscovite. One pegmatite dike approximately 3.0 m wide and 1.0 km long was mapped.

Pennsylvanian System

Wood and Northrop (1946) mapped three Pennsylvanian units in the map area, the upper clastic member of the Sandia Formation, the lower gray limestone member of the Madera Formation, and the upper arkosic limestone member of the Madera Formation. Based on the paleontologic evidence, Wood and Northrop dated the upper clastic member of the Sandia Formation as Morrow to Lampasas in age, the lower gray limestone as early Des Moines to Virgil. In this report the Pennsylvanian rocks have been divided into an informal unit of Morrow-age strata and the Madera Formation.

Morrow-Age Strata

Armstrong (1955, p. 9) recognized Morrow-age fauna occurring in strata at Arroyo Peñasco, 3.0 km north of the study area. The section described by Armstrong was visited by this writer who noted that the Morrow-age limestones are recrystallized, crossbedded and contain abundant megafossils and well-rounded granules of quartz and chert. These characteristics make the Morrow-age limestones lithologically

Figure 7. Zoned pegmatite dike cutting quartz diorite xenolith. Symbols are the same as Figure 1.

distinct from the limestones of the overlying Madera Formation.

Strata containing limestones lithologically similar to those of the Morrow-age strata are present on the Mesa Cuchilla anticline. In this report the contact of the Morrow-age strata with the overlying Madera Formation was placed at the top of the uppermost lithologically distinct limestone bed. It is possible that in using only lithologic criteria in placing the contact, some Morrow-age strata was included in the Madera Formation. At measured section 1 (Figs. 1 and 8) the Morrow-age strata is 6.2 m thick and has an erosional unconformity with the underlying Precambrian rock. The base of the unit consists of a non-lithified mudstone containing cobbles of Precambrian rock. This bed is 0.1 to 0.7 cm thick and is overlain by 5.5 m of cross-bedded, recrystallized, arenaceous, lenticular, highly fossiliferous limestone containing rounded quartz and chert granules that is intercalated with mudstone and highly fossiliferous marl beds.

Madera Formation

The Madera Formation was named by Keyes (1903) for exposures in the Sandia Mountains, New Mexico. Because paleontologic criteria are more reliable than lithology in determining stratigraphic position in the Madera, it was not subdivided into members in this report. Three sections of the Madera were measured and they indicate that the formation is marked by diverse lithologies, rapid facies changes and considerable variation in thickness. At measured section 1 (Fig. 1 and 8) the Madera overlies Morrow-age strata and alluvium obscures its upper contact with the Abo Formation. It is approximately 100 m thick and is characterized by the cyclic repetition of unfossiliferous mudstone, fossiliferous shale and fossiliferous limestone beds. Feldspathic arenite beds make up approximately 10 percent of the unit.

Measured sections 2a and 2b were measured along the Arroyo Peñasco (Figs. 1 and 8). At that location the Madera has an irregular erosional contact with the underlying Precambrian rock and overlying Abo Formation. At section 2a the Madera is 7.7 m thick and consists of a 2.3 m thick conglomeratic arkose bed that is overlain by 5.4 m of fossiliferous limestone that locally contains angular Precambrian lithic fragments up to 10 cm in diameter. At section 2b the Madera is 1.0 m thick. Except for a small local remnant of the fossiliferous limestone, only the conglomeratic arkose bed is present.

Measured section 3 (Figs. 1 and 8) was measured outside of the map area, approximately 5.0 km north of section 2 and 1.0 km west of Log Springs. At this locality the Madera is approximately 165 m thick. It has an erosional basal contact with the Precambrian and its upper contact with the Abo Formation is obscured by alluvium. Arkose, conglomeratic arkose, arkosic limestone and feldspathic arenite beds make up approximately 50 percent of the section, fossiliferous limestone 35 percent, and mudstone and fossiliferous shale 15 percent. The basal 100 m consists almost entirely of intercalated limestone and arkose beds, while the upper 65 m is characterized by the cyclic repetition of arkose, limestone, and mudstone beds.

The Madera is absent in the north-central part of Jack Rabbit Flats, 2 km north of the study area (Martinez, personal communication, 1973). There the Abo Formation has a sedimentary contact with the Precambrian. This locality is nearly midway between sections 1 and 3.

Permian System

Abo Formation

The Abo Formation was named by Lee and Girty (1909) for exposures in Abo Canyon at the south end of the Manzano Range, New Mexico; however, they gave no specific type locality. Needham and Bates (1943, p. 1654) redefined the Abo and specified a type locality. On the basis of plant and vertebrate fossils and subsurface correlation of the Abo with marine fossiliferous strata in the Permian Basin, Bates and others (1947, p. 28) tentatively considered the Abo to be Wolfcamp to Leonard in age.

The Abo is generally about 180 m thick in the area. Wood and Northrop (1946) reported that the Abo thins across the axis of the Nacimiento Mountains. Because a complete Abo section occurs at only one locality in the study area, changes in its thickness could not be determined. It consists of approximately 65 percent reddish-brown mudstone with 35 percent crossbedded, lenticular, reddish-brown to greenish-gray feldspathic arenite interbeds that locally contain abundant ripple marks, biogenic structures (Fig. 9) and plant debris. The arenite beds are 0.2 to 5.0 m thick and fine- to coarse-grained. Nodular argillaceous limestone beds are present also. Copper deposits associated with carbonaceous material in sandstone beds were found at four localities in the Abo (Fig. 1).

Yeso Formation

The Yeso Formation was named by Lee and Girty (1909) for exposures on the slopes of Mesa del Yeso, 12 miles northeast of Socorro, New Mexico. Needham and Bates (1943, p. 1657-1658) redefined the Yeso

Figure 9. Biogenic structures in fine-grained channel-sandstone of the Abo Formation.

because Lee and Girty did not designate a type section and had included beds of the San Andres Formation and Glorieta Sandstone in the Yeso. Bates and others (1947, p. 26-27) included beds in the Yeso that had been mapped previously as Abo Formation. These authors also considered the Yeso to be Leonard in age. Wood and Northrop (1946) divided the Yeso Formation in the Nacimiento Mountain into two members, in ascending order, the Meseta Blanca Member and the San Ysidro Member. Baars (1962, p. 191) correlated the Meseta Blanca Member with the De Chelly Sandstone and urged that the term Meseta Blanca Member be dropped; he also restricted the Yeso Formation in the Nacimiento Mountains to Wood and Northrop's (1946) San Ysidro Member.

In this report the Yeso Formation is mapped as one unit but four informal units were recognized. The subdivisions are based on distinct differences in the geometry of the beds of each unit, their lithology, grain size, and sedimentary structures. All of these units have been recognized in the southern Nacimiento Mountains and Jemez River Valley near Jemez Springs. The Yeso is generally about 140 m thick and has a gradational contact with the underlying Abo Formation. For mapping purposes the contact was placed at the base of the first 2.0 m thick sandstone bed typical of the basal Yeso Formation. The subunits are described in ascending order below.

Unit 1 is 15.0 m thick at measured section 4 (Fig. 1), and consists of orangish-red and subordinate grayish-blue, well indurated, fine-grained, predominantly crossbedded, moderately well sorted, ledge forming calcareous feldspathic arenites which make up 60 percent of the unit. This sandstone occurs in lenticular beds 90 to 300 cm thick. Red mudstone forms 40 percent of the unit and occurs in beds 50 to

130 cm thick. Unit 1 has a gradational contact with the Abo Formation, but is brighter orange-red in color, finer grained, better sorted and has a higher quartz content than the Abo.

Unit 2 is 34.5 m thick at measured section 4 (Fig. 1), and forms steep, rounded cliffs. Its contact with Unit 1 is sharp and is placed at the base of the lowest high-angle crossbedded arenite typical of the unit. It consists of high-angle crossbedded (Fig. 10) and locally non-crossbedded, friable, orange-red, medium- to coarse-grained, well rounded, well sorted, calcareous, feldspathic arenite. Cross-bed sets are 80 to 700 cm thick and have frosted, spherical quartz grains up to 2.0 mm in diameter floating in the predominantly medium-grained sandstone. Unit 1 and Unit 2 are equivalent to the Meseta Blanca Member of Wood and Northrop (1946).

Unit 3 is 67.6 m thick at measured section 5 (Fig. 1), and forms steep cliffs. Its contact with Unit 2 is sharp and marks the highest position of large sets of high-angle crossbedded sandstones. It consists of fine- to medium-grained, poorly to moderately well sorted, low-angle crossbedded, sub-rounded, well indurated, calcareous feldspathic arenite to feldspathic wacke. Sandstone beds form 70% of the unit, are generally lenticular, and range in thickness from 20 to 100 cm. Breccia zones (Fig. 11) are locally abundant in the upper sandstone beds. Red mudstones form 30% of the unit. The uppermost bed of Unit 3 is 130 cm thick and consists of laminated, yellowish-gray dolomite. Unit 3 is readily distinguished from Unit 4 above because it is finer grained, its sandstone beds are more lenticular and its upper beds are very undulose (Fig. 12). The undulose bedding and breccia beds may have resulted

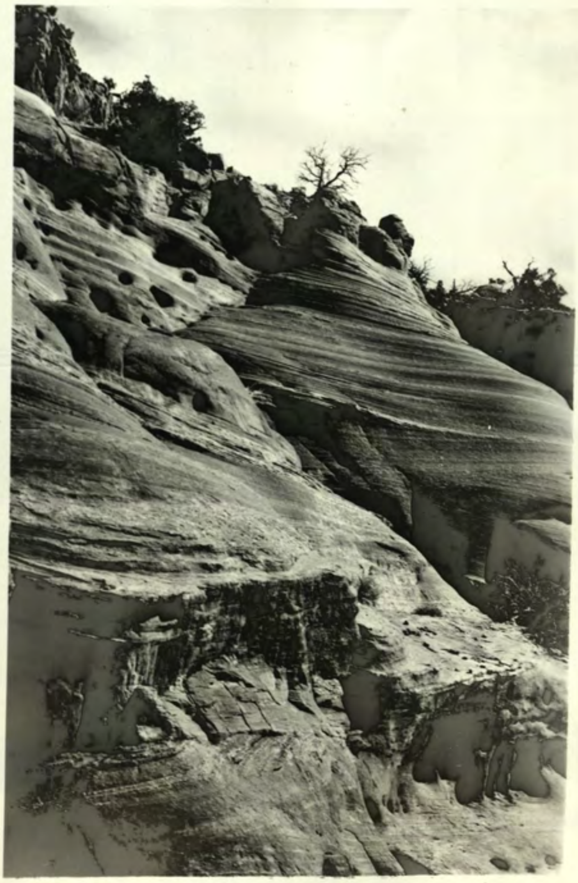


Figure 10. High-angle crossbedding typical of unit 2 of the Yeso Formation.

Figure 11. Breccia zone in the upper sandstone bed of unit 3 of the Yeso Formation. Lense cap 5 cm in diameter.

Figure 12. View of the contact between unit 3 and unit 4 of the Yeso Formation showing typical undulose bedding of the upper sandstone of unit 3.

from the solution removal of underlying gypsum beds. Gypsum makes up 50% of the upper Yeso in the Lucero uplift, 40 mi south of San Ysidro (Kelley and Wood, 1946) but is absent in the Nacimiento Mountains.

Unit 4 is 22.4 m thick at measured section 6 (Fig. 1), forms steep cliffs, and is composed of grayish-red very well indurated, low-angle crossbedded, medium-grained, well sorted, calcareous feldspathic arenite occurring in tabular beds 20 to 120 cm thick. Sandstone beds make up 70% of the unit and are separated by red mudstone beds 10 to 40 cm thick. Units 3 and 4 are equivalent to the San Ysidro Member of Wood and Northrop (1946).

Glorieta Sandstone

The name Glorieta Sandstone was first used by Keyes (1915) for what he considered to be strata equivalent to the Dakota Formation of Cretaceous age, near Glorieta Mesa, New Mexico. He gave no type locality for his Glorieta, so it was assumed that he was describing a prominent sandstone on Glorieta Mesa in north-central New Mexico. The Glorieta Sandstone was placed in the Permian by Hager and Robitaille (1919) as a member of the Yeso Formation. Needham and Bates (1943, p. 1662-1664) elevated the Glorieta Sandstone to formational rank and redefined its type section at Glorieta Mesa. The Glorieta Sandstone has a conformable contact with the underlying Yeso Formation throughout central New Mexico (Baars, 1962, p. 198; Needham and Bates, 1943, p. 1664).

Baars (1962, p. 198-199) stated that the Glorieta was deposited under marine conditions, but he was uncertain of the depositional facies. He also assigned the Glorieta an upper Leonard age on the basis of its stratigraphic position between the Yeso and San Andres Formations.

In the study area the Glorieta Sandstone is 28.2 m thick at measured section 6 (Fig. 1). Its basal contact was placed at the top of the highest red sandstone of the Yeso Formation. At this locality, the Glorieta has a conformable contact with the overlying San Andres Formation. The contact was placed at the base of the dusky red sandstones of the San Andres. At measured sections 7 and 8, the Glorieta is overlain by the Bernal Formation with an erosional unconformity. The contact was placed at the base of the red sandstones of the Bernal Formation.

In the map area the Glorieta Sandstone is a calcareous quartz arenite to subarkose, that is very light gray to yellowish-gray, cliff-forming, laminated to low-angle crossbedded, very well indurated, well sorted, medium-grained, occurring in tabular beds 40 to 200 cm thick. Mudstone partings up to 6.0 cm thick separate individual sandstone beds. No fossils or biogenic structures were observed in the unit. The Glorieta was mapped with the San Andres Formation and the Bernal Formation.

San Andres Formation

The Permian San Andres Formation was defined by Lee and Girty (1909) for limestones and thinly interbedded sandstones exposed in the San Andres Mountains in central New Mexico. Because Lee and Girty did not give a detailed section or specific type locality, Needham and Bates (1943, p. 1664) redefined the type section. Wood and Northrop (1946) included the overlying Bernal Formation with the San Andres Limestone as the upper clastic member of the San Andres Formation. Needham and Bates (1943, p. 1666) stated that the contact of the San Andres Limestone with the underlying Glorieta Sandstone was conformable in central New Mexico with some possible local erosional disconformities.

A unit very similar in lithology to a partial section of the San Andres measured by Baars in the Zuni Mountains (1962, p. 203) was measured approximately 2.0 mi west of Jemez Pueblo at measured section 6 (Fig. 1). There, the San Andres Limestone has an apparently conformable basal contact with the Glorieta Sandstone and is 7.1 m thick, consisting of interbedded, slope-forming, dusky red, highly calcareous, medium-grained sandstones in beds 10 to 60 cm thick, and very dark red shale beds 20 to 150 cm thick. A moderate reddish-orange, argillaceous, highly fossiliferous limestone 60 cm thick occurs at the top of the unit. A 70 cm covered interval obscures the upper contact with the Bernal Formation. The San Andres Limestone is absent along Mesa Cuchilla, at measured section 7 at Arroyo Peñasco (Fig. 1), and at measured section 8 in the Cañoncitos area, where the Bernal Formation lies directly on the Glorieta Sandstone along an erosional unconformity. It is uncertain whether this rapid thinning is due to non-deposition, erosion due to channeling by the Bernal or by post-San Andres and pre-Bernal regional tilting and subsequent erosion of the San Andres.

Because of its thinness and the scale of the map, the San Andres is not mapped as a separate unit and is included with the Glorieta Sandstone and Bernal Formation.

Bernal Formation

The Permian Bernal Formation was described by Bachman (1953) for exposures near the town of Bernal, New Mexico. Wood and Northrop (1946) considered the Bernal to be a member of the San Andres Formation and called it the upper clastic member. Baars (1962, p. 208) also included the Bernal in the San Andres.

The Bernal Formation ranges considerably in thickness in the area, from 4.5 m at measured section 6 (Fig. 1) near the Jemez Pueblo, 17.25 m at measured section 7 (Fig. 1) in Arroyo Peñasco to 11.45 m at measured section 8 in the Cañoncitos area. At Arroyo Peñasco, the Bernal Formation lies directly on the Glorieta Sandstone along an erosional unconformity. Overlying this unconformity is a basal conglomerate bed 6.0 to 20 cm thick containing angular fragments up to 4 cm in diameter of Glorieta Sandstone and possibly San Andres Limestone. The basal 14 m is a laminated, well indurated, slope-forming, ripple marked, pale red, slightly calcareous, fine-grained feldspathic arenite. Dusky red mudstone, 50 cm thick, occurs 11.5 m above the base of the Bernal. The upper 3.3 m is a limonitic-stained, orange-gray laminated, fine-grained sandstone similar to the sandstone of the basal 14 m of the Bernal except that it appears to have been bleached and veins of goethite up to 4.0 cm thick occur along fractures (Fig. 13). The contact with the overlying basal member of the Triassic Chinle Formation is a sharp erosional unconformity (Fig. 14). The thinness of the Bernal Formation at the Jemez Pueblo section may be due to erosion by channeling during Triassic time. An unusually thick section of the basal member of the Chinle was noted in that area.

Of all the stratigraphic units in the study area, the Bernal is the least described in the geologic literature. Baars (1962, p. 209) considered the Bernal to be marginal marine and late Leonardian to Guadalupian in age based on its relationship with the San Andres Limestone.

Figure 13. Veins of goethite (g) cutting the bleached upper sandstone beds of the Bernal Formation. Lense cap 5 cm in diameter.

Figure 14. Erosional unconformity between the basal member of the Chinle Formation and the Bernal Formation. Symbols are the same as Figure 1.

Because of its thinness and the scale of the map, the Bernal was mapped with the Glorieta Sandstone

Triassic System

Chinle Formation

The Triassic Chinle Formation was named by Gregory (1917) for exposures in Chinle Valley in northeastern Arizona. The most comprehensive report on the Chinle Formation is that of Stewart and others (1972) who considered the Chinle to be middle Late Triassic in age on the basis of vertebrate and plant remains. Wood and Northrop (1946) divided the Chinle Formation into the Agua Zarca Sandstone and the Chinle Shale Members in the San Ysidro area. Stewart and others (1972, p. 23) modified the terminology used by Wood and Northrop for the Chinle in that area; Stewart and others did not consider the Agua Zarca Sandstone to be present in the San Ysidro area, but recognized a new informal unit, the sandstone member of the Chinle, for strata mapped by Wood and Northrop as Agua Zarca. They also correlated the Chinle Shale Member of Wood and Northrop with the Petrified Forest Member of the Chinle. In this report the Chinle Formation is divided into an informal basal member and the Petrified Forest Member.

Basal Member. Stewart and others (1972, p. 206-207) considered the basal sandstone and conglomerate of the Chinle Formation near San Ysidro to be an informal sandstone member and not the Agua Zarca Sandstone on the basis of minor differences in lithologies and possibly a different source area. Their informal sandstone member was not used in this report because my field observations at several localities in the area indicate the crossbedding in the lower part of the basal sandstone and conglomerate has a predominantly southern dip, whereas crossbedding in the upper part of the unit is dipping almost exclusively in a northerly direction. This bimodal distribution is very different from directions reported by Stewart and others (1972, p. 23-24). Also the only section of their sandstone member which they refer to specifically in their text (Stewart and others, 1972, fig. 8, loc. A, p. 22 and NM-13, San Ysidro, p. 206-207) is crossed by at least 2 faults (Fig. 1, southern part of 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 would give the upper part of the unit, which has a northern cross-bed dip direction and is not conglomeratic, an erroneous increased thickness.

A complete section of the basal member is present at measured section 8 (Fig. 1) where it is 43.5 m thick and forms steep cliffs. The basal member increases in thickness east of this section where it is about 60 m thick near Blue Water Spring in sec. 25, T. 16 N., R. 1 E. Throughout the map-area the basal member overlies the Bernal Formation with an erosional unconformity. At the contact, conglomerates of the basal member overlie laminated, fine-grained sandstone beds of the Bernal Formation.

At measured section 8 the basal 28.5 m is estimated to consist of 20% conglomerate, 25% conglomeratic sandstone, and 55% sandstone. Because of the lenticular nature of individual beds the percentages of the rock types present are different at various localities. Crossbeds generally dip to the south in the lower part of the basal member.

Conglomerates are poorly sorted, well indurated with calcareous cement and in some cases silica cement; most are crossbedded, and most occur in beds up to 2.5 m thick. The pebbles consist of quartz, quartzite and chert; the largest pebble seen was 5 cm in diameter. The conglomerate beds are very discontinuous, generally occurring in channels less than 40 m wide. In most cases the conglomerates grade into conglomeratic sandstone. Silicified logs up to 150 cm long and occasionally coal lenses up to 25 cm thick, were observed in the conglomerate beds. The conglomeratic sandstone (Fig. 15) and medium- to coarse-grained sandstone are crossbedded and are gradational with one another.

The upper 15 m is thinner bedded, finer grained, and more crossbedded than the basal part of the unit. The contact between the upper and lower units is gradational and was placed at the top of the highest local conglomerate bed. The cross-bed dip direction is almost exclusively to the north. This upper unit is estimated to contain 15% conglomeratic sandstone and 85% fine- to coarse-grained sandstone. The sandstones are generally calcareous, very well indurated, crossbedded (fig. 16), yellowish-gray, feldspathic arenites occurring in beds 80 to 150 cm thick. Intercalated, flat-bedded, fine- to medium-grained feldspathic arenites with parting lineations occur in beds up to 50 cm thick. Bluish-gray claystone and siltstone lenses are present in the upper portion of the unit, although none occur in the measured section.

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. It is a nonresistant, slope-forming unit and a complete section is not present in the study area. In this report the Petrified Forest Member has been divided into three informal units, numbers 1 through 3 in ascending order.

Figure 15. Conglomeratic sandstone channel (Cgl) and medium-grained sandstone bed (S) in the lower part of the basal member of the Chinle Formation.

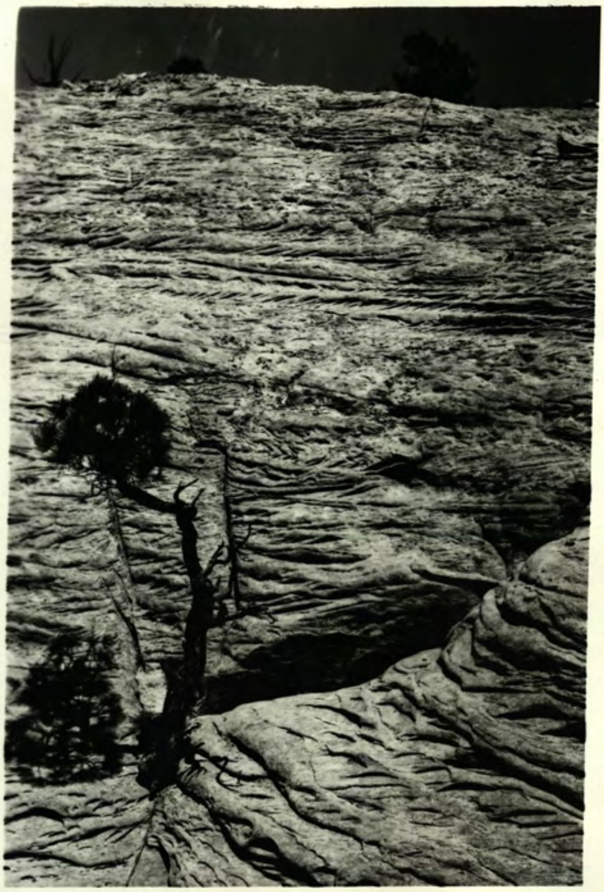


Figure 16. View east of the upper part of the basal member of the Chinle Formation showing the consistent northerly dip of cross-bed sets.

Unit 1 is 9.5 m thick at measured section 9, Fig. 1). Poorly to moderately well sorted, calcareous, ripple laminated, well indurated, yellowish-gray, silty, fine-grained feldspathic arenite beds 30 to 70 cm thick make up 40% of the unit. These sandstones have abundant ripple marks, load casts and biogenic structures. Bluish gray mudstone and siltstone occur in beds 60 to 130 cm thick and comprise 60% of the unit. This unit marks the transition from the sandstones of the basal member of the Chinle to the mudstones of the Petrified Forest Member. Its contact with the basal member is conformable and is placed at the top of the highest high-angle crossbedded arenite bed of the basal sandstone.

Unit 2 was not measured because of the lack of a complete section. Based on the drill hole data reported in Stewart and others (1972, p. 206), Unit 2 is estimated to be approximately 330 m thick in the study area. It consists of grayish-red mudstone with subordinate sandstone and limestone pebble conglomerate beds. The basal contact was placed at the base of the lowest grayish-red mudstone bed in the Petrified Forest Member.

Unit 3 is 13 m thick at White Mesa at measured section 10 (Fig. 1). Its basal contact with Unit 2 was placed at the base of the well developed channels which cut 1.0 to 2.0 m into the grayish-red mudstone of Unit 2.

The lower part of the unit 3 is 7.5 m thick and is yellowish-gray to moderate brown, ledge-forming, medium- to coarse-grained, moderately well sorted, friable, crossbedded feldspathic arenite occurring in beds 20 to 80 cm thick that locally contains lenses of calcareous, conglomeratic feldspathic litharenite with rounded clasts of sandstone and limestone up to 8 cm in length and wood fragments up to 35 cm long.

The upper part of unit 3 is about 5.5 m thick and consists of slope-forming, intercalated mudstone and crossbedded, ripple marked, fine-grained sandstone that occur in beds 5.0 to 60 cm thick. The upper part of unit 3 sharply truncates the cross-bed sets of the underlying bed. Upsection the sandstone beds become finer grained with an increased content of clay- and silt-sized matrix.

Stewart and others (1972, p. 209) also measured an upper Chinle section at White Mesa. They included unit 3 in the Entrada Sandstone but indicated that it may correlate with the Wingate Sandstone. At a section measured at Arroyo de los Piños, approximately 3.5 km north of the study area, the lower part of unit 3 is more conglomeratic than at White Mesa and Stewart and others (1972, p. 204) included it in the Petrified Forest Member and included strata equivalent to the upper part of Unit 3 in the Entrada Sandstone. They indicated that these strata may belong to the Chinle Formation.

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). Twelve cross-stratification planes from the basal part of unit 3 have an average strike of N.43° E, and dip of 14° NW. This is similar to the average strike of N.67° E, and dip of 19° NW reported by Moench and Schlee (1967, p. 6) for the basal part of the Correo Sandstone. Stewart and others (1972, p. 38) reported the Correo overlies and underlies strata lithologically similar to the typical Petrified Forest Member and the only known outcrop of the Correo is around Mesa Gigante. For these reasons they did not consider the Correo Sandstone to be a member of the Chinle and considered it to be a bed within the Petrified Forest Member.

Jurassic System

Entrada Sandstone

The Entrada Sandstone was named by Gilluly and Reeside (1928) for exposures on Entrada Point in the northern part of the San Rafael Swell, Utah. Wood and Northrop (1946) mapped Wingate Sandstone in the Nacimiento Mountains, but Moench and Schlee (1967, p. 6) correlated that unit with the Entrada Sandstone of Utah. Stewart and others (1972, p. 209) divided the Entrada into two informal members, the medial silty member and the upper sandy member, in the San Ysidro area. Their terminology will be followed in this report. However, part of their medial silty member should be included in the Petrified Forest Member of the Chinle Formation for reasons discussed previously.

Medial silty member. At measured section 10 (Fig. 1), the medial silty member consists of 12.4 m of pale reddish-brown, cliff-forming, massive, calcareous, well indurated, laminated, very fine-grained sandstone. The base of the medial silty member was placed at the contact between the massive, laminated sandstone and the thin-bedded sandstone and mudstones. There is an undulating erosional contact between the medial silty member and the overlying upper sandy member that is marked by an abrupt lithologic and color change from reddish-brown laminated fine-grained sandstone to yellowish-orange medium-grained, crossbedded sandstone.

Upper sandy member. The upper sandy member is 22.9 m thick at measured section 10 (Fig. 1), and is a highly crossbedded to non-crossbedded, well sorted, pale yellowish-orange, friable, calcareous, medium- to coarse-grained feldspathic arenite in its lower part and a fine- to medium-grained, yellowish-gray, calcareous, friable, cliff-forming, low-angle crossbedded to parallel-bedded feldspathic arenite in its upper part. The contact with the overlying limestones of the Todilto Formation is generally sharp, but locally is gradational.

The Entrada Sandstone is mapped with the Todilto Formation because the Entrada has a narrow outcrop as it occurs on steep cliffs below the Todilto.

Todilto Formation

The Todilto Formation was named by Gregory (1917) for exposures at Todilto Park, New Mexico. Wood and Northrop (1946) included the Todilto as a member of the Morrison Formation. The most detailed description of the Todilto Formation is that of Anderson and Kirkland (1970) who, partially on the basis of a fauna which they considered to be of fresh water affinity, concluded that the Todilto Formation was non-marine.

Only a partial section of Todilto was measured at measured section 10 (Fig. 1). The basal 1.8 m consists of laminated, fissile limestone, with laminae of limestone, organic material, clastic grains and gypsum. There is a gradational contact between the laminated limestone and the massive gypsum.

The upper portion of the Todilto is about 35 m thick, and consists of massive white gypsum that forms conspicuous cliffs. A chalcedony bed 6.0 to 10 cm thick occurs in the Todilto near its contact with the Summerville formation. Gypsum from the Todilto is quarried on White Mesa.

Summerville Formation

The Summerville Formation was named by Gilluly and Reeside (1928) for exposures in the San Rafael Swell, Utah. Harshbarger, Repenning and Irwin (1957, p. 29) recognized the Summerville in northwestern New Mexico. In the Laguna area the Summerville is 27 to 60 m thick (Moench and Schlee, 1967, p. 14). Woodward and Schumacher (1973, p. 1) did not recognize the Summerville as a mappable unit in the Nacimiento Mountains north of the San Ysidro area because it cannot be distinguished from the overlying Recapture Member of the Morrison Formation. They included possible Summerville strata with the lower member of the Morrison Formation.

In the San Ysidro area the Summerville contains gypsum beds which distinguish it from the overlying Recapture Member of the Morrison. An accurate measurement of the thickness of the Summerville in the map-area was impossible because there are no complete sections in that area that have not been tectonically disturbed and the presence of several stringers of satin spar gypsum 1.0 to 6.0 cm thick which cut obliquely across the bedding indicate there has been post-depositional introduction of gypsum into the unit. A nearly complete section of Summerville that is 13.4 m thick was measured on White Mesa at measured section 11 (Fig. 1). It forms slopes, has a distinctive layered appearance, and consists of approximately 60 percent fine-grained to silty, well sorted, calcareous, light gray to red brown, thin-bedded sandstone (Fig. 17), 10 percent massive white gypsum that occurs in beds up to 0.3 m thick, and 30 percent grayish-green to reddish-brown mudstone. Gray limestone beds were observed in the Summerville at other localities. The Summerville has a sharp basal contact with the Todilto in the area (Fig. 18) and the contact was placed at the base of the first clastic bed of the Summerville. The contact with the overlying Recapture Member of the Morrison is generally obscured by alluvium. The contact appears to be gradational and was placed at the top of the highest gypsum bed of the Summerville.

Morrison Formation

The Morrison of Upper Jurassic age was defined by Emmons and others (1896) for rocks near Morrison, Colorado. It is present throughout most of the western interior of the United States. Baker, Dane, and Reeside (1936, 1947) and Craig and others (1955) are the standard references for the stratigraphy of the Morrison in the Four Corners area and their work has clarified much of the terminology and distribution of its various members.

Freeman and Hilpert (1956, p. 323-325) measured a partial section approximately 8 km north of this study area where they divided the unit into three members. Moench and Schlee (1967) followed their terminology in the Laguna area. They also mapped a fourth unit, the Jackpile sandstone of economic usage but did not recognize it as a formal separate member. Woodward and Schumacher (1973, p. 3) in a report on the Morrison Formation of the southeastern San Juan basin, combined the Recapture Member of the Morrison and possible Summerville strata into the informal lower member. They also designated a new informal member,

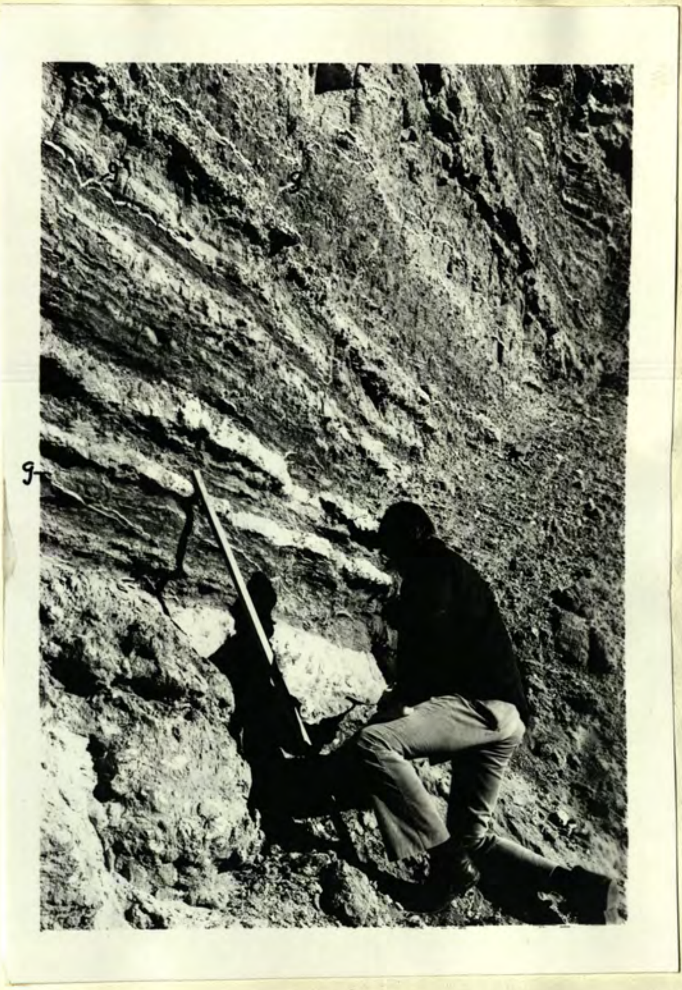


Figure 17. Interbedded mudstones and thin-bedded sandstones typical of the Summerville Formation. Small veinlets of satin spar gypsum (g) cut obliquely across the bedding.

Figure 18. View of the contact between the Summerville Formation and the Todilto Formation. Symbols are the same as Figure 1.

the upper member, which is lithologically similar to the Jackpile sandstone. In this report the terminology of Moench and Schlee (1967) is used. Their Jackpile sandstone of economic usage is here considered a separate informal member, the Jackpile sandstone. In ascending order, members of the Morrison Formation are the Recapture, the Westwater Canyon, the Brushy Basin, and the Jackpile sandstone.

The base of the Morrison Formation in the San Ysidro area appears to be gradational with the Summerville; however, good exposures of the contact are lacking. In my report the contact is placed at the top of the uppermost gypsum bed of the Summerville. The Morrison is unconformably overlain by the Dakota Formation of Cretaceous age.

Recapture Member. The Recapture member is approximately 58 m thick at measured section 12 (Fig. 1). The basal 9.2 m consists of crossbedded, very light gray to greenish-gray, fine-grained arkosic wacke interbedded with light greenish-gray to grayish-red mudstone, and subordinate channels 10 to 30 cm thick and generally less than 15 m wide of poorly indurated, highly crossbedded, medium-grained, feldspathic litharenite that form approximately 15 percent of the basal Recapture. A gray, unfossiliferous, highly indurated, structureless limestone bed 20 cm thick, occurs 180 cm below the top of the basal Recapture. This bed has been observed over a distance of 4.0 km.

The upper 48.7 m of the Recapture consists of slope-forming, grayish-red with subordinate, intercalated, greenish-gray mudstone, fine-grained arkosic wacke and channels of highly bioturbated, crossbedded, medium-grained feldspathic arenite beds 20 to 50 cm thick.

The presence of mudstone, poorly sorted sandstones, and possible lacustrine limestone supports the conclusions of Craig and others

(1955, p. 151) and Cadigan (1967, p. 109) that the Recapture was deposited in a rapidly subsiding, low energy, flood-plain environment. This flood plain was occasionally crossed by small, higher energy streams which are represented by the thin, medium-grained feldspathic arenite channel deposits. The contact of the Recapture with the overlying Westwater Canyon Member is intertonguing and in this report the contact is placed at the base of the lowest, thick, ledge-forming, massive sandstone typical of the Westwater Canyon.

Westwater Canyon Member. The Westwater Canyon Member in the map area is approximately 49.4 m thick at measured section 12 (Fig. 1), and consists of approximately 60 percent friable to moderately well indurated, ledge-forming, medium-grained to conglomeratic, moderately well sorted, crossbedded, locally bioturbated, lenticular feldspathic arenite beds 0.4 to 5.0 m thick and 40 percent interbedded slope-forming, lenticular, grayish-red to greenish-gray mudstones that are 60 to 220 cm thick. In this report the contact with the Brushy Basin Member is placed at the base of the lowest mudstone intercalated with recognizable dark red mudstone or dark red sandstone typical of the Brushy Basin. The Westwater Canyon interfingers with the Brushy Basin and some beds included with the Brushy Basin may be laterally equivalent to the Westwater Canyon.

The Westwater Canyon represents a sudden coarsening of sediments over the predominant mudstones of the Recapture. Craig and others (1955, p. 157) and Cadigan (1967, p. 109) both believe this is due to an uplift in the source area in west-central New Mexico. Sedimentary structures, and the geometry of the sand bodies indicate the Westwater Canyon was deposited in an alluvial plain environment.

Brushy Basin Member. The Brushy Basin Member is 86 m thick at measured section 13 (Fig. 1). It is grayish-green, with subordinate grayish-red, slope-forming, bentonitic mudstone beds 200 to 900 cm thick. These mudstones are similar in lithology to those occurring in the Westwater Canyon Member. Crossbedded, very light gray to grayish-pink, well indurated, moderately well sorted, calcareous feldspathic arenites that are locally conglomeratic with chert and limestone pebbles, occur in lenses 20 to 70 cm thick intercalated with the mudstone and as lenticular channels 200 to 500 cm thick separating mudstone beds. These sandstones are similar to those occurring in the Westwater Canyon Member except that the Brushy Basin sandstones are thinner and generally better indurated. Moderate red, highly indurated siltstone to medium-grained sandstone beds 10 to 60 cm thick are intercalated with the mudstones and give the Brushy Basin Member its characteristic red color. Three very light gray, highly fractured, irregular, dense, micritic limestone beds 10 to 25 cm thick were measured. These limestones are locally replaced by chalcedony.

The high bentonite content, abundant volcanic fragments (Cadigan, 1967, p. 81), unreworked volcanic shards (Keller, 1962) and tuff beds (Moench and Schlee, 1967) indicate major volcanic activity during deposition of the Brushy Basin. The high mudstone/sandstone ratio and thin limestone beds support the interpretation of Craig and others (1955, p. 157) and Cadigan (1967, p. 109) that the Brushy Basin was deposited in a rapidly subsiding, low energy, floodplain environment.

Jackpile Sandstone. The Jackpile sandstone is the uppermost member of the Morrison Formation, and is used as an informal unit in this report. The Jackpile was named by Freeman and Hilpert (1956, p. 315) for exposures at the Jackpile mine near Laguna, New Mexico. They treated the Jackpile as an informal unit, as did all subsequent workers in the Laguna area. The most detailed description of the Jackpile sandstone is by Schlee and Moench (1961). Woodward and Schumacher (1973, p. 5) correlated the Jackpile with their informal upper member of the Morrison in the Nacimiento Mountains on the basis of stratigraphic position and similar lithologies.

The Jackpile sandstone is 11.5 m thick at measured section 13 (Fig. 1). However, because the basal sands intertongue with the claystones of the Brushy Basin Member, its thickness varies. The Jackpile forms resistant ledges and is fine- to medium-grained, poorly to moderately well sorted, friable feldspathic arenite that is cemented by calcite and kaolinite and occurs in highly crossbedded, lenticular beds 50 to 150 cm thick.

Clay galls, silicified wood, and biogenic structures are locally abundant in the sandstone beds. Variegated mudstone generally makes up 10 to 30 percent of the Jackpile but locally comprise as much as 60 percent of the unit.

In the map area, the Dakota Formation of Cretaceous age overlies the Jackpile with an erosional unconformity. The contact is sharp, and marks the change from the white sandstones of the Jackpile to the carbonaceous sandstones and shales of the Dakota.

Cretaceous System

Dakota Formation

The Upper Cretaceous Dakota Formation was named by Meek and Hayden (1862) for exposures near Dakota, Nebraska. It is approximately 54 m thick at measured section 13 (Fig. 1), and consists of 3 sandstone and 2 shale units. Siemers and others (1973, in press) correlated these units with the Dakota section at Laguna described by Landis and others (1973, in press). From oldest to youngest these units are: an unnamed carbonaceous basal sandstone; the Oak Canyon Member; the Cubero Sandstone Tongue; the Clay Mesa Shale Tongue and the Paguate Sandstone Tongue.

Unnamed basal sandstone. The unnamed basal sandstone is highly lenticular, ledge-forming, ranges from 0 to 8 m in thickness, and is coarse-grained to conglomeratic, crossbedded, well indurated, feldspathic arenite that contains abundant biogenic structures, plant impressions and carbonaceous material. Channel coal beds 0.1 to 0.4 m thick are locally abundant in the unit. Its contact with the Oak Canyon is marked by an abrupt change from sandstone to carbonaceous shale.

Oak Canyon Member. The Oak Canyon Member is approximately 15 m thick, nonresistant and consists of dark gray carbonaceous shale that increases in silt and fine-grained sand content up-section. Abundant bentonite beds and oyster-bearing septarian concretions are present. The Oak Canyon Member has a gradational contact with the Cubero Sandstone.

Cubero Sandstone Tongue. The Cubero Sandstone Tongue is 11 m thick, forms ledges, and is composed of highly bioturbated, calcareous, locally cross-bedded, moderately well to poorly indurated, fine-grained feldspathic arenite that is intercalated with thin shale and siltstone beds. Its contact with the Clay Mesa Shale is marked by an abrupt change from sandstone to shale.

Clay Mesa Shale Tongue. The Clay Mesa Shale Tongue is approximately 19 m thick and is lithologically similar to the Oak Canyon member except it is less carbonaceous, more arenaceous, and contains no bentonite beds in the study area. The Clay Mesa Shale has a gradational contact with the Paquate Sandstone.

Paguate Sandstone Tongue. The Paguate Sandstone Tongue is approximately 10 m thick and is very similar in lithology to the Cubero Sandstone Member; additionally it contains concretions. Its contact with the Mancos Shale is marked by the abrupt change from sandstone to shale.

Mancos Shale

The Upper Cretaceous Mancos Shale was named by Cross and others (1899) for exposures along the Mancos River in southwestern Colorado. The Mancos is the youngest pre-Tertiary unit exposed in the map area. It is generally over 600 m thick in the San Juan basin but only approximately 100 m is exposed in the mapped area. It is slope-forming carbonaceous shale and silty calcareous, bioturbated fine-grained sandstone. It has a conformable contact with the underlying Dakota Formation.

Tertiary System

Miocene Series

Zia Sand Formation

The Zia Sand Formation was named by Galusha (1966, p. 1-3) for exposures near Zia Pueblo, New Mexico. On the basis of several vertebrate fossils, Galusha dated the Zia as early to medial Miocene.

A complete section of Zia is not present in the study area. Galusha (1966, p. 3) reported the Zia is about 330 m thick at the type locality. Where the base of the Zia is exposed, it rests on the basal member of the Chinle Formation near Jemez Pueblo and at sec. 25, T. 16 N., R. 1 E., it lies on the Petrified Forest Member of the Chinle. Galusha (1966, p. 5) reported that the Zia lies on the Galisteo Formation at its type locality, approximately 15 km south of Salt Springs.

The Zia is a very light-gray, highly crossbedded, coarse- to medium-grained, friable, feldspathic arenite to feldspathic wacke that forms characteristic vertical cliffs when capped by travertine-cemented gravel (Fig. 19). The Zia is stained moderate reddish-orange along many of the faults which cut it. Except for this local color change, there are no major lithologic variations in the Zia across the map-area.

The uniform lithology of the Zia Sand and the absence of abundant conglomerate beds in the unit suggest that the Zia Sand extended onto the southern Nacimiento uplift and has been removed by post middle-Miocene erosion.

Quaternary System

Pleistocene Series

Pediment and Terrace Gravels

Renick (1931, p. 59-62) assigned a Pleistocene age to the pediment and terrace gravels in the area (Fig. 1). Pediment and terrace gravels are mapped as one unit in this report. Both are conglomeratic sediments that contain cobbles and boulders of Precambrian rocks. Near Peñasco Tank, Cañoncitos and Salt Springs, gravel beds 1.0 to

Figure 19. View north near the Jemez Pueblo of the Zia Sand Formation capped by Quaternary gravels and travertine.

4.0 m thick are cemented by thermal spring deposits and overlain by travertine. At these localities the gravels were mapped with the travertine.

Pleistocene and Recent Series

Travertine Deposits

Travertine deposits and gravels that are cemented by thermal spring deposits crop out throughout much of the study area. Favorable stratigraphic horizons and/or faults are the controlling factors in determining the sites of travertine deposition. Renick (1931, p. 63) stated that the oldest of these travertine deposits are Pleistocene in age, a time when the springs were most active. He gave no reason for assigning some of the deposits a Pleistocene age; however it appears to be a reasonable assumption based on the travertine deposits near Peñasco Tank which cover an area over 4.8 km long and 1.5 km wide, have been dissected by several streams, and where only a few small active springs are now depositing travertine.

Approximately 95 percent of the travertine deposits are associated with the Chinle Formation, especially the contact between the basal member and Petrified Forest Member. In most cases the travertine-bearing solution associated with the Chinle have sources at or near faults. Travertine deposits not associated with the Chinle occur at fault zones.

In many cases, the springs depositing travertine issue from nearly circular travertine mounds that are up to 20 m higher than the surrounding area. A crater with vertical walls generally occurs at the tops of the mounds. These craters are up to 16 m wide and 17 m deep.

Various stages of mound and crater development are represented by active and inactive springs in the area. The greatest number of mounds and craters occur in the Peñasco Tank area.

On the basis of the dissolved gas content of the waters, their probable northeastern source area, and their high temperatures, Renick (1931, p. 88-89) concluded that the waters represent original volcanic waters modified by the addition of meteoric waters. Further work, especially on the isotopic ratios of oxygen, hydrogen, and carbon of the water is necessary before the presence of original volcanic waters in these springs can be confirmed. The heating of the spring waters is best explained by a heat source related to the Jemez volcanic center. Waters may be heated in the area of the Jemez volcanic center and brought to the San Ysidro region along fractures. It should be noted that no travertine deposits have been reported on the western side of the Nacimiento Mountains north of the Warm Springs dome and no faults are known to cut completely across the uplift north of the Warm Springs dome. Travertine deposits associated with the Jemez, San Ysidro, and other faults occur at several locations on the east side of the Nacimiento uplift from north of Jemez Springs to San Ysidro.

Recent Series

Landslide Deposits

Several areas of unconsolidated landslide deposits were mapped along the slopes of the mesas of the area. These deposits consist of angular to subrounded boulders derived from the adjacent cliffs. The landslide deposits obscure stratigraphic contacts and structures.

Several large consolidated landslide deposits were mapped in the area. Most are large blocks of Todilto gypsum over 15 m wide that have slid intact off the steep face of White Mesa. Toreva blocks were also mapped 1.0 km east of Salt Springs and along the base of Red Mesa. The block near Salt Springs consists of a consolidated block approximately 25 m long and 10 m wide of the basal member of the Chinle Formation that is lying on Zia Sand Formation. At Red Mesa the block consists of Glorieta Sandstone, Bernal Formation and the basal member of the Chinle and is approximately 70 m long and 10 m wide and rests on the Chinle Formation, Entrada Sandstone, Todilto Formation and the Summerville Formation.

Alluvium

Alluvial deposits consisting of unconsolidated and locally consolidated clay- to gravel-sized clastic sediments occur in most of the valleys in the area. Contacts between alluvium and landslide deposits are generally gradational. In some cases the exposed alluvium may be Pleistocene in age.

STRUCTURAL GEOLOGY

Regional Tectonic Setting

The map-area includes structural elements of the Eastern Rocky Mountains, Colorado Plateau and the Rio Grande depression. The Eastern Rocky Mountain structures were initiated during the latter part of the Laramide orogeny; however the timing of their main period of vertical uplift is still not known. The Colorado Plateau formed during the latter part of the Laramide orogeny. Since that time the plateau has been relatively tectonically stable compared to the surrounding areas. The Rio Grande depression developed during the middle to late Tertiary time and is still tectonically active. The timing of the initial development of the depression is not known.

The Nacimiento Mountains are a part of the Eastern Rocky Mountains and are a north-trending uplift that is about 80 km long and 13 to 16 km wide. The uplift is asymmetric with a steep western margin bounded by high-angle reverse, thrust, and normal faults, and consists of several fault blocks that are tilted to the east. Woodward and others (1972, p. 2384) determined that there was at least 3,048 m of structural relief between the highest part of the uplift and the adjacent basin.

The San Juan basin lies in the southeastern part of the Colorado Plateau and is a nearly circular depression with the structurally deepest part near the northern margin. Structural features of the basin present in the map area are northwest- and north-trending folds, a synclinal bend adjacent to the Nacimiento uplift and a uniform westward dip of the strata toward the basin.

The Rio Grande depression is approximately 960 km long and consists of a series of interconnected and en échelon north-trending basins and grabens. The internal geometry of the depression is obscured in most places by late Tertiary and Quaternary alluvial deposits. Features related to the development of the Rio Grande depression in the map area are north- and northeast-trending high-angle normal faults that are generally downthrown to the east. This faulting involves the Santa Fe Formation of Early Pliocene age.

Structure of the Map-Area

General Statement

The map-area straddles boundaries of the Colorado Plateau, southern Rocky Mountains, and the Rio Grande trough. Because structural elements of all three of these tectonic provinces have been superimposed on the area, deformation has been extensive and diverse in style. Boundaries between provinces in parts of the map-area are ill-defined and consist of linear transition zones. Those structures lying east of the Pajarito fault, west of the San Ysidro fault, and north of the Rio Salado are within the Nacimiento uplift and are part of the Rocky Mountains. The structures east of the San Ysidro fault, and west of the Jemez fault, are considered to be transitional between the Rio Grande trough and the Rocky Mountains. Structures east of the Jemez fault are considered to be transitional between the Rio Grande depression, Rocky Mountains, and the Colorado Plateau. Rocks west of the Pajarito fault and north of the Rio Salado are part of the Colorado Plateau.

Five structural elements each have over a thousand feet of structural relief: 1) the Pajarito fault, 2) the San Ysidro fault, 3) north-trending folds, 4) the Jemez Pueblo fault zone, and 5) the Jack Rabbit Flats fault zone. Stratigraphic separation along a sixth major structural feature, the Jemez fault, cannot be determined because much of its trace is obscured by alluvium. In addition to these major structural features there are several minor faults such as the Querencia Arroyo fault-zone and the Mesa Cuchilla fault and some minor folds.

Pajarito Fault

The Pajarito fault is a high-angle reverse to vertical fault that is well exposed at several locations. The fault strikes N.5°-15° W and dips 76° E to vertical. No transverse faults cut the Pajarito fault. The fault zone is consistently narrow, never more than 4.5 m wide, and locally, as is the case south of Arroyo Peñasco, the fault is a sharp break. The fault cuts the east limb of the Tierra Amarillo anticline; however landslide debris, alluvium and travertine obscure much of the fault trace near the anticline.

Stratigraphic separation along the fault cannot be accurately determined along most of its length because the precise thicknesses of the Pennsylvanian strata, Abo Formation, and the Chinle Formation are not known in the area. Separation ranges from approximately 550 m near the northern end of the map area (Section A-A'; Fig. 2) to less than 25 m at the southern end of the Tierra Amarillo anticline. At Red Mesa (Section B-B' Fig. 2) stratigraphic separation along the fault is approximately 500 m. Three km south of that location (Section

C-C; Fig. 2) the separation is approximately 300 m. On the south side of Rio Salado (Section D-D'; Fig. 2) the separation is approximately 30 m. The movement along the fault dies out to the south. Where the fault cuts the inclined strata on the southern nose of the Tierra Amarillo anticline, there is no indication of strike slip component. Therefore, dip-slip movement along the fault can be estimated with some limitations and appears to be close to the stratigraphic separation.

San Ysidro Fault

The San Ysidro fault is a normal fault (Section A-A', B-B'; Fig. 2) with a dip of 70° E. to vertical and a strike of N.20° W to N.15° E. A fault zone that is generally between 9 and 18 m wide is associated with the San Ysidro Fault in the northern half of the area. This fault zone consists of slices of Yeso, Glorieta and Agua Zarca. In the southern half of the study area, the San Ysidro fault has a very narrow fault zone which is less than 1 m wide.

Maximum stratigraphic separation occurs 2.4 km northwest of San Ysidro where it is approximately 360 m. To the south, at White Mesa, separation is approximately 210 m. In the northern portion of the area the Jemez Pueblo fault zone and the southerly dip of the downthrown block combine to decrease the stratigraphic separation along the fault to less than 90 m. The variable strike of the fault suggests that it is not a strike-slip fault.

Jemez Pueblo Fault Zone

The Jemez Pueblo fault zone (Section A-A'; Fig. 2) is a belt 2.8 km wide consisting of several northeast-trending, high-angle normal faults that, with a few exceptions, are downthrown to the south.

Stratigraphic separations along these faults range from 310 to nearly 90 m. The faults terminate on the southwest at the San Ysidro fault, and on the northeast at the Jemez fault.

Mesa Cuchilla Fault

This fault (Section A-A'; Fig. 2) is completely covered by alluvium in the study area; however, it is exposed approximately 0.6 km north of the study area where it is a high-angle, normal fault downthrown to the west with between 90 and 100 m of stratigraphic separation. Its presence in the study area is based on stratigraphic juxtaposition. Stratigraphic separation on the fault is 80 to 90 km at the north in the study area and decreases to the south where it may die out.

Jemez Fault

The Jemez fault (Section A-A', B-B'; Fig. 2) is a high-angle normal fault that strikes N. 30° W to N. 30 ° E. The fault is a sharp break at all localities. Stratigraphic separation along the fault cannot be accurately determined because only the Zia Sand Formation is exposed on the downthrown side. Based on the fact that the Zia sand lies on the basal member of the Chinle Formation near Salt Springs, stratigraphic separation along the fault has been estimated to range from nearly 360 m (Section A-A'; Fig. 2) to about 60 m (Section B-B'; Fig. 2).

Querencia Arroyo Fault-Zone

Five north-trending, high-angle, normal faults (Section D-D'; Fig. 2) that are all downthrown to the east were mapped in the southwestern margin of the study area. These faults parallel the north-trending fold axis in this area. Stratigraphic separations along these faults range from 6.0 to 13 m.

Jack Rabbit Flats Fault Zone

A zone of high-angle normal faults that strike N.40° - 65° E. cut the Cañoncitos homocline and the Red Mesa anticline. The northernmost fault has stratigraphic separation ranging from 240 to 300 m and is downthrown to the south. The remaining faults, with a few exceptions, are downthrown to the north and their stratigraphic separations range from 13 to 30 m. The faults end at the Pajarito fault.

Cañoncitos Homocline

In the Cañoncitos region, strata dip in a southerly direction at a uniform rate of 2° to 12° over an area that is 2.5 km wide and 8.0 km long. The homocline is bordered to the east by a synclinal bend and on the west by the Red Mesa anticline. These two synclinal bends give the homocline the appearance of being a flat-bottomed syncline. To describe this feature as a syncline would be misleading because it has no fold axis. The Jack Rabbit Flats Fault zone cuts across the northern end of the homocline and two minor faults cut across its southern end.

North-trending Folds

A system of north-trending folds are present along the western margin of the study area. These folds are either doubly-plunging or south-plunging, and are asymmetric and open. All have been faulted. The larger folds are the Red Mesa anticline, the Cañada de las Milpas syncline, Tierra Amarillo anticline and the Mesa Cuchilla anticline.

The Red Mesa anticline (Section B-B'; Fig. 2) is located on the upthrown side of the Pajarito fault which cuts obliquely across the anticline and has removed much of the western limb. A series of northeast-trending faults cut across the northern part of the eastern limb; north of most of these faults, a block of Precambrian rock is exposed and the fold cannot be traced north of this fault. The eastern limb of the anticline rises abruptly from the Cañoncitos homocline through a synclinal bend that is locally overturned but generally dips 25° to 40° E. Longitudinal faults occur along part of the axis of the synclinal bend. One km north of the Rio Salado the anticline plunges rapidly to the south, and 2 km south of the river the fold dies out into several small folds.

The Cañada de las Milpas syncline (Section D-D'; Fig. 2) has a horizontal axis in most of the map-area; to the south it begins to plunge to the south. In most areas it is asymmetric with a steep eastern limb. Alluvium covers the axis and much of the flanks except at the northern end. North- to northeast-trending faults parallel the western flank and a north-trending fault bisects the north end of the syncline along its axis. The Tierra Amarillo anticline forms the eastern margin of the syncline except along its northern extremity where it abuts directly against the Pajarito fault.

The Tierra Amarillo anticline (Section D-D'; Fig. 2) is doubly-plunging and nearly symmetric. The eastern flank of the anticline is cut by several transverse faults. Most of these are high-angle dip faults. Because of the large number of faults in this area and the small stratigraphic separation of most of these faults, only faults with over 3.0 m of stratigraphic separation were mapped.

Travertine, alluvium, and landslide deposits obscure the axial trace of the anticline for most of its length. A longitudinal fault which appears to be the Pajarito fault lies slightly east of the axial trace. The geometry of this fault is obscured by landslide debris but its presence can be inferred from the outcrop pattern and the alignment of both active and inactive warm springs.

On the southeastern limb of the anticline there is evidence of tectonic thinning of the Todilto Formation. At this location the gypsum is estimated to range from 3.0 to 15 m in thickness. There is no indication of strike-faults in the Todilto.

The Mesa Cuchilla anticline (Section A-A'; Fig. 2) plunges south, and has a Precambrian core that is bounded on the east by the San Ysidro fault which is downthrown to the east and by the Mesa Cuchilla fault on the west which is downthrown to the west. The geometry of the structure is also that of a narrow horst. The geometry of the fold is obscured by the large travertine deposit and alluvium at its southern end where the fold, the Mesa Cuchilla fault, and the San Ysidro fault may intersect. The fold is cut by a high-angle, normal, transverse fault with 130 to 170 m of stratigraphic separation. The northern and southern extensions of this fault are covered by alluvium.

The anticline near San Ysidro may be related to the Mesa Cuchilla anticline; the relationship between these two structures is obscured by the San Ysidro fault. This would explain the anomalous westward dip of the strata on this mesa.

Structural Analysis

Pre-Laramide Structural Events

Due to the limited extent of outcrops of Precambrian rocks, many of the details of Precambrian orogenic activity are obscured. The major event appears to be the intrusion of a pluton and its later regional metamorphism to produce the quartz monzonite gneiss with a uniform trend of foliation to the northeast. The gneiss was intruded by several leucocratic dikes. East-trending shearing occurred and placed two unlike facies of the quartz monzonite gneiss in juxtaposition in Peñasco Arroyo.

The next known tectonic activity in the area occurred during post-Meramecian, pre-Morrow time when part of the area was uplifted and much of the Mississippian strata originally deposited in the area was eroded.

The area was again active during post-Morrow, pre-Madera time. A fault that was active during this time was mapped by Armstrong (1955, p. 10) 3.0 km north of the study area in Los Piños Canyon.

Wood and Northrop (1946) mapped a north-trending Pennsylvanian-Permian structural high at the site of the present-day Nacimiento uplift. This high has been called the Peñasco uplift (Kelley, 1955). Some evidence for the high is the presence of large boulders of granitic rock up to 25 cm in diameter in the Madera Formation; abundant arkose beds in the Madera composed of angular granitic rock fragments; the absence of Pennsylvanian strata in Jack Rabbit Flats; and an angular unconformity between the Madera and probable Abo Formation at Arroyo Peñasco where the Madera thins eastward from 7.0 m to 1.0 m over a distance of 170 m.

Laramide and Younger Deformation

Based on structural relationships of Tertiary units exposed on the flanks of the northern Nacimiento uplift, Laramide deformation began during latest Paleocene or earliest Eocene time when the San Juan Basin was downwarped and *en échelon* northwest-trending folds began to develop across the present boundary between the San Juan basin and Nacimiento uplift (Baltz, 1967, p. 86-87). During the deposition of the early Eocene San Jose Formation, a west-facing monocline developed along the west side of the uplift (Baltz, 1967, p. 87; Woodward and others, 1972, p. 2394). The range-marginal faults developed after the deposition of the San Jose Formation as this unit is strongly deformed by these faults (Woodward and others, 1972, p. 384).

Strata equivalent in part to the Tertiary units exposed along the northern Nacimiento uplift, are present south of the San Ysidro area. Details of the stratigraphy and ages of most of these units have not been clarified, and at this time, only limited information on the development of deformation in the area can be inferred from these units.

Renick (1931, p. 54) mapped the Wasatch Formation 3 mi south of the study area. Baltz (1967, p. 37) reported that the term Wasatch Formation is no longer used in the San Juan basin, and strata mapped by Renick as Wasatch are now considered to be part of the San Jose Formation. Galusha (1966, p. 11) mapped the same strata as the Galisteo Formation, a unit that Baltz (1967, p. 57) said is equivalent, in part, to the San Jose Formation. Renick (1931, p. 54-55) reported that the basal San Jose in the San Ysidro area rests with an erosional unconformity on the underlying Nacimiento Formation and the basal 35 km of the San Jose consists of sandstones and conglomerates with pebbles up to 12 cm in diameter. He further said that the San Jose, with some exceptions, has a conformable strike with the underlying formations. A similar situation between the San Jose and underlying Nacimiento Formation in the northern Nacimiento uplift lends support to an early Eocene age for the beginning of the Laramide orogeny in the area.

The early to middle Miocene Zia Sand Formation overlies the San Jose Formation with an erosional unconformity (Galusha, 1966, p. 11). Renick (1931, p. 57-58) mapped the Zia Sand as part of the Santa Fe Formation. Although he noted that much of the San Jose (Wasatch) had been eroded prior to the deposition of the Zia Sand (Santa Fe), he found no considerable differences between the strikes and dips of the two units. At the SW 1/4 sec. 20, T. 16 N., R. 2 E., the Zia Sand lies on the basal member of the Chinle Formation. The Zia lies on the Petrified Forest Member of the Chinle Formation at the southernmost exposure in the map-area.

Because strata equivalent in age to the Zia Sand Formation are not present in the northern Nacimiento uplift (Galusha, 1966, p. 1), the structural relationships of the Zia provides additional information on the tectonic history of the area. The uniform lithology and absence of abundant conglomerate beds in the Zia Sand in the map-area indicate that the unit extended onto the southern Nacimiento uplift. The basal contact of the Zia with the Chinle Formation indicates that a minimum of 1700 m of strata had been eroded prior to its deposition. Further, if the Zia Sand originally extended onto the uplift, a minimum of 400 m of uplift, relative to the Rio Grande depression, has occurred during post-middle Miocene time.

The late Pleistocene Upper Buff Member of the Santa Fe Formation has been faulted south of the map area, by the Jemez and Cañada de las Milpas faults (Galusha, 1966, p. 4). Smith and others (1970) have mapped several faults in the Quaternary volcanic rocks of the Jemez volcanic field north and northeast of the map-area that appear to have developed as a consequence of the formation of the Jemez caldera. It is possible that the formation of the caldera resulted in some movement along the faults in the San Ysidro area; however, this movement could only account for a fraction of the total uplift.

Analyses of Structures

The Red Mesa anticline, the Mesa Cuchilla anticline, the Tierra Amarillo anticline and other folds in the map area are part of a larger system of northwest-trending folds (Fig. 20) such as the Zuni uplift, San Juan basin and the Paradox folds, which indicates a northeast shortening of the Colorado Plateau and right-lateral shift between the Plateau and the Eastern Rocky Mountains (Kelley, 1955, p. 66-68; Woodward, 1973, in press). Baltz (1967, p. 70-71), Cloos (1955), and Wilcox and others (1973) have constructed simple mechanical models to simulate the effects of right shift between two plates. The various stages in the development of deformation in these models are graphically summarized on Figure 21. The experimentally produced trends closely approximate many of the structures associated with the southern Nacimiento uplift and indicate right-lateral shift was involved in the evolution of the uplift.

The right-lateral shift model assumes that the Colorado Plateau moved in a northeastern direction relative to the Eastern Rocky Mountains. The mechanism which acted to compress the Plateau in that

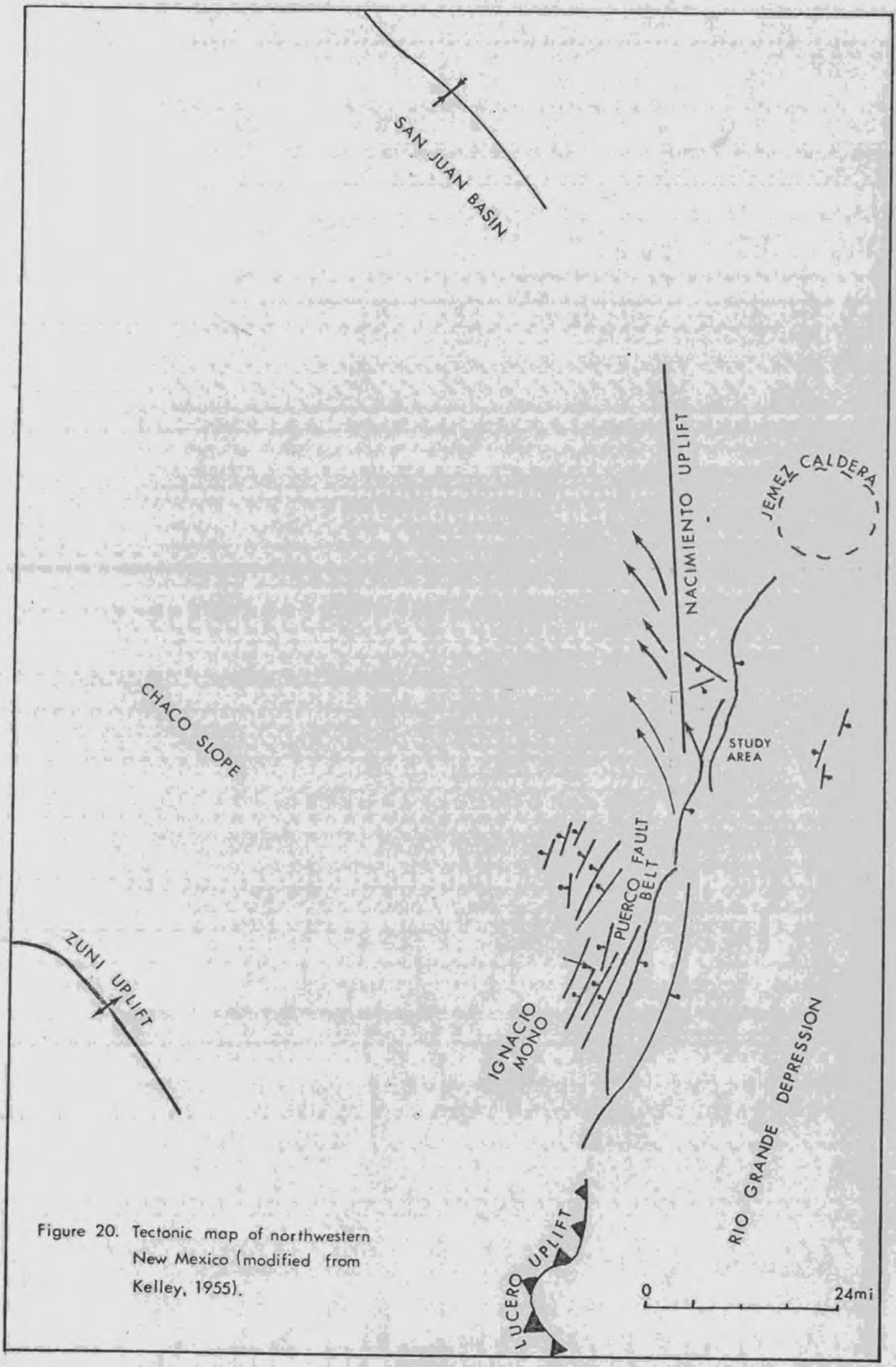
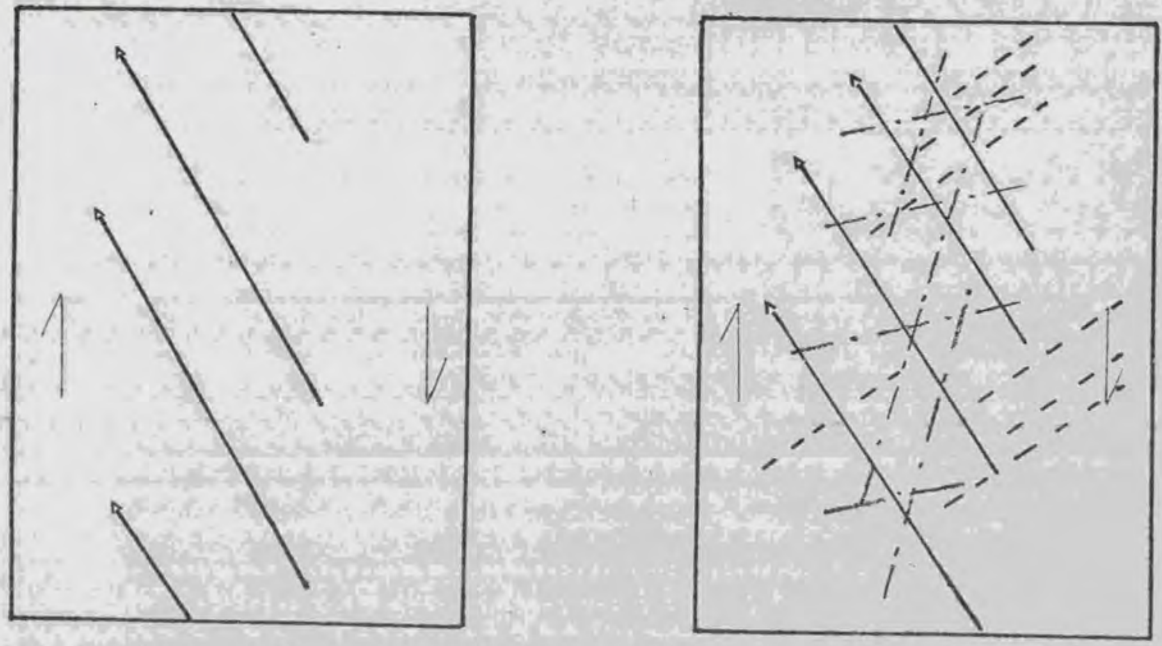


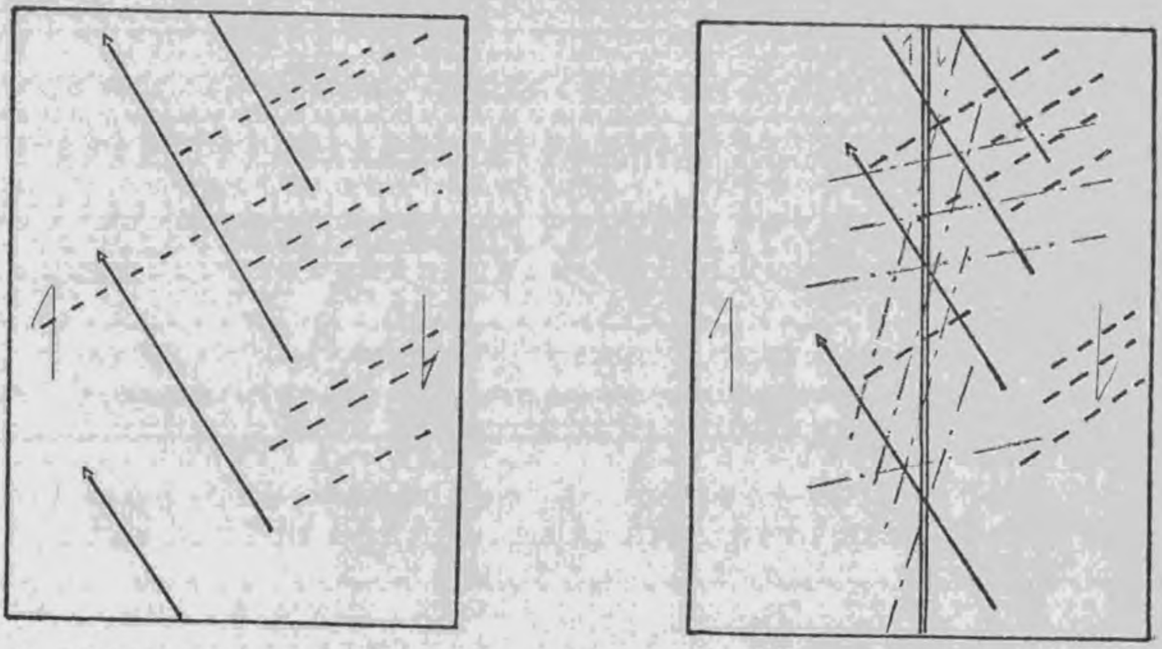
Figure 20. Tectonic map of northwestern New Mexico (modified from Kelley, 1955).

Postulated sequence of events in the Laramide deformation of the study area based on a model of right-lateral shift.



a. Development of northwest trending en échelon folds.

c. Continued right-lateral shift leads to the formation of two sets of conjugate fractures.



b. Tension fractures form perpendicular to the en échelon folds.

d. Creation of a master wrench fault.

direction may have been early Cenozoic thrusting in the Cordilleran foldbelt. However, Kelley (1955) pointed out that this alone cannot explain the evolution of Laramide structures in the eastern Plateau; there appears to be some older or deep-seated lines of weakness with a northerly or northwesterly direction on the Plateau that influenced the positions and trends of the Laramide structures. The north-trending Pennsylvanian Peñasco uplift which was located at approximately the same position as the present Nacimiento uplift, may have served as a line of weakness along which Laramide stress acted.

The first phase of right-lateral shift (Fig. 21a) is the development of northwest-trending folds. Northwest-trending folds are present in the study area and were the first Laramide features to develop, as these folds are cut by other structures.

With continued movement, tension fractures developed (Fig. 21b) that are oriented parallel to the major axis of the compressive stress (Wilcox and others, 1973, p. 87; McKinstry, 1953, p. 412-413). These fractures should cross the en échelon folds at right angles (Wilcox and others, 1973, p. 87) and the intersection of these fractures with the main fault should point in the direction in which the block on its own side of the fault has moved (McKinstry, 1953, p. 413). The Jack Rabbit Flats fault zone, the Jemez Pueblo Fault zone, and other northeast-trending faults appear to be tensional fractures. For example, the Red Mesa anticline is cut at nearly right angles by the Jack Rabbit Flats fault zone. The intersection of these faults with the master faults that bound them points in the direction of movement that right-lateral shift predicts. Because these tensional fractures are bounded in most cases by master faults, for example the Jemez

Pueblo fault zone is bounded on the east by the Jemez fault and on the west by the San Ysidro fault, major movement along most of the tension fractures occurred after the north-trending faults developed.

Continued right-lateral shift leads to the development of two sets of intersecting, vertical conjugate fractures (Fig. 21c) that form at angles between 10° and 30° and between 70° and 90° with the wrench strike (Wilcox and others, 1973, p. 79; Tchalenko, 1970, p. 1626-1628). Soon after conjugate fractures develop, the rocks generally fracture in a relatively narrow zone and a master wrench fault is created (Fig. 21d) (Wilcox and others, 1973, p. 82-87).

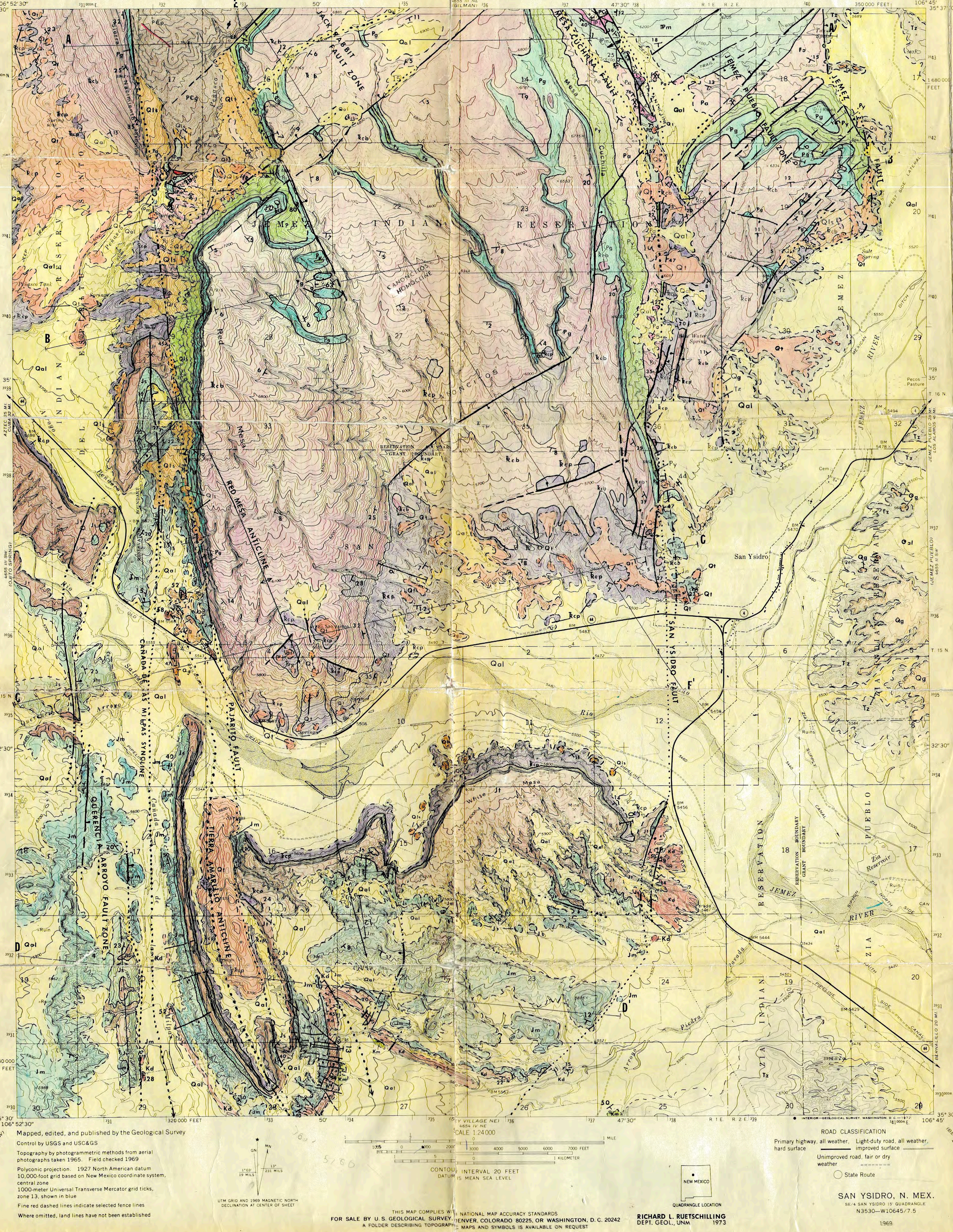
At this point, the right-lateral wrench model breaks down in explaining the tectonic evolution of the southern Nacimiento uplift. On the basis of possible staggering of northwest-trending folds, Baltz (1967, p. 70) postulated as much as 5 km of right shift occurred on the Nacimiento fault. However, Woodward and others (1972, p. 2394) pointed out that the geometry of the <u>en échelon</u> folds does not seem to warrant such a large amount of shift. As discussed in the section on the geometry of the Pajarito fault, all movement on that fault appears to be dip-slip. Right-lateral shift must have ceased before major movement began on the Pajarito fault.

The strike of the Pajarito fault appears to parallel the strike expected of a wrench fault, approximately 30° from the axis of the <u>en échelon</u> folds (Moody and Hill, 1956, p. 1212-1213). These faults also parallel the main structural trend of the Rio Grande depression (Kelley, 1954) and all but the Pajarito fault have proven post-middle Miocene displacement. A possible explanation of why these faults have the trend of a wrench fault and are also parallel to the main trend of the Rio Grande depression is that the Rio Grande depression began to form at the same time as the uplift developed. Right-lateral shift developed to the point where fractures were formed but not to the point of actual strike-slip movement. These zones of weakness were later activated during a period of vertical movement. It is also possible that the fact that these faults parallel the trend of a wrench fault is coincidental and their formation is unrelated to the right-lateral shift.

Kelley (1955, p. 88) and Woodward and others (1972, p. 2385) have suggested that vertical uplift of the Nacimiento Mountains is related more to the development of the Rio Grande depression than the Laramide orogeny. There are several lines of evidence which support their suggestion. Woodward and others (1972, p. 2394-2395) have shown that the high-angle reverse and thrust faults that form the western margin of the uplift can best be explained as resulting from primary vertical uplift. Also, if these faults were the direct result of right-lateral shift, conjugate strike-slip faulting should be well developed (Wilcox and others, 1972, p. 89). The north- and northeast-trending faults on the eastern side of the uplift formed after middle-Miocene time and there has been a minimum of 400 m of vertical uplift of the southern Nacimiento Mountains relative to the Rio Grande depression along these faults.

The margins of large rift zones like the Rio Grande depression are generally rimmed by uplifts (Freund, 1965, p. 341; McConnell, 1972, p. 2564-2567; Beloussov, 1969; Osmaston, 1971, p. 396), and many of these uplifts are comparable in size to the Nacimiento Mountains. Chapin (1971) has estimated that between 5,000 and 12,000 ft of uplift

FIGURE 1. GEOLOGIC MAP OF THE SAN YSIDRO QUADRANGLE, SANDOVAL COUNTY, NEW MEXICO



Mapped, edited, and published by the Geological Survey
Control by USGS and USC&GS
Topography by photogrammetric methods from aerial photographs taken 1965. Field checked 1969
Polyconic projection. 1927 North American datum
10,000-foot grid based on New Mexico coordinate system, central zone
1000-meter Universal Transverse Mercator grid ticks, zone 13, shown in blue
Fine red dashed lines indicate selected fence lines
Where omitted, land lines have not been established

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
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A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

RICHARD L. RUETSCHILLING
DEPT. GEOL., UNM 1973

SAN YSIDRO, N. MEX.
SE/4 SAN YSIDRO 15' QUADRANGLE
N3530—W10645/7.5
1969
AMS 4655 III SE—SERIES V881

EXPLANATION

QUATERNARY

Qal

Alluvium

Unconsolidated and locally consolidated clay- to gravel-sized clastic sediments.

Qls

Landslide Deposits

Unconsolidated deposits consisting of boulders derived from adjacent cliffs; most consolidated blocks occur at the base of White Mesa and consist of gypsum from the Todilto Formation, toreva blocks were mapped 1.0 km east of Salt Springs and along the base of Red Mesa.

Qt

Travertine Deposits

Laminated limestone and gravels cemented by thermal spring deposits; occur in mounds up to 20 m high and in blanket deposits up to 4.0 m thick.

Qg

Pediment and Terrace Gravels undivided

Unconsolidated conglomeratic sediments that contain cobbles and boulders of Precambrian and sedimentary rocks; 0 to 5.0 m thick.

TERTIARY

Tz

Zia Sand Formation

Light gray, crossbedded, coarse- to medium-grained, friable sandstone; approximately 100 m exposed in map-area, 330 m thick 6.0 km south of map-area.

CRETACEOUS

Km

Mancos Shale

Slope-forming, olive-gray, carbonaceous shale and silty, calcareous, bioturbated, fossiliferous, fine-grained sandstone; approximately 100 m of lower part of unit exposed in map-area, generally over 600 m thick in the San Juan basin.

Kd

Dakota Formation

Five members in ascending order: Unnamed basal sandstone: highly lenticular, ledge-forming, coarse-grained to conglomeratic sandstone that locally contains channel coal beds; Oak Canyon Member: slope-forming, dark gray carbonaceous shale that increases in fine-grained sand content upsection, contains abundant bentonite beds and septarian concretions; Cubero Sandstone Tongue: bioturbated, calcareous, fine-grained sandstone; Clay Mesa Shale Tongue; arenaceous, slope-forming shale; Paquate Sandstone Tongue: bioturbated, calcareous, fine-grained sandstone; total 64 m thick.

JURASSIC

Jm

Morrison Formation

Four members in ascending order: Recapture Member: slope-forming grayish-red to greenish-gray mudstone and very light gray to greenish-gray fine-grained wacke; Westwater Canyon Member: ledge-forming, approximately 60 percent lenticular medium-grained to conglomeratic, crossbedded sandstone, 40 percent interbedded grayish-red to greenish-gray mudstone; Brushy Basin Member: slope-forming grayish-red to greenish-gray bentonitic mudstone and intercalated well indurated sandstone, limestone and red siltstone beds; Jackpile sandstone: ledge-forming, light gray, fine- to medium-grained, crossbedded sandstone, total thickness 205 m.

Js

Summerville Formation

Slope-forming, light red, thin-bedded fine-grained sandstone, gypsum and mudstone; 13 m thick.

Jt

Entrada Sandstone and Todilto Formation undivided

Todilto: basal part is light gray, laminated limestone, 2 m thick overlain by white, cliff-forming gypsum 35 m thick; Entrada: 2 members in ascending order: medial silty member: pale reddish brown, cliff-forming, laminated fine-grained sandstone 12 m thick; upper sandy member: cliff-forming, cross-bedded, yellowish-gray sandstone, 23 m thick.

TRIASSIC

CHINLE FORMATION

Ŧcp

Petrified Forest Member

Three informal units in ascending order: unit 1: slope-forming, intercalated, thin-bedded, ripple laminated, fine-grained sandstone and bluish-gray mudstone, 10 m thick; unit 2: slope-forming, grayish-red mudstone with intercalated sandstone and nodular limestone beds, 330 m thick; unit 3: lower part ledge-forming cross-bedded sandstone, upper part slope-forming, thin-bedded sandstone and shale, 8 m thick.

Ŧcb

Basal Member

Lower part cliff-forming conglomerate; conglomeratic sandstone and sandstone, upper part highly crossbedded, light gray sandstone and subordinate conglomeratic sandstone; total thickness 44 m.

PERMIAN

Pg

Glorieta, San Andres and Bernal Formations undivided

In descending order; Bernal: slope-forming, pale red, fine-grained, laminated sandstone with intercalated dusky red mudstone, 4.5 to 17.25 m thick; San Andres: interbedded, thin-bedded, slope-forming, dusky red, calcareous sandstone, mudstone and fossiliferous limestone, 7 m thick; Glorieta: light-gray, cliff-forming, medium-grained sandstone, 28 m thick.

Py

Yeso Formation

Four units in ascending order: unit 1: slope-forming, orangish-red, fine-grained sandstone and intercalated mudstone; unit 2: orangish-red, crossbedded cliff-forming sandstone; unit 3: cliff-forming, lenticular orange-red sandstone containing breccia zones in upper part of unit, red mudstone, and 1.5 m laminated dolomite bed at top of unit; unit 4: cliff-forming, grayish-red, well sorted, medium-grained sandstone; 140 m thick.

Pa

Abo Formation

Slope-forming, reddish-brown mudstone and intercalated lenticular, crossbedded sandstone; approximately 180 m thick.

PENNSYLVANIAN

IPm

Madera Formation

Grayish-red and bluish gray mudstone and fossiliferous shale, gray fossiliferous limestone, and light red arkose; 1.0 to 100 m thick.

IPl

Morrow-age strata

Crossbedded, recrystallized, arenaceous, fossiliferous limestone; 6 m thick.

PRECAMBRIAN

P€p

Leucocratic dike rocks

Pink aplite, pegmatite, and fine-grained granite or quartz monzonite in small dikes or irregular bodies.

P€g

Quartz Monzonite Gneiss

Moderate red to grayish-pink, medium- to coarse-grained gneiss consisting of quartz, microcline, plagioclase and biotite.

P€x

Xenoliths

Irregular shaped xenoliths of dark greenish-gray, fine-grained, schistose rock composed of plagioclase, quartz, microcline and biotite.

SYMBOLS

\- - - - - -

Contact of surficial deposits

Contact of bedrock, dashed where approximate

High-angle fault; dashed where approximate, dotted where covered

Strike and dip of inclined and overturned bedding

Strike of vertical foliation

Anticline (top) and syncline, showing trace of axial plane and direction of plunge of axis, dotted where covered

Measured sections

⚒

Copper mineralization

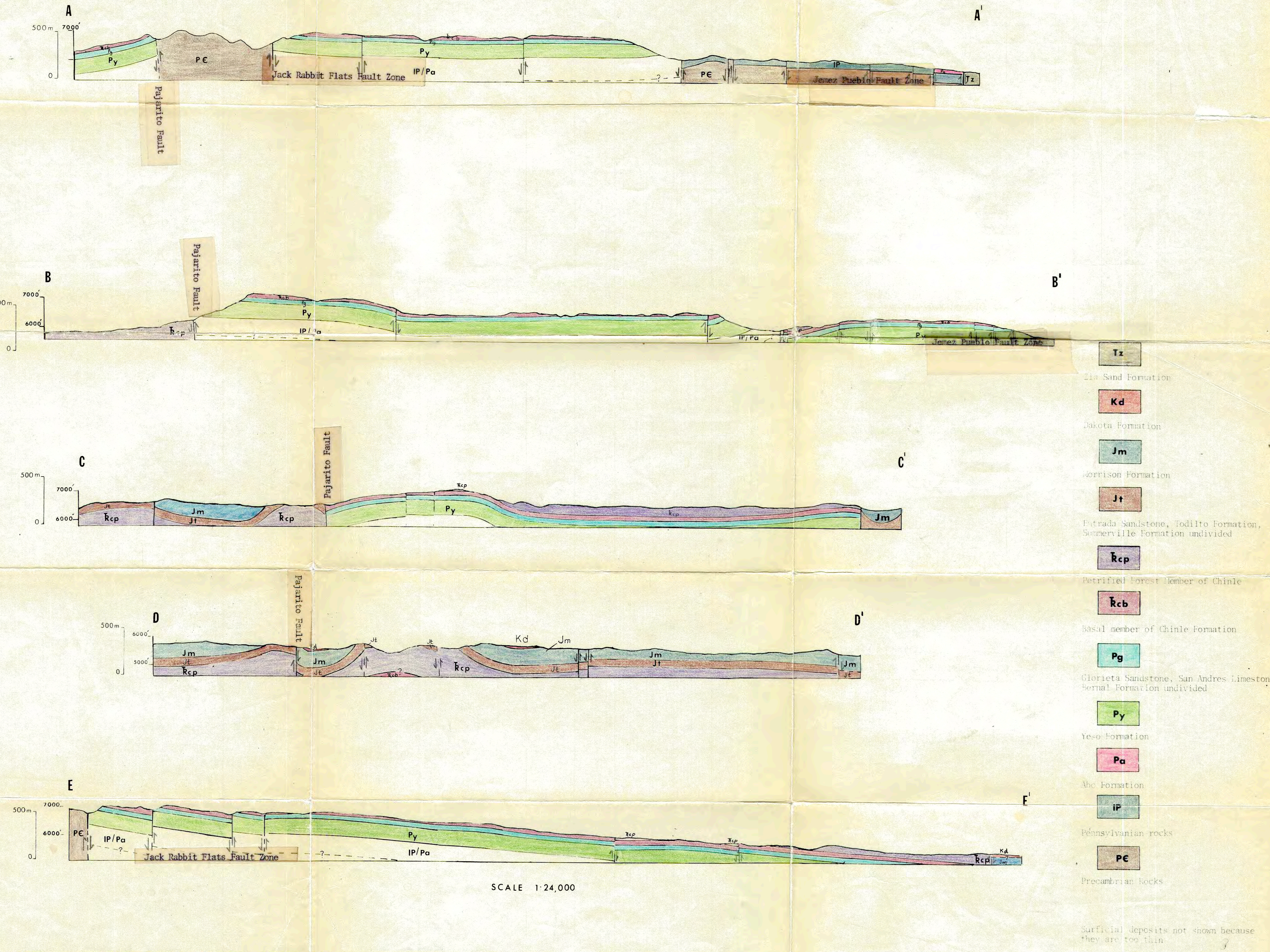

FIGURE 2. GEOLOGIC CROSS SECTIONS OF THE SAN YSIDRO QUADRANGLE, NEW MEXICO

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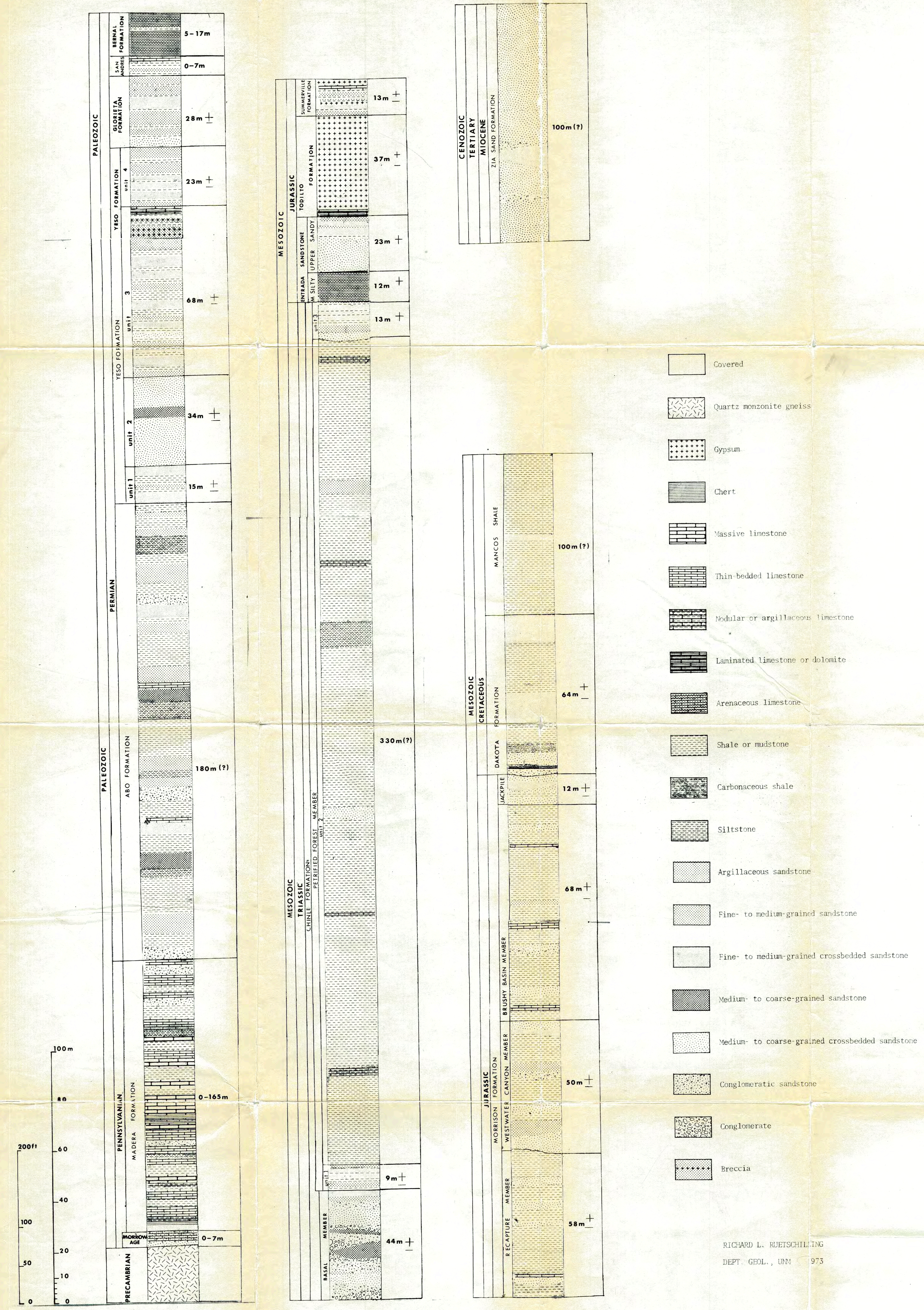

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FIGURE 3. GENERALIZED STRATIGRAPHIC COLUMN, SAN YSIDRO QUADRANGLE

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