GEOLOGY OF THE LEMITAR MOUNTAINS
SOCORRO COUNTY, NEW MEXICO

by

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ABSTRACT

The Lemitar Mountains in central New Mexico form a west-dipping, intra-rift horst within the Rio Grande rift zone; the horst is composed of igneous and metamorphic rocks of Precambrian age overlain by sedimentary rocks of Paleozoic age and volcaniclastic and volcanic rocks of Cenozoic age.

Rocks of Precambrian age consist of an older sequence of folded, sheared and metamorphosed clastic sediments intruded by younger, slightly metamorphosed sequences of mafic to sialic plutons and dikes. Paleozoic strata unconformably overlie the Precambrian basement and consist of a lower sequence of limestones, sandstones and shales overlain by massive limestones of Pennsylvanian age.

Late Mesozoic to early Cenozoic faulting of the Laramide orogeny uplifted the area of the Lemitar Mountains, and caused extensive erosion. A thick sequence of volcaniclastic sediments overlain by ash-flow tuffs and andesite flows of Oligocene age unconformably overlie the post-Laramide (Eocene) erosion surface.

The onset of basin and range faulting began in early Miocene time with the deposition of fanglomerates and playa deposits in central New Mexico. Renewed uplift and normal faulting along the north-south axis of the Rio Grande rift zone began in late Miocene time, forming the Socorro-Lemitar intra-rift horst. Bifurcation of the main rift structures truncated the northern end of the Lemitar Mountains

and complexly faulted the original north-trending blocks of the range. Continued uplift and tilting of individual fault blocks accompanied by erosion formed the present topographic features of the Lemitar Mountains.

INTRODUCTION

Statement of Purpose

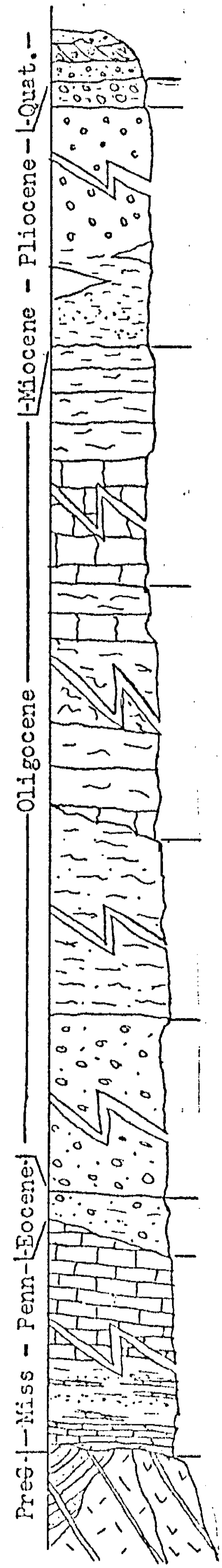
In the past, geological data regarding the structural features of the Rio Grande rift zone in Socorro County, New Mexico, has been limited to reconnaissance mapping (Debrine and others, 1963; Kelley and Wood, 1946; Wilpolt and Wanek, 1952) and scattered geophysical data (Sanford, 1963, 1970; Sanford and Long, 1965; Sanford and others, 1972).

The purpose of this report is to compile and interpret detailed geological data from mapping an area within the Rio Grande rift zone in light of current models of rift zone tectonics.

The Lemitar Mountains are located near the eastern margin of the Datil volcanic field of mid-Tertiary age and occupy an intra-rift horst within the Rio Grande rift zone tectonic system. Along the footwalls of uplifted fault blocks, the existing section (fig. 1) is well exposed. Recognition and mapping of major stratigraphic and structural units allow an interpretation of structural and tectonic history for north-central Socorro County, New Mexico.

Location and Extent

The Lemitar Mountains are located approximately 7 miles northwest of Socorro, New Mexico, and extend from Strawberry Peak northward to Canoncito de las Cabras, a distance of



Alluvial deposits, talus cones, slump blocks and pediment gravels. 0-160'

Moderately consolidated alluvial debris. 0-150'

Popatosa Formation - Red conglomerates and sandstones overlying buff to greyish-white mudstones, siltstones and sandstones interbedded with the andesite of Silver Creek. 1000-2000'

Unconformity

Potato Canyon Formation - Grey to reddish-brown rhyolitic ash-flow tuffs overlying dark red to grey andesite flows. 150-900'

A. L. Peak Formation - Composite sheet of interbedded grey to dark red rhyolitic ash-flow tuffs and dark greyish to reddish brown andesite flows. 200-1400'

Regional unconformity

Hells Mesa Formation - Grey to pink latitic to quartz latitic ash-flow tuffs. 0-700'

Spears Formation - Purplish-grey conglomerates and sandstones. 0-800'

Regional unconformity

Baca Formation - Red conglomerates and sandstones. 0-200'

Regional unconformity

Paleozoic sediments - Massive beds of grey limestones overlying interbedded sequences of quartzites, shales and limestones. 0-1200'

Regional unconformity

Precambrian basement - Quartzites, meta-arkoses, metagabbro and granite.

Scale: one inch equals five hundred vertical feet

Figure 1. Generalized stratigraphic column

about 8 miles. The Lemitar Mountains are bounded on the west by the La Jencia basin (Snake Ranch Flats) and on the east by the Socorro basin (fig. 2).

The map area extends from Canoncito del Puertocito del Lemitar (Corkscrew Canyon), about 3 miles north of Strawberry Peak, northward about 5 miles to near Canoncito de las Cabras. The eastern and western boundaries of the map area are formed by the pediment gravels of the Socorro and La Jencia basins, respectively. The total area mapped was about 20 square miles (fig. 3).

Field Work

Mapping was done on a topographic base map of 1:12,000 scale. The map was made by enlarging and matching portions of the U. S. Geological Survey Lemitar (7.5 minute) and Magdalena (15 minute) quadrangle maps.

Field mapping and sampling was carried out during the summer of 1971 through the Fall of 1972 whenever weather, road and vehicle conditions were favorable. Thin sections were prepared from representative samples and studied microscopically.

Access by four-wheel drive vehicles is possible on several primitive ranch roads connecting to U. S. 60 on the west and U. S. 85 or frontage roads of Interstate 25 on the east.

Physiography, Climate and Vegetation

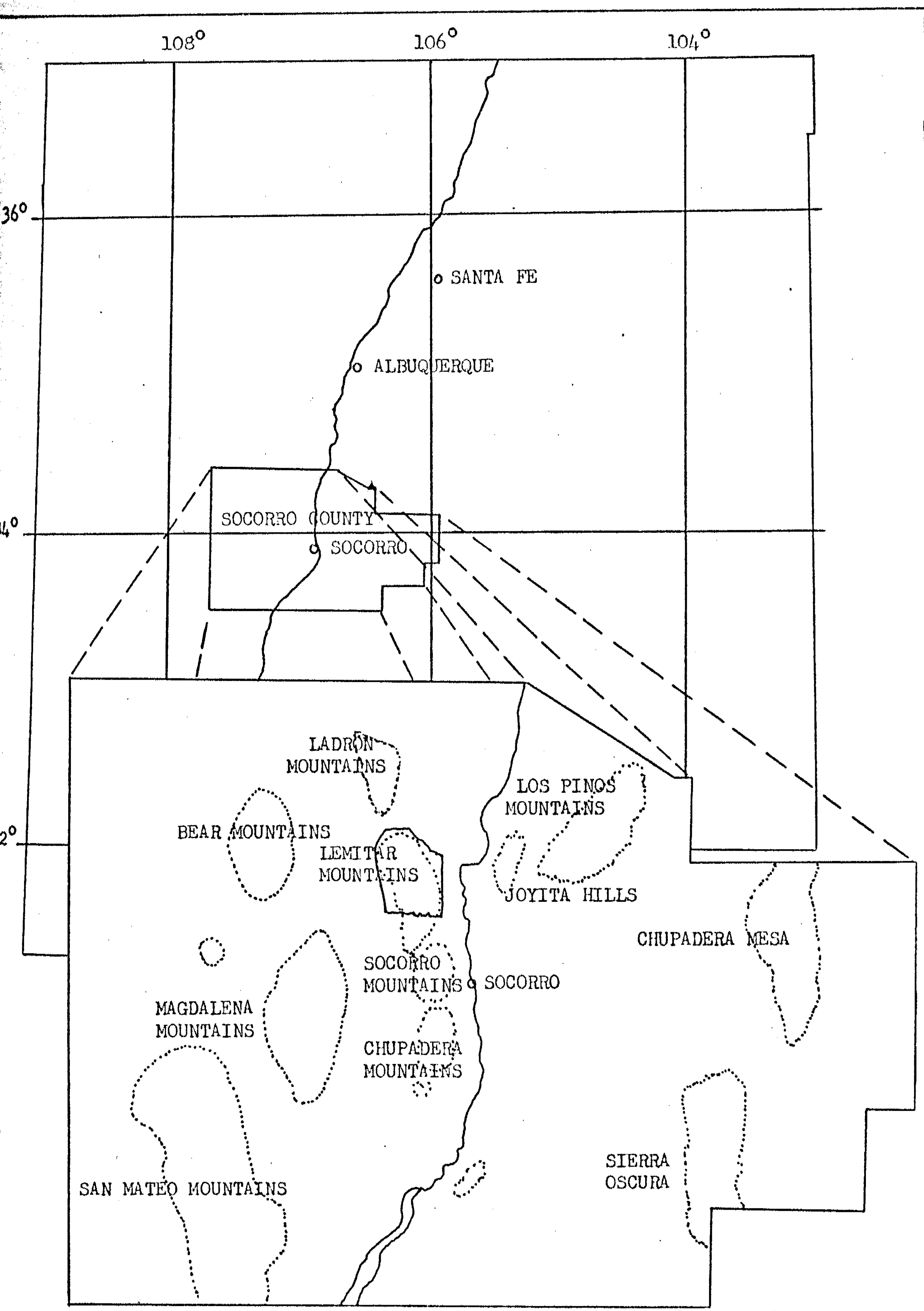


Figure 2. Index map of central New Mexico showing location of study area.

The topography of the Lemitar Mountains is rugged. Maximum topographic relief is nearly 1900 feet from the top of Polvadera Mountain eastward to the pediment gravels in Socorro basin. The map area is characterized by many steep canyons, hogbacks, small steep-walled valleys and numerous cliffs. All streams in the map area are intermittent, carrying water only after heavy rains. The streams are directly or indirectly tributaries of the Rio Grande River.

The climate in central New Mexico is arid, with sufficient moisture to support only scattered vegetation except in the larger arroyos. Predominent flora consist of creosote, sage brush, and cactus with some grass and stunted pinon pines in the larger valleys.

PRECAMBRIAN ROCKS

General Statement

Precambrian igneous and metamorphic rocks are exposed over approximately one-third of the map area. Rocks of Precambrian age crop out along the eastern sides of upthrown fault blocks forming the two major north-trending hogbacks of the Lemitar Mountains.

The oldest unit consists of a sequence of interbedded quartzites and micaceous quartzo-feldspathic metasediments. Intruding this sequence on the north is a metagabbro pluton which is in turn intruded on the north and west by a large granite pluton. Following emplacement of the granite, the entire Precambrian sequence was intruded by mafic dikes and sills.

Regional metamorphism of amphibolite facies grade was followed by periods of dynamic and thermal metamorphism with minor retrograde metamorphism occurring after the last known Precambrian events. A few altered dikes of lamprophyre of unknown age intrude the Precambrian complex in the southeastern part of the map area. No intrusive relationships for these dikes with overlying rocks of Paleozoic or Tertiary age could be found in the map area, therefore, these dikes have been arbitrarily assigned a Precambrian age in this report.

Radiometric dates obtained from Precambrian granite and gneiss outcrops and well cuttings in Bernalillo, Lincoln, and Socorro counties indicate a range of ages from about 1.6 to 1.35

billion years before present for central New Mexico (Muehlberger and others, 1968). Radiometric dates have placed Precambrian igneous events in the southwestern United States at 1.1 to 1.6 b. y. before present (Rankama, 1970; Lanphere, 1967).

No unit or formation names exist in the literature for the rocks of Precambrian age in the Lemitar Mountains; therefore, several rock units have been informally named by the author.

Corkscrew Canyon Sequence

A thick sequence of interbedded quartzites and micaceous quartzo-feldspathic metasediments crops out along the foot-walls of normal faults in the extreme southeastern part of the map area.

This sequence is intruded on the north by the Lemitar stock, an intrusive body of metagabbro, and by the Polvadera granite. The western limit of exposure is formed by the unconformable contact with the overlying Caloso Formation of Mississippian age. The eastern boundary is formed by downfaulted rocks of Paleozoic and Tertiary ages. The southern boundary is unknown as the Corkscrew Canyon sequence extends south of the map area. The Corkscrew Canyon sequence also crops out at the base of the western hogback of the Lemitar Mountains in the central part of the map area. Here the sequence is bounded on the north by the Polvadera Granite, on the west by the unconformable contact with the overlying

Sandia Formation of Pennsylvanian age and on the south and east by downfaulted rocks of Tertiary age.

Maximum thickness of the sequence exposed in Corkscrew Canyon, the largest area of exposure, is approximately 1500 feet. However, the rocks have been cut by several north-trending faults of Precambrian age and in places have been sheared to the extent that bedding has been obliterated. Therefore, a true thickness of the exposed section cannot be accurately determined.

Bedding is distinguishable by color and textural contrasts between beds of quartzite and the micaceous quartzo-feldspathic rocks (fig. 4). The beds strike northeast and dip to the southeast with dips ranging from about 25 degrees to more than 60 degrees near the western contact with rocks of Paleozoic age. Due to the limited outcrop area and poor exposures, no definite structures of Precambrian age could be distinguished.

Characteristically, the quartzite ranges from light grey to light reddish-brown, depending on the percentage of iron oxide minerals. Both fresh and weathered surfaces show about the same color. The micaceous quartzo-feldspathic rocks are generally dark grey-brown to brown on both fresh and weathered surfaces and are easily distinguishable from the quartzite beds by color and the conspicuous biotite foliation.

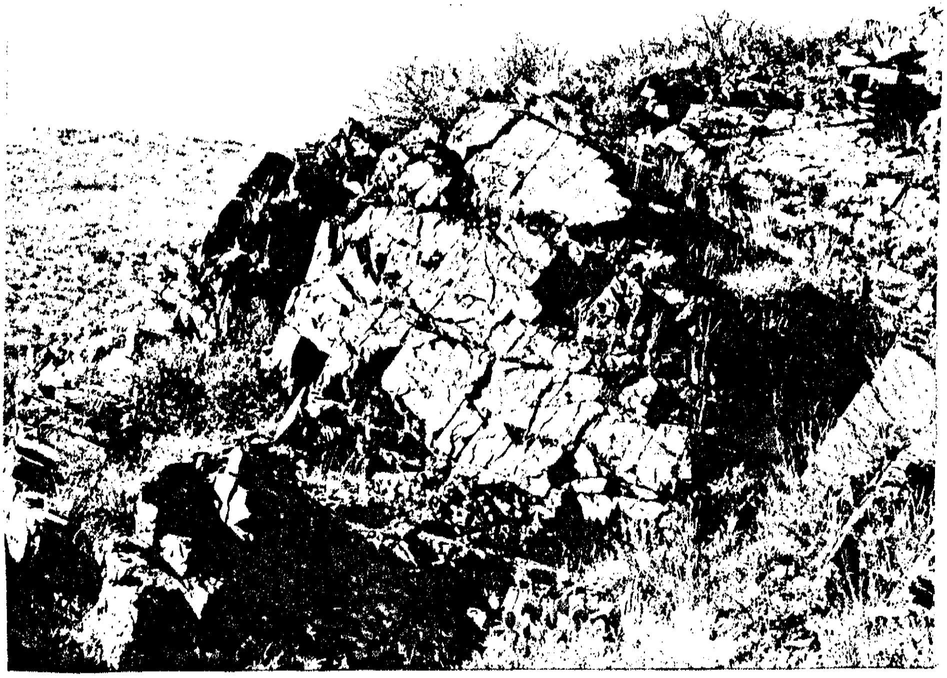
Mineralogically, the quartzite is rather pure with only minor amounts of muscovite, biotite and sericitized feldspar (fig. 5). The texture is generally fine to medium-grained

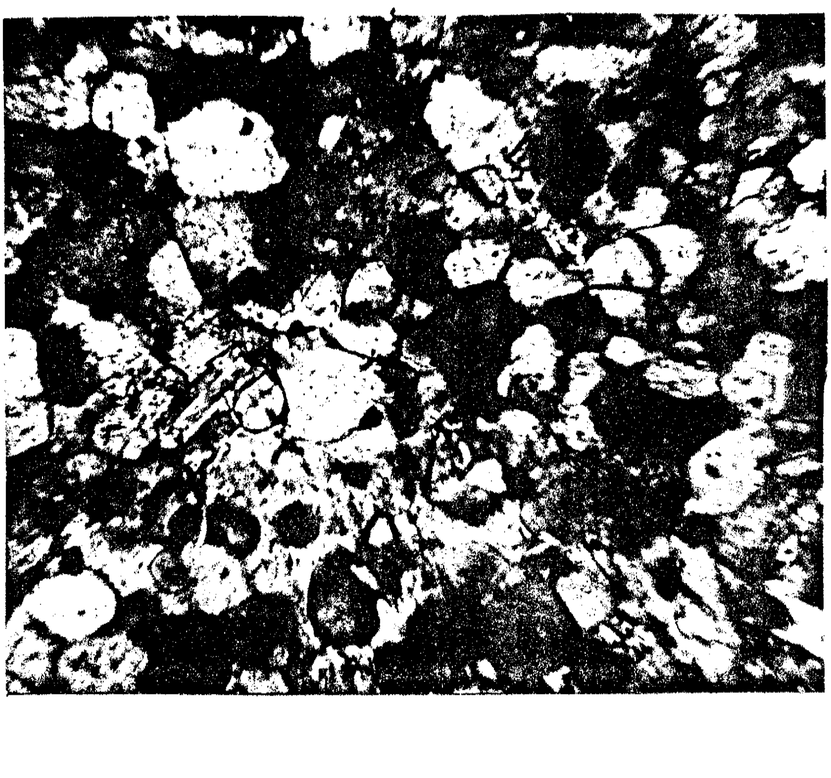
Figure 4.

Massive, east-dipping beds of the Corkscrew Canyon sequence. Photograph taken in Corkscrew Canyon looking northwest.

Figure 5.

Photomicrograph of quartzite from the Corkscrew Canyon sequence (X-nicols)(X 100). Quartz occurs as fine-grained granoblastic crystals, with minor amounts of crystalloblastic muscovite.





with typical interlocking quartz grains. The muscovite occurs as thin, scattered grains bounding some of the quartz grains, while biotite occurs as skeletal porphyroblasts. Seriticized feldspar appears as very irregular small crystals in a few samples. Iron-oxide minerals form a coating on grain boundaries in some specimens which tends to obscure texture and gives the rocks a reddish-brown appearance. No foliation is visible in the pure quartzite beds.

The micaceous quartzo-feldspathic rocks form volumetrically the major part of the Corkscrew Canyon sequence. The texture is crystalloblastic, medium to coarse grained, with large broken porphyroblasts of biotite and microcline. The microcline displays sieve texture. Quartz, biotite and microcline are the dominant minerals, with percentages ranging to as much as 50 percent, 25 percent and 20 percent, respectively. Minor amounts of sericite, apatite, albite, garnet and opaque minerals are present. Megascopic foliation in the form of biotite-rich lenses gives the micaceous quartzo-feldspathic rocks a gneissic appearance (fig. 6).

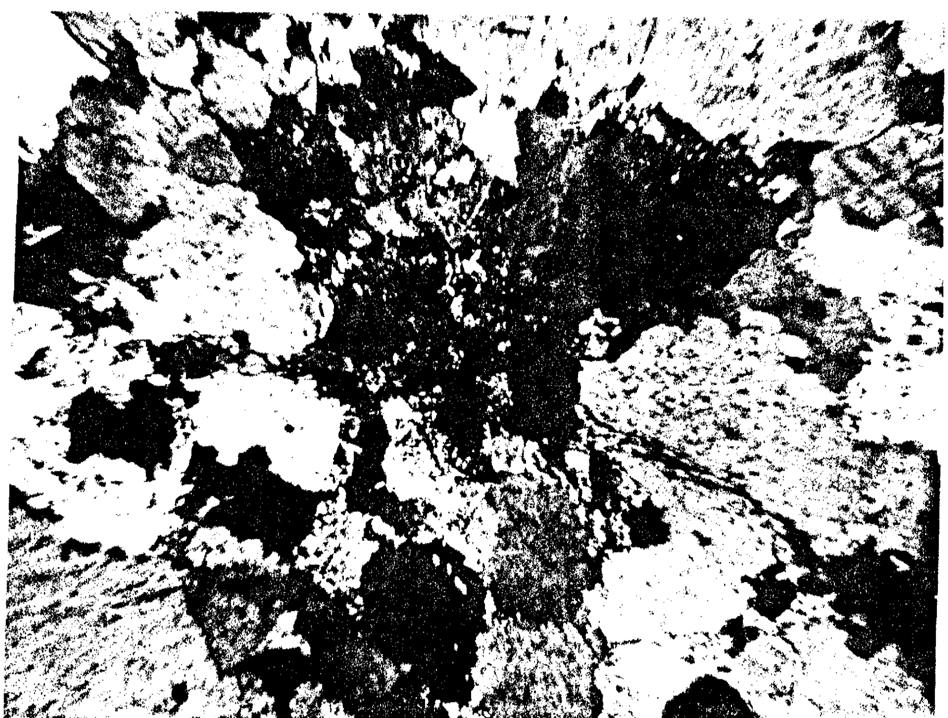
Where the Corkscrew Canyon sequence has undergone shearing, cataclastic textures are present with sutured grain boundaries and undulatory extinction of the grains (fig. 7). Bedding and foliation are not visible in outcrop although light to dark reddish-brown streaks of hematite are present, probably along individual shear planes. Small irregular lenses of medium to coarse-grained granitic pegmatites are common in the sheared rocks.

Figure 6.

Biotite foliation in micaceous quartzo-feldspathic rocks of the Corkscrew Canyon sequence. Photograph taken in Corkscrew Canyon looking east at a small ledge about 5 inches in width.

Figure 7.

Photomicrograph of micaceous quartzo-feldspathic rock from the Corkscrew Canyon sequence (X-nicols)(X 100). Sutured grain boundaries of many quartz and feldspar crystals indicate recrystallization.



Mafic dikes and sills up to 20 feet in thickness, small pegmatite dikes and scattered quartz veins intrude the Corkscrew Canyon sequence. The dikes appear to have intruded along fault zones in some cases and the northeast strike and steep dip follow the Precambrian trend of faulting and dike intrusion that is predominant throughout the map area.

The Corkscrew Canyon sequence appears to have originally been composed of interbedded quartzose to feldspathic sandstones and arkoses; although some rocks may have a volcanic origin. Similar rock types have been described in the Ladron Mountains (Headerle, 1966; Black, 1964), Manzano Mountains (Stark, 1956) and Los Pinos Mountains (Mallon, 1966).

Lemitar Stock

The Lemitar metagabbro stock crops out due north of the Corkscrew Canyon sequence in the southeastern part of the map area. It forms many of the lower ridges of the eastern hogback of the Lemitar Mountains southeast of Polvadera Peak.

The southern boundary of the Lemitar stock forms a southward dipping intrusive contact with the older Corkscrew Canyon sequence. To the west, the contact is formed by unconformably overlying beds of the Sandia Formation of Pennsylvanian age. The Polvadera granite intrudes the Lemitar stock on the north forming an irregular, nearly vertical, northeast-striking intrusive contact which disappears to the east beneath onlapping Quarternary alluvium.

Scattered small thin layers of both the older Corkscrew

Canyon sequence and younger Paleozoic limestones exist as caps on a few of the low ridges in the southern part of the pluton. Inclusions of metasediments up to six inches across are found in the southern and central part of the stock.

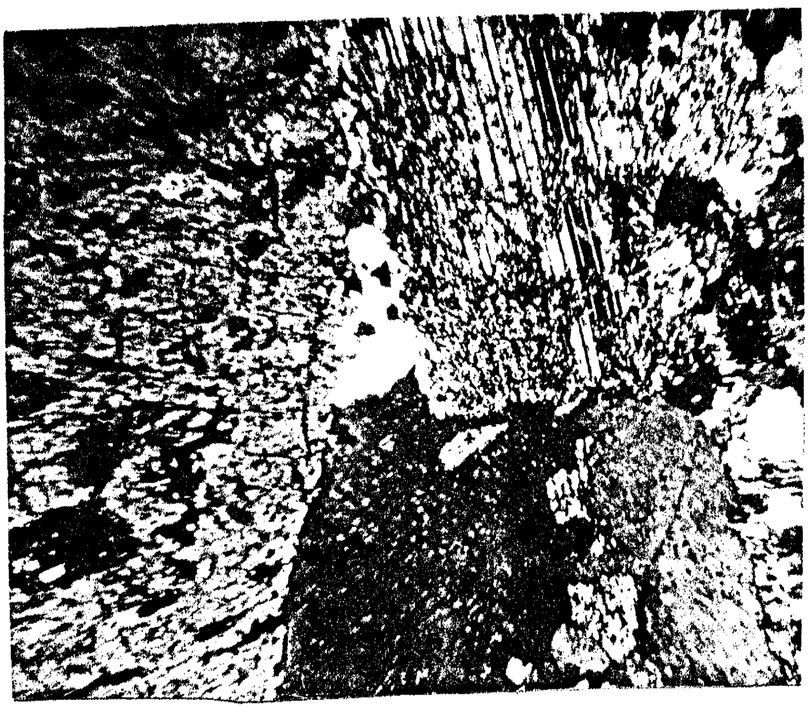
The metegabbro is randomly coarse to fine-grained with no evidence of layering. The fine-grained portions of the pluton are dark greenish- to brownish-black, while coarser-grained varieties, although similar in color, tend to have a speckled appearance due to large crystals of whitish-grey plagioclase feldspar. The rock is slightly foliated near the contact with the Polvadera granite. Weathered surfaces tend to be dark brown to greenish-brown.

The bulk of the metagabbro stock, which retains the subophitic to ophitic texture of a typical phaneritic igneous rock, is probably derived from a gabbro. Eleven samples were studied microscopically, with compositions ranging from gabbro to diorite. The high color index (45 to 55) and low quartz content in most of the samples indicate a gabbroic composition for the bulk of the stock, while a few samples display a higher quartz content with more sodic plagioclase indicating that a small part of the original mafic magma was dioritic in composition.

In thin section, the texture is blastophitic, with large poikioblastic crystals of hornblende and plagioclase; some sections show mortar structure (fig. 8). Biotite, epidote, chlorite, apatite, quartz and opaque minerals occur in varying small amounts. Mineral percentages are about the same regard-

Figure 8.

Photomicrograph of Lemitar metagabbro (X-nicols)(X 100). Large crystals of hornblende and partially sericitized plagioclase showing albite twinning.



less of texture with the average following composition: brown and green hornblende, 40 - 50 percent; plagioclase (average An 37), 45 - 55 percent; biotite, 2 - 4 percent; quartz, 1 - 6 percent; epidote and apatite, one percent or less. Opaque mineral content varies, with pyrite common in the northwest part of the stock.

Where the metagabbro has undergone shear, larger amounts of chlorite, biotite and epidote are evident, especially in shear zones where the metagabbro has been transformed into a chlorite-rich gouge. Several dike-like bodies of dark greenish-black schistose amphibolite cut the pluton, with strikes ranging from north to east, but with a uniformly steep dip. Dislocation metamorphism and recrystallization give a nematoblastic texture to these schistose bodies in which relative percentages of chlorite and epidote have increased.

The blastophitic texture, remnant pyroxene outlines in a few hornblende crystals and the plagioclase composition indicate a mafic intrusive, such a a gabbro, for the original plutonic rock prior to metamorphism.

Polvadera Granite

The Polvadera granite crops out in the central and northern parts of the Lemitar Mountains, making up about two-thirds of all Precambrian rocks exposed in the map area. A northeast-trending, nearly vertical intrusive contact forms the southern boundary of the granite. The western boundary is formed by an unconformable contact with the overlying Sandia Formation of Pennsylvanian age. To the north, the granite disappears beneath volcanic conglomerates of the Popatosa Formation of Tertiary age; in the northwest, the granite is faulted against volcanic rocks of Tertiary age and to the east the granite is overlain by pediment gravels of Quaternary age.

Granite also crops out at the base of the western hogback in the central part of the map area. Here the granite intrudes the Corkscrew Canyon sequence to the south and is unconformably overlain by the Sandia Formation of Pennsylvanian age. A normal fault forms the contact to the north and east where granite is faulted against rocks of Tertiary age.

The Polvadera granite varies in color from light and dark red to reddish-green and brown on weathered surfaces to a reddish-green on fresh surfaces. The granite is deeply weathered and in areas of low relief the rock decays in place to a coarse arkosic sand. A weak foliation is expressed by the parallel orientation of chloritized biotite; at the southern boundary with the Lemitar stock the foliation is more pronounced. Pegmatite dikes and quartz veins cut the granite and have a northeast strike. A few granite dikes also appear in the southeastern part of the map area where they cut the Lemitar stock. A series of north- to northeast-trending mafic dikes intrude the granite over the entire exposed area.

Mineralogically, the Polvadera granite is a uniformly coarse-grained phaneritic rock consisting of quartz, feldspar and chloritized biotite. Mineral percentages average: quartz, 40 percent; perthitic microcline, 45 percent; and chloritized biotite, 12 percent. Minor amounts of albite, epidote, apatite, hornblende and opaque minerals are present. The feldspars display intense sericitic alteration while the biotite has been partially converted to chlorite. Larger crystals are poikilitic, with undulatory extinction and mortar textures common (fig. 9).

Mafic Dikes

Following the emplacement of the Polvadera granite, an episode of mafic dike intrusion occurred throughout the rocks of Precambrian age in the map area. The dikes are fine to coarse grained, strike north to northeast and have a steep dip. The dike and sill intrusions in the Corkscrew Canyon sequence may belong to this episode of mafic dike emplacement (fig. 10).

The mafic dikes are megascopically similar to the Lemitar metagabbro, with blastophitic textures. However, the plagioclase feldspars are more calcic in composition, averaging about An 50, indicating a gabbroic composition of the original magma.

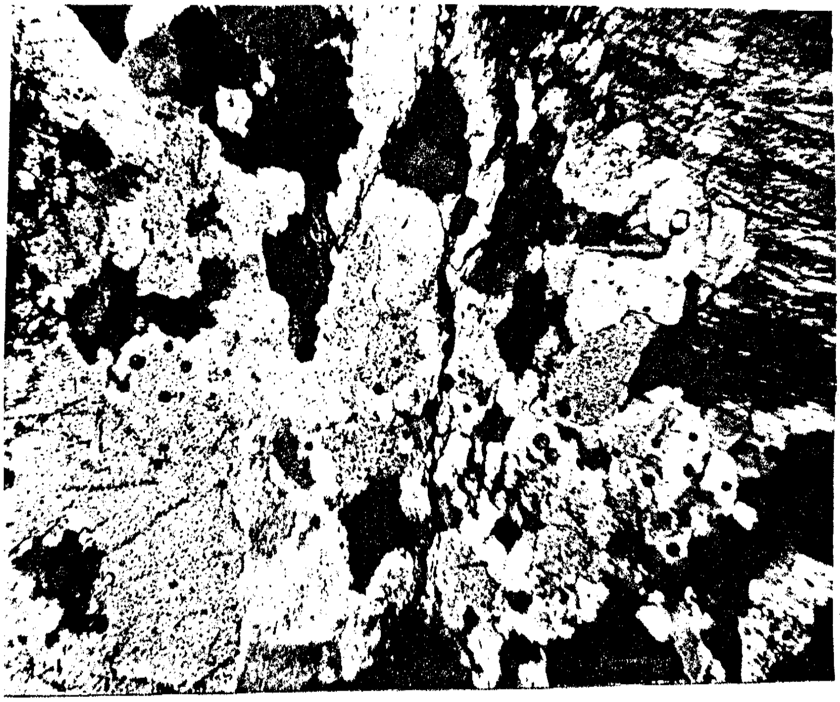
Scattered, small, dark-brown dikes of indeterminate age cut the rocks of Precambrian age in the east-central and southeast parts of the map area. The rocks are fine-grained, porphyritic with a subophitic groundmass. Euhedral phenocrysts

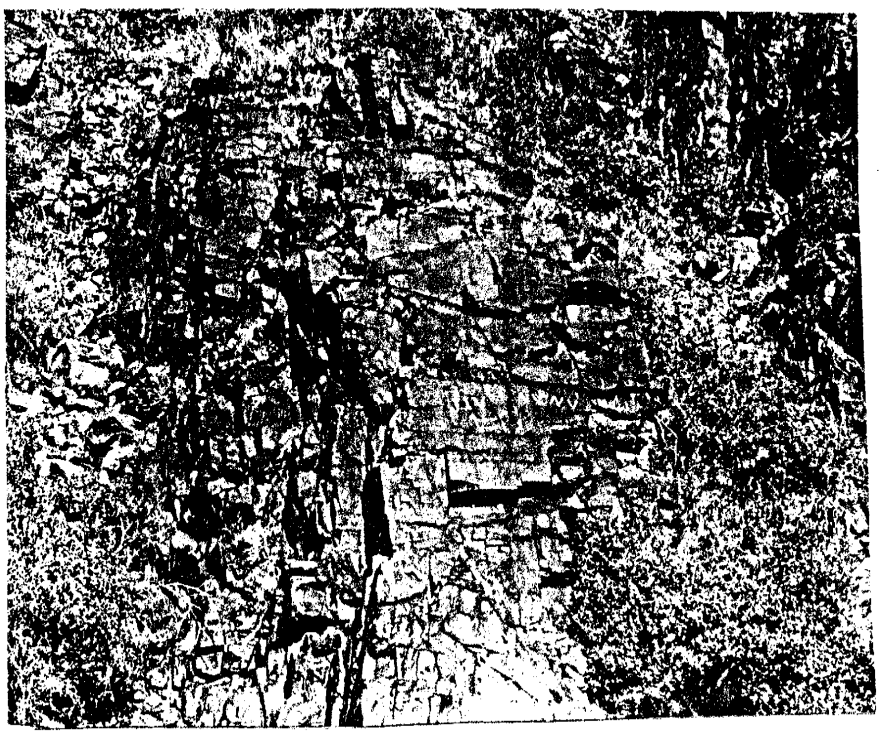
Figure 9.

Photomicrograph of Polvadera granite (X-nicols)(X 25). Large crystals of quartz and sericitized feldspar surrounded by smaller broken grains indicating mortar texture.

Figure 10.

Precambrian mafic dike cutting the shear zone in the Corkscrew Canyon sequence. Photograph taken in Corkscrew Canyon looking northeast.





of biotite are abundant, with the matrix consisting of subhedral to anhedral feldspar, possibly orthoclase, biotite and opaque minerals. Minor quartz and albite are also present. These rocks are tentatively identified as lamprophyre, although intense alteration with calcite replacing the feldspars makes positive identification difficult. Undulatory extinction on most of the grains indicates minor deformation but no mortar texture was noticed.

Metamorphism

The Precambrian rocks exposed in the Lemitar Mountains are probably polymetamorphic in nature. Regional, dynamic, thermal and retrograde metamorphic effects are recognizable in the exposed rock types.

The oldest unit in the map area, the Corkscrew Canyon sequence underwent folding, faulting and shearing prior to, or during, the emplacement of the Lemitar metagabbro stock. The intense deformation in shear zones, presence of almandine garnets, and gneissic foliation in the micaceous quartzo-feldspathic rocks point toward a regional grade of amphibolite facies metamorphism.

Deformation of the metagabbro in the Lemitar stock is restricted mostly to shear zones which do not penetrate into either the older Corkscrew Canyon sequence or the younger Polvadera granite. The presence of a few folded quartz veins and mortar texture in the unsheared portions of the Lemitar stock also indicate a dynamic deformation, possibly related to the intrusion of the Polvadera granite.

The mortar texture and biotite foliation in the Polvadera granite may be related to emplacement of the granite and may not be true metamorphic features. The presence of both brown and green hornblende in the Lemitar metagabbro may indicate either a primary crystallization of this mineral, or may be due to late magmatic alteration of the pre-existing pyroxenes. Deuteric alteration may be responsible for the widespread presence of chlorite; this effect followed the last thermal event, caused by the emplacement of the mafic dikes.

The lamprophyre dikes display only slight undulatory extinction in the biotite and feldspar grains. In these dikes, the feldspars have been partially to completely altered to calcite by hydrothermal processes. The presence of calcite in many fault zones of late Cretaceous and Tertiary age indicates the probability that alteration of these dikes occurred long after Precambrian time.

PALEOZOIC ROCKS

General Statement

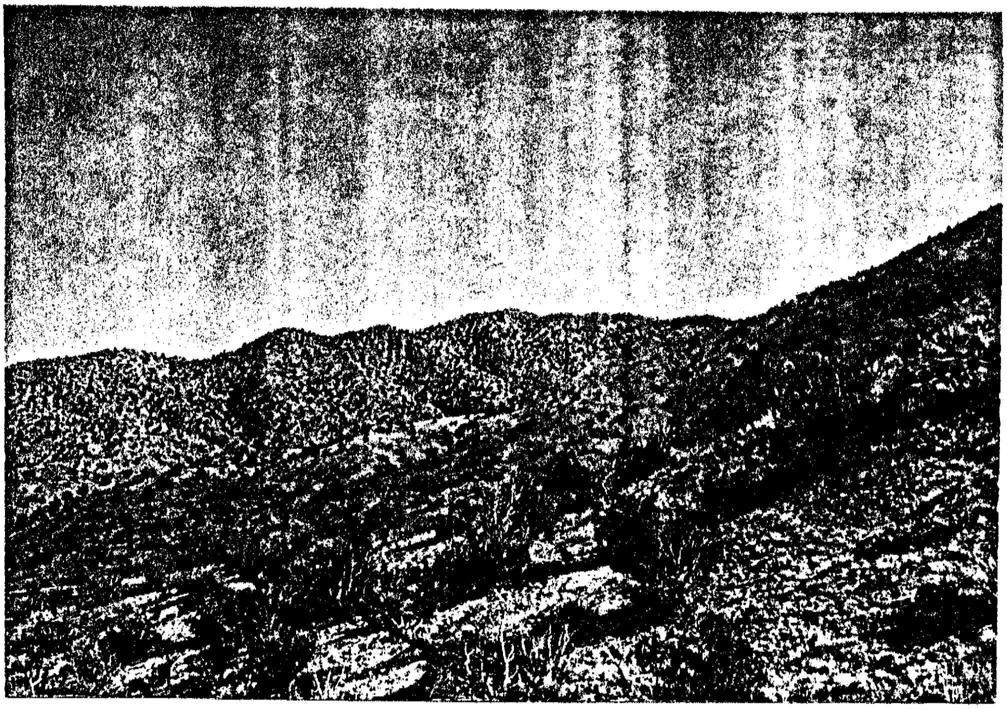
Paleozoic sedimentary rocks of Mississippian, Pennsylvanian and Permian age unconformably overlie the Precambrian basement complex in the Lemitar Mountains. Outcrops occur along the eastern side of upthrown fault blocks, commonly capping ridges of Precambrian rocks or forming distinct westward-dipping hogbacks within the map area. Volcanic or sedimentary rocks of Tertiary age unconformably overlie the Paleozoic strata to the west (fig. 11). To the north and southwest, rocks of Paleozoic age are faulted against rocks of Tertiary age; in the southeast, Paleozoic strata extend south of the map area.

Thickness of the Paleozoic section varies from a maximum of nearly 1200 feet in the western and northeastern parts of the map area to zero south of Polvadera Mountain. The tremendous difference in thickness is attributed to erosion due to uplift along faults of Laramide age.

It is not the purpose of this paper to consider the origin and depositional environments of the sedimentary rocks of Paleozoic age in the map area. For detailed descriptions of lithologic character, the reader is referred to previous work by Armstrong (1958, pp. 112-122), Kottlowski (1963, pp. 102-111) and Wilpolt and others (1946, map). Although individual units were recognized and are briefly described in this paper, the entire Paleozoic section was mapped as a single undifferentiated unit with emphasis on obtaining

Figure 11.

Northern Lemitar Mountains. View looking southeast at steeply west-dipping beds of the Madera Limestone of Pennsylvanian age unconformable overlain by the Spears and Hells Mesa Formations of Oligocene age.



structural and tectonic data.

Mississippian Rocks

In the southeastern part of the map area at Corkscrew Canyon, approximately 100 feet of Mississippian limestones, underlain by a basal clastic member, rest unconformably on rocks of Precambrian age. These units have been identified by Armstrong (1963, op cit) as the Caloso Formation overlain by the Kelly Limestone.

The Caloso Formation consists of a basal clastic member, ranging from pebble conglomerates composed of angular to subrounded clasts of quartzite and gneiss derived from the underlying rocks of Precambrian age to a dark greenish-grey shale. The Caloso grades rapidly upwards into a massive fine-grained limestone.

The overlying Kelly Limestone is generally similar in color and texture to the Caloso Formation but can be easily distinguished in the map area by the presence of a sequence of argillaceous grey dolomitic limestones and calcareous shales known as the "silver pipe zone" from the Kelly Mining District in the Magdalena Mountains (Loughlin and Koschmann, 1942).

Pennsylvanian Rocks

Pennsylvanian sedimentary rocks of the Magdalena Group (Gordon, 1907) rest unconformably on either the Kelly Limestone of Mississippian age or igneous and metamorphic rocks of Precambrian age. The Sandia Formation forms the basal unit and consists of a sequence of quartz sandstones and quartz pebble conglomerates, grading upwards into interbedded dark shales and thin, dark limestone beds. The Madera Limestone overlies the Sandia Formation and consists of grey, massive, cliff and ridge-forming limestone beds with a few interbedded shales and clean quartz sandstones.

Several linear zones of intense hydrothermal alteration occur in the massive limestone beds of the Madera Limestone. Mineralization is restricted to silicification with considerable iron oxides, often giving these zones a dark-brown to black color. Barite, galena and minor fluorite occur in the limestones on the east flank of the Polvadera Mountain.

Permian Rocks

North of Polvadera Mountain, at the north end of Sec 25, T1S, R2W, a small outcrop of dark red shale of the Abo Formation is present in a creek bed. No other outcrops of Permian rocks were found in the map area, but clasts of Abo sandstone are present in the Baca Formation of Eocene age.

TERTIARY ROCKS

General Statement

Sedimentary and volcanic rocks of Tertiary age are exposed over approximately one-half of the map area. Maximum exposed thickness of recognizable Tertiary rocks is approximately 4000 feet in the western part of the map area. The Tertiary section forms cliffs and ridges in the western range of the Lemitar Mountains and crops out as hogbacks and cappings on older rocks in the eastern range. Where the lower part of the section is exposed, Tertiary rocks rest unconformably upon rocks of Paleozoic or Precambrian age. The section extends north and south of the map area and dips west under pediment gravels of Quaternary age.

Seven units were mapped in the field: (1) the Baca Formation (Eocene), (2) the Spears Formation (Oligocene), (3) the Hells Mesa Formation (Oligocene), (4) the A. L. Peak Formation (Oligocene), (5) an upper ash-flow sequence consisting of the Potato Canyon Rhyolite (Oligocene) underlain by an unknown andesite unit, possibly the andesite of Landavaso Reservoir or its equivalent, (6) the lower Santa Fe Group (Miocene-Pliocene?), consisting of the Popatosa Formation, interbedded with the andesite of Silver Creek of Miocene age, and (7) a local alluvial sequence of probable late Tertiary age.

Mapping and subsequent division of Tertiary rocks exposed in the Lemitar Mountains serves a two-fold purpose: (1) the units can be recognized and correlated with similar exposures in mountain ranges west of the map area, and (2) the structural features can be interpreted in light of the stratigraphic relationships.

General petrologic descriptions of Tertiary rock units based on mineralogical content are provided in this paper. The major priority of this study lies in interpreting the tectonic development of the area and, therefore, the reader is referred to Brown (1972, pp. 9-55), Chapin (in preparation), Deal and Rhodes (in press) and Tonking (1957, pp. 23-27) for petrologic and petrographic descriptions of a more detailed nature.

Baca Formation

The oldest rock unit of Tertiary age found in the Lemitar Mountains consists of a sequence of medium to very coarse-grained arkosic sandstones and conglomerates of probable Eocene age. Equivalent strata in the Bear Mountains were originally mapped as the lower portion of the Datil Formation by Winchester (1920). Wilpolt and others (1946) later separated the lower 684 feet of Winchester's section and raised it to formational status. They proposed the name Baca Formation, with the type locality at Baca Canyon in the Bear Mountains about 20 miles northwest of the map area.

Although the unit is widespread throughout Socorro County, outcrops of the Baca were extensive enough to map in only the western range of the Lemitar Mountains. In the western range, the Baca lies unconformably upon the Madera Limestone of Pennsylvanian age and is overlain to the west by the Spears Formation of earliest Oligocene age. To the north, the Baca is faulted against volcanic rocks of Oligocene age, while the southern boundary is covered by alluvium of Quaternary age. In the central part of the western range of the Lemitar Mountains, the Baca is truncated by a large paleovalley filled with the A. L. Peak Formation of Oligocene age. Thickness of the Baca varies from zero to a maximum of about 200 feet.

The Baca is recognizable in the map area by its reddish-brown color, lack of volcanic clasts, and abundance of clasts of limestones and sandstones of Paleozoic age; all these characteristics serve to distinguish it from the overlying sandstones and conglomerates of the Spears Formation. The base of the unit consists of coarse conglomerates containing cobbles of the underlying Paleozoic and Precambrian rocks, grading upwards into well-bedded arkoses and sandstones. Reconnaissance mapping of the western range of the Lemitar Mountains by DeBrine and others (1963, p. 123) mistakenly identified the basal Baca outcrops as patches of the Abo Formation of Permian age, probably due to the presence of large clasts of Abo-like siltstones and shales and the red color of the overlying arkose beds. A small area of Abo Formation crops out in the Lemitar Mountains but it is located in the eastern range north of Polvadera Mountain.

The Baca appears to consist of fluvial, basin-fill deposits formed as a consequence of Laramide tectonic activity and subsequent erosion. Genetically similar deposits of early Tertiary rocks have been mapped elsewhere in New Mexico under different names (Galisteo Formation, El Rito Formation, etc.) and are probably Baca equivalents.

Spears Formation

The accumulation of a sequence of volcaniclastic sediments, lava flows and ash-flow tuffs of latitic and andesitic composition marks the beginning of Tertiary volcanism in the Lemitar Mountains. They are correlative with the Spears Member of the Datil Formation (Tonking, 1963); the Spears has recently been raised to formational status (Chapin, in preparation). Outcrops of the Spears are widespread throughout western Socorro County, with the thickness exceeding 1300 feet at the type section on Hells Mesa in the Bear Mountains. A latite tuff boulder from the upper part of a similar sequence in the Joyita Hills yielded a K/Ar age of 37.1 m. y. (Weber, 1971), which is on the Oligocene-Eocene boundary.

The Spears crops out sporadically in the Lemitar Mountains, being absent in the west central section and parts of the southeast section of the map area. Maximum thickness occurs south and east of Polvadera Mountain where nearly 800 feet of the unit is present. The Spears unconformably overlies the Baca or Madera Formations. The unit dips westward beneath the overlying ruffs of the Hells Mesa or A. L. Peak Formations and is cut off to the north and southwest by normal faults.

Typically, the Spears appears greyish to brownish-purple and is easily distinguished from the underlying Baca Formation in the Lemitar Mountains by color, cruder bedding and the dominance of volcanic clasts. The color and lack of quartz phenocrysts in the lithic fragments helps to distinguish the unit from the Popatosa Formation of Miocene age, also present in the map area.

The unit crops out on the lower parts of several ridges in the map area, often forming swales and small north-trending valleys between the more resistant beds of the underlying limestones and overlying welded tuffs. The Spears consists mostly of coarse to very coarse volcanic conglomerates, with interbedded thin sandstones and occasional latitic to andesitic lava flows. The clasts are of latitic to andesitic composition and usually a reddish to purplish-brown in color; individual clasts are as much as three or four feet in diameter.

Hells Mesa Formation

Outcrops of the Hells Mesa Formation in the map area consist of a sequence of densely-welded latitic to quartz-latitic ash-flow tuffs overlain by a poorly consolidated, lithic-rich, laharic tuff breccia. These rocks are correlative with the basal portion of Tonking's (1957) Hells Mesa Member of the Datil Formation. Chapin (in preparation) has restricted the term Hells Mesa to the basal crystal-rich cooling unit of Tonking's Hells Mesa Member and raised it to formational status. Overlying ash-flow units have been assigned new formational names by Deal and Rhodes (in press). K-Ar dates from samples of the Hells Mesa Formation give ages ranging from 31.6 to 32.4 m. y. (Weber, 1971) which are middle Oligocene. The Hells Mesa, like older Tertiary rocks in the map area, crops out discontinuously along both ranges of the Lemitar Mountains. Maximum estimated thickness is about 900 feet north of Polvadera Mountain (fig. 12). The unit is characterized by a light pinkish-grey or buff color and massive, blocky jointing.

The basal, quartz-free portion of the Hells Mesa Formation appears to be a multiple-flow simple cooling unit of densely-welded latitic ash-flow tuffs. Outcrops of these basal ash-flows reach a maximum thickness of nearly 200 feet in the western range, contrasting with only 10-25 feet in the Magdalena and Bear Mountains (Brown, 1972; Chapin, in preparation). However, W. H. Wilkinson (oral communication, 1973) has observed a thick, quartz-free basal section of the Hells Mesa Formation on Grey Hill, about 10 miles west of Magdalena.

In hand specimen, the basal ash-flows can easily be distinguished from those comprising the bulk of the Hells Mesa by the presence of considerable pumice and lithic fragments, the pinkish-grey color and absence of quartz. Phenoclasts consist mostly of sanidine, plagioclase, and biotite, with the latter ofter considerably altered to hematite. In thin section, the texture is porphyritic with an aphanitic, devitrified goundmass. Sanidine, plagioclase and biotite occur in large euhedral to subhedral crystals in amounts ranging up to nearly 50 percent of the rock. Alteration of the biotite and feldspars is moderately intense, with hematite occurring as coatings on minerals and as very fine-grained aggregates in the groundmass.

The main, quartz-rich portion of the Hells Mesa appears to consist of a multiple-flow, simple cooling unit of densely-welded quartz latite ash-flow tuffs. Major differences with the lower member consist of a lighter grey to buff color, paucity of pumice and lithic fragments, decreased biotite content and a great abundance of large, anhedral quartz phenocrysts (fig. 13). Texturally, the two members are very similar, although hematite content in the upper member is greatly reduced, probably due to the lower biotite content. Maximum thickness of the quartz-rich ash-flows is about 150 feet near Polvadera Mountain. Chemical analyses by Deal (in preparation) show that the lower quartz-free member of the Hells Mesa is rhyodacitic in composition while the upper quartz-rich member is rhyolitic.

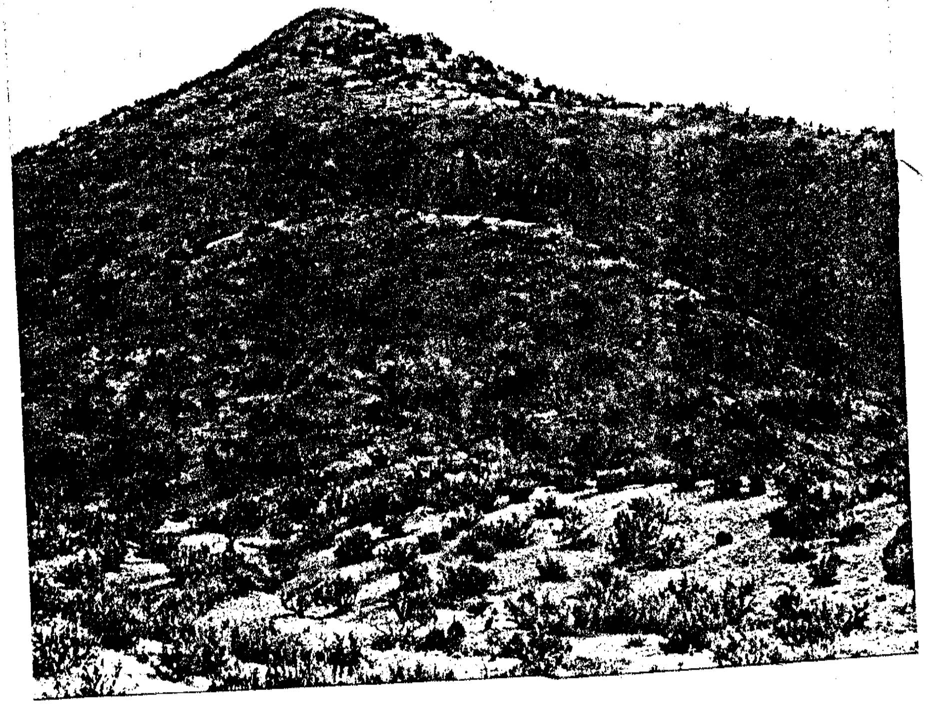
A poorly-consolidated, lithic-rich, laharic tuff breccia crops out above the upper portion of the Hells Mesa. The unit is very thin with a maximum observed thickness of about five feet. True outcrops are scarce due to its poor induration, but fragments of the unit are often found in the Hells Mesa float and make an excellent marker horizon for the upper boundary of the Hells Mesa. Where the upper portion of the Hells Mesa is thin or absent, no trace of the laharic unit could be found. Andesitic laharic breccias are interbedded with poorly-welded Hells Mesa near North Baldy in the Magdalena Range (Dieter Krewedl, oral communication, 1973). The laharic breccia described here may represent a similar, local phenomenon.

Figure 12.

View of Polvadera Mountain from the north. Ash-flow tuffs of the Hells Mesa Formation cap the peak, overlying volcanic conglomerates of the Spears Formation.

Figure 13.

Photomicrograph of the quartz-rich member of the Hells Mesa Formation (X-nicols)(X 25). Large anhedral quartz phenoclasts in a matrix of devitrified glass.



A. L. Peak Formation

The A. L. Peak Formation consists of a composite sheet of alternating rhyolitic ash-flow tuffs and andesite flows. These welded-tuffs and andesite flows are correlative with the upper part of Tonking's Hells Mesa Member of the Datil Formation; Deal and Rhodes (in press) have designated them the A. L. Peak Formation after A. L. Peak in the northern San Mateo Range. Like the underlying Hells Mesa and Spears Formations, the A. L. Peak has been recognized over a wide area in western Socorro County. The unit consists of as much as 2000 feet of densely-welded, crystal-poor, banded rhyolitic tuffs in a cauldron centered about Mount Withington in the San Mateo Mountains. However, in the northern Magdalena Mountains, Bear Mountains and Lemitar Mountains the unit grades into several distinct member, separated by two or more cooling breads (Brown, 1972; Chapin, in preparation; Deal and Rhodes, in press). Thicknesses approaching 1400 feet are present in the southern Bear Mountains and in parts of the map area. The unit was apparently erupted over a considerable period of time, possibly from more than one source, with andesite flows becoming interbedded on the depositional apron. A fission track date (Smith and others, in press) of 31.8 m. y. places the unit in the middle Oligocene, approximately the same age as the underlying Hells Mesa Formation.

Due to the alternating lithologic character of the A. L. Peak Formation, the unit tends to crop out as a series of hogbacks with the more resistant tuff beds forming the cliffs and dip slopes and the andesite flows forming the intervening low areas.

Although the A. L. Peak was mapped as a single unit, several distinct members were recognized in the field: (1) a basal andesite member; (2) a grey to dark-grey massive, crystal-poor tuff; (3) a light pinkish to greyish, banded, crystal-poor tuff grading into; (4) a dark reddish-brown, banded, crystal-poor tuff; (5) a middle andesite member; (6) a dark reddish-brown, massive, crystal-poor tuff, (7) an upper andesite member; and (8) a dark, red-brown, crystal-rich tuff. The five lower members crop out discontinuously in the map area while the upper three members are much more continuous.

The basal andesite crops out only in the western range of the Lemitar Mountains. About 75 feet thick, it rests on the Madera Limestone of Pennsylvanian age and is overlain by the grey to dark grey, massive, ash-flow tuff. It is bounded on the south by an abrupt unconformable contact with older rocks of the Baca and Spears Formations. To the north, the unit thins out and eventually disappears. The unit is thin-bedded, somewhat porphyritic, and dark greyish-brown in color with abundant plagioclase phenocrysts.

About 200 feet of the grey to dark grey, massive crystal-poor tuff crops out above the lower andesite member in the western range, forming a series of north-trending westward-dipping hogbacks. Minor outcrops of the unit occur in two places along the eastern range of the Lemitar Mountains north of Polvadera Peak; at one place, it overlies Hells Mesa tuffs and at the other, it apparently overlies the Spears Formation.

In the western range, the grey to dark-grey, massive member is highly variable in color and texture. Different units within the member range from slightly to densely-welded with some units rather crystal-rich. These variations probably represent several separate eruptive events.

Above the grey to dark-grey massive tuff is a sequence of light purplish-grey, rhyolitic, flow-banded ash-flow tuffs. This unit crops out in the northern and western parts of the map area but is absent in the south. Thickness varies, but approaches a maximum of about 200 feet in the northern part of the map area. The banded appearance is due to elongated grey-white pumice. Except for the banded texture and pumice, the unit resembles the underlying grey to dark-grey massive member.

Above the light-colored, flow-banded ruff is another unit with a similar texture. Contact with the banded unit was not found, but according to observation of the two units in the Bear Mountains (Brown, 1972), the contact is sharply gradational. The upper banded unit is a densely-welded, rhyolitic ash-flow ruff about 100 feet thick and dark reddish-brown in color. Due to its resistant nature and platy jointing, the upper banded unit forms conspicuous outcrops in the southern part of the map area. Flow banding in the upper unit is due to extreme stretching of grey pumice indicating laminar flow. Outcrops of the unit at Corkscrew Canyon dip nearly vertically and the unit was originally thought to be a dike; however, upon closer examination no intrusive contacts were found and correlation with similar outcrops in the map area conclusively showed the unit's extrusive nature. Lithologically, the unit is composed of flattened, elongated pumice and small amounts of sanidine and quartz in a devitrified groundmass (fig. 14).

Discontinuously overlying the banded members is a sequence of dark grey to reddish-brown andesite flows, characterized by a lack of plagioclase phenocrysts and an abundance of oxidized pyroxene phenocrysts. The member attains a maximum thickness of about 70 feet in the northern part of the map area.

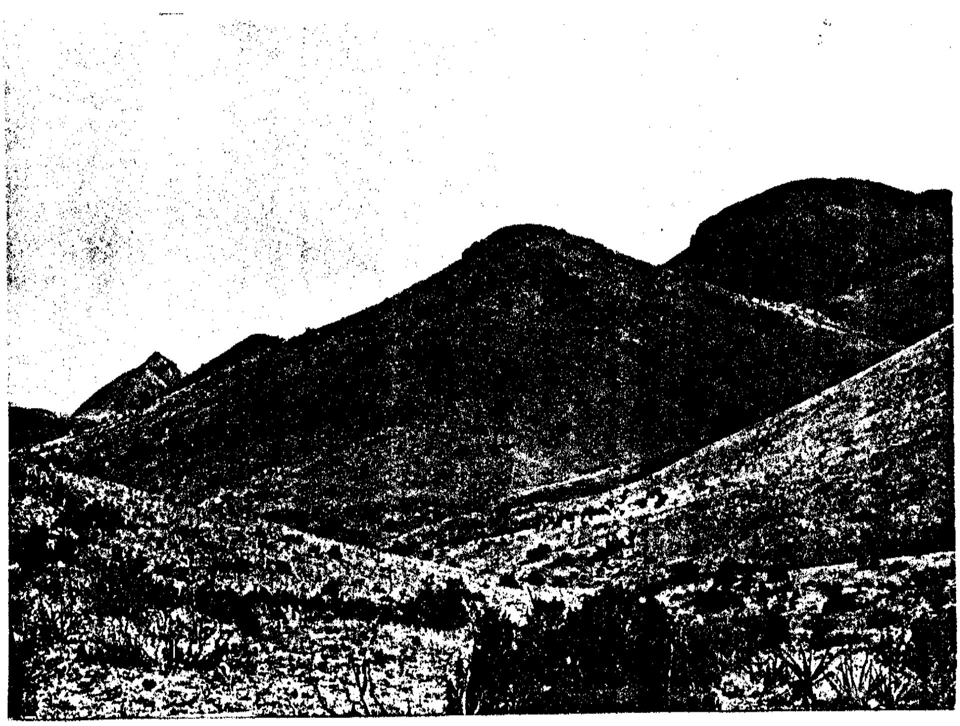
The lower five members of the A. L. Peak Formation are not continuous in the Lemitar Mountains. Scattered outcrops of the lower members suggest considerable relief in the map area during early A. L. Peak time. Deal and Rhodes (in press) observed an unconformity of "several tens of meters" between the A. L. Peak and the Hells Mesa in the San Mateo Mountains. Relief in the Lemitar Mountains appears to be greater, with the A. L. Peak in basal contact with rocks of Oligocene to Paleozoic age. In the western range, lower members of the A. L. Peak apparently filled a paleovalley at least 700 feet deep, as the units are in lateral contact with the Hells Mesa, Spears and Baca Formations (fig. 15). Elsewhere in the map area, lower members of the A. L. Peak are found overlying thin, discontinuous sequences of the Hells Mesa and Spears Formations. In contrast, where the Hells Mesa and Spears are rather thick, several of the lower members of the A. L. Peak are missing. At some of

Figure 14.

Photomicrograph of flow-banded member of the A. L. Peak Formation (X 25). Greyish-white "ghost" is part of a devitrified pumice fragment.

Figure 15.

Western range of the Lemitar Mountains. View looking south at the north end of a large paleovalley filled with the lower members of the A. L. Peak Formation which are in lateral contact with the older Baca, Spears and Hells Mesa Formations.



these localities, the dark, reddish-brown, massive tuff, which is the sixth member from the bottom of the A. L. Peak, rests on the Hells Mesa or older rocks. The upper three members of the A. L. Peak are fairly continuous throughout the map area, except where faulted out, indicating a lack of relief in the Lemitar Mountains during late A. L. Peak time.

In the map area, the lowest continuous member of the A. L. Peak Formation consists of a dark reddish-brown, crystal-poor, densely-welded, rhyolitic ash-flow ruff. This unit overlies lower members of the A. L. Peak sequence or older rocks. The member crops out fairly continuously forming cliffs along ridges and hogbacks of both ranges of the Lemitar Mountains. The unit is generally densely welded and its resistant nature causes it to form pinnacles with a splintery or massive-platy to blocky jointing. A spherulite zone about five feet thick commonly occurs at its base. Slump blocks of the unit are found on the upper dip slope on the west side of Polvadera Mountain where uplift and steep tilting have caused the member to slump over the underlying, weak, middle andesite member. Thickness of the unit varies from 100 feet at Corkscrew Canyon to about 250 feet in the northern part of the map area.

In hand specimen, the unit appears densely-welded with a fine-grained aphanitic texture. Pumice and lithic fragments are present in minor amounts but are usually not conspicuous except as scattered bands. In thin section, the groundmass is devitrified with scattered, broken phenocrysts of subhedral to anhedral sanidine and quartz. Hematite is present in small opaque blebs and forms a fine dust in the groundmass, giving the member its dark red color.

The upper andesite overlies the red, massive tuff and is continuous throughout the map area, with a maximum thickness of about 60 feet on a ridge northwest of Polvadera Mountain. The upper andesite is petrologically similar to the middle andesite member but can be distinguished from it by the presence of thin flows of black, vesicular basalt or basaltic andesite (fig. 16).

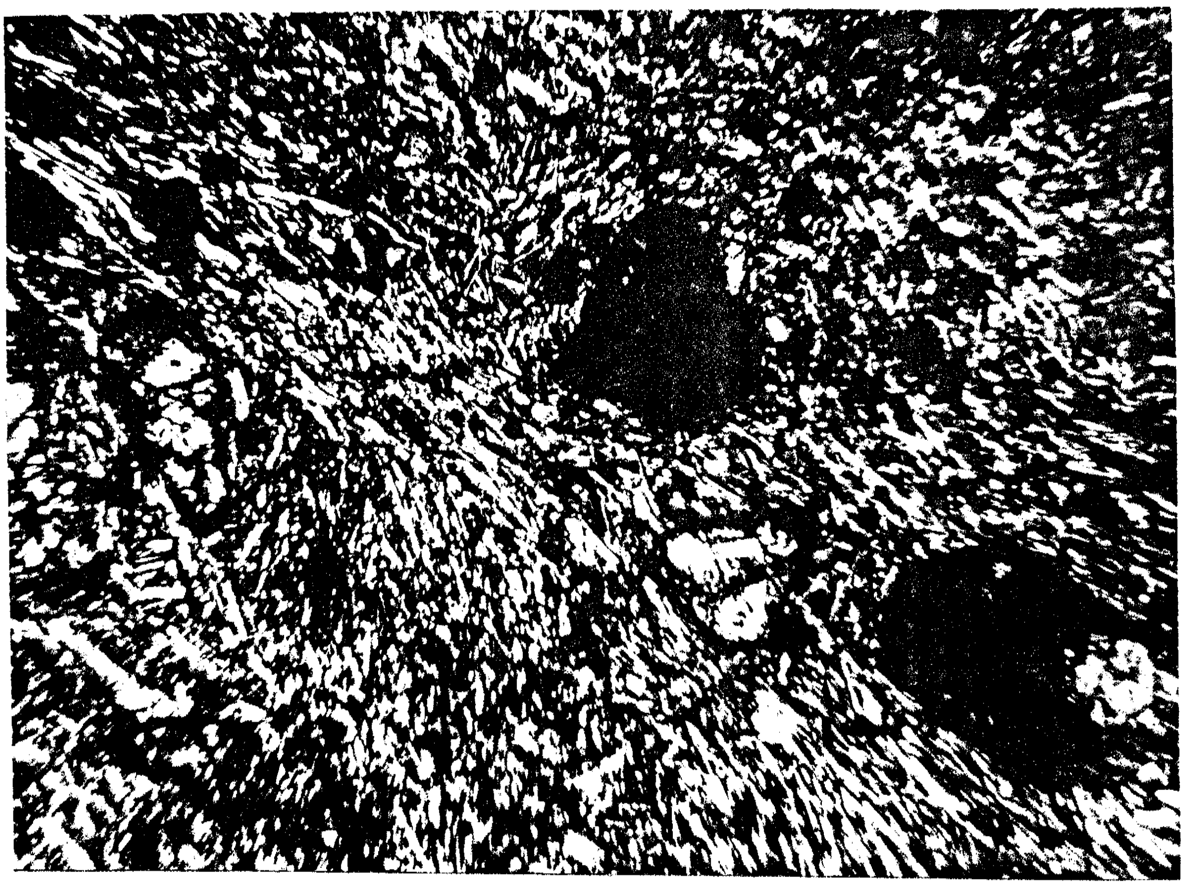
The tuff of Allen Well (Brown, 1972) overlies the upper andesite and forms the last eruptive member of the A. L. Peak composite sheet. Thickness varies from zero on a ridge north of Polvadera Peak to about 80 feet in Corkscrew Canyon. The unit is a dark, reddish-brown, densely-welded, crystal-rich, ash-flow tuff similar in composition, but not in color, to the upper Hells Mesa welded tuffs. Quartz, sanidine, plagioclase and bronze biotite form the phenocrysts and make up about 40 percent of the rock. Pumice is present in small amounts, but lithic fragments are scarce.

<u>Potato Canyon Formation</u>

Overlying the A. L. Peak Formation is a series of andesite flows capped in the southern part of the map area by a multiple-flow unit of highly variable ash-flow tuffs. The andesite is highly variable in appearance. Flows range from thin flows of dark, reddish-brown phorphyritic andesite with phenocrysts

Figure 16.

Photomicrograph of basaltic andesite from upper andesite member of the A. L. Peak Formation (X-nicols) (25). Lath-shaped plagioclase crystals show flow structure around black phenocrysts of augite.



of feldspar to thick autobrecciated flows, reddish to greyish-brown in color, with numerous oxidized phenocrysts of pyroxene. These andesites may be in part correlative to the andesite unit above the A. L. Peak Formation in the Magdalena-Tres Montosas area which has been named the andesite of Landavaso Reservoir (Chapin, in preparation). The andesite varies in thickness from 20 feet in the southwest part of the map area to over 600 feet in the west-central and northern Lemitar Mountains.

In the northern part of the Lemitar Mountains, the andesite of Landavaso Reservoir, or its equivalent, attains a thickness of several hundred feet. This andesite, assigned in this report to the basal Potato Canyon Formation, may be in contact with the La Jara Peak Andesite of Miocene age where the Potato Canyon tuffs are missing.

Another andesite unit, and the andesite of Silver Creek is found interbedded in the basal section of the overlying Popatosa Formation of Miocene age (Bruning, in press). The andesite of Silver Creek and La Jara Peak Andesite are similar in outcrop and hand specimen but apparently differ appreciably in age (La Jara Peak Andesite - 23.8 m. y., Chapin, 1971; andesite of Silver Creek - 15.8 m. y., Weber, 1971). It is difficult to determine without further K-Ar dating whether the andesites near the base of the Popatosa in the map area belong to the La Jara Peak or to the Silver Creek or whether the La Jara Peak and Silver Creek are equivalent, as the upper La Jara Peak is found interfingering with basal Popatosa at at the northwest end of the Bear Mountains (Tonking, 1957). Until further dating and correlation can be done, the author has decided to arbitrarily group all andesite units below the Popatosa Formation and above the A. L. Peak Formation in the andesite of Landavaso Reservoir or its equivalent within the Potato Canyon Formation. All andesite units found interbedded in the Popatosa Formation have been arbitrarily assigned to the andesite of Silver Creek.

Overlying the andesite unit is a sequence of ash-flow tuffs of highly variable texture and composition. Deal and Rhodes (in press) mapped a similar sequence of crystal-poor to crystal-rich, slightly to densely-welded, rhyolitic ash-flow ruffs cropping out in the Mount Withington cauldron in the northern San Mateo Mountains. They named this sequence the Potato Canyon Formation after Potato Canyon on the east flank of Mount Withington. A fission track date (Smith and others, in press) of 30 m. y. places the Potato Canyon Formation in the upper Oligocene. These tuffs crop out as caps on hogbacks in the southern part of the Lemitar Mountains and form the highest cliffs on the western range. Several different units were recognized and are probably equivalent to the Potato Canyon sequence of Deal and Rhodes.

The most extensive cooling unit of the Potato Canyon in the map area consists of a sequence of light-grey, densely-welded, rhyolitic, moderately crystal-rich, ash-flow tuffs. These tuffs rest unconformably on the underlying andesite and probably make up the basal member of the Potato Canyon tuffs.

They can be distinguished from the Hells Mesa tuffs by smaller phenocrysts of quartz and sanidine and by the greater percentage of groundmass. They more nearly resemble the A. L. Peak tuffs but are appreciably richer in crystals.

Two other recognizable units were identified in the map area but are confined to outcrops in the southern part of the Lemitar Mountains. Overlying the crystal-rich tuffs is a thin, flow-banded, reddish-brown, ash-flow tuff found only along the dip slope of a hogback at the south end of the map area west of Corkscrew Canyon. This unit resembles the flow-banded tuffs of the A. L. Peak Formation. Another distinctive unit, a grey to buff, massive, slightly to moderately welded, crystal-poor tuff, forms scattered outcrops in the southern part of the map area. The base of the unit is not exposed due to faulting and alluvial cover but probably lies above the flow-banded member where present. Total thickness of the Potato Canyon tuffs varies from zero in the north to about 300 feet in the extreme southern part of the map area.

Popatosa Formation

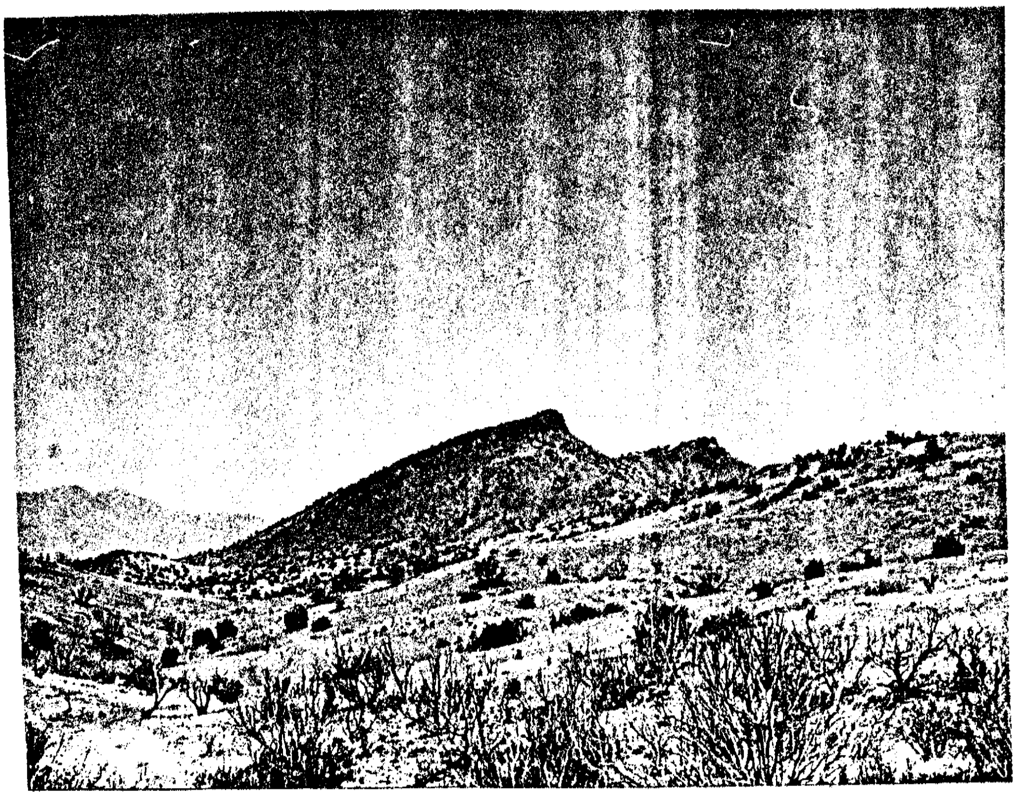
The accumulation of a sequence of volcanic conglomerates, sandstones, siltstones, mudstones, and water-laid tuffs marks the end of major Tertiary volcanism and the last major episode of sedimentation in the area of the Lemitar Mountains prior to uplift. The Popatosa Formation was originally named and described by Denny (1940, pp. 77-84) and forms the lower member of the Santa Fe Group in western Socorro County (Tonking, 1957). The Popatosa overlies unconformably the Potato Canyon Formation. The Popatosa is poorly exposed along the eastern range, being faulted out or ofter buried under alluvium. In the western range, the Popatosa is mostly buried under the alluvial gravels of Snake Ranch Flats in the south and emerges to the north as a series of north to northeast-trending hog-backs (fig. 17). Maximum thickness is unknown but at Red Mountain in the northwest part of the map area, about 2000 feet of conglomerates and siltstones are exposed. At the extreme north end of the Lemitar Mountains, a major west-trending fault has truncated the range with units north of the fault dipping north instead of west. Here, the Popatosa overlies the Potato Canyon Formation in the north-central part of the map area, while to the northwest the Popatosa apparently rests unconformably upon the Polvadera granite of Precambrian age.

According to Denny (1940, pp. 81-83) and Bruning (in press), the lower Popatosa consists of alluvial fan and playa deposits laid down in an enclosed basin. The playa-like red to greyish-white and buff sandstones and mudstones form the basal beds of the Popatosa in the Lemitar Mountains indicating the map area was near the depositional axis of the original basin.

The vast majority of the Popatosa found in the map area consists of dark red conglomerates with thin, interbedded red sandstones. The red color is derived from both the fine-grained matrix and clasts of andesite. Clasts range from fine-sand to boulder size and consist of fragments of the underlying

Figure 17.

View of Red Mountain from the south. Red Mountain hogback capped with red volcanic conglomerates of the Popatosa Formation overlying interbedded andesite flows of the andesite of Silver Creek.



Tertiary volcanic units, especially the tuffs and andesites of the Potato Canyon Formation, with recognizable clasts of Hells Mesa and A. L. Peak. Most of the clasts are rounded to subangular indicating a moderate transport distance, and occasional channel scours can be seen within the conglomerate layers.

Tertiary Alluvium

Scattered outcrops of moderately well-indurated alluvium occur as small rounded hills in the central and northern part of the map area. Along the base of the dip slope on the west side of the main eastern range northwest of Polvadera Mountain, a series of scattered low hills of boulder alluvium unconformably overlie the Popatosa Formation. Thickness is unknown due to extremely poor exposures and lack of bedding. A few exposures in gullies indicate the alluvium is composed of fragments of the Popatosa Formation, many still coated with the typical red matrix. This alluvial unit is distinguished from the younger pediment gravels of Quaternary age by the degree of induration, coarser texture and restriction of clasts to fragments of the Popatosa Formation. The unit probably formed in paleovalleys carved during initial uplift and normal faulting of the Lemitar Mountains during late Miocene or Pliocene time.

Another alluvial sequence crops out at the east end of Corkscrew Canyon where normal faulting has truncated bedding; drag along the fault has caused the beds to dip steeply to the northeast. This deformed alluvium includes a lower bed of volcanic-derived breccia about 10 feet thick, with fragments resembling the dark, reddish-brown, flow-banded tuff of the A. L. Peak Formation. Overlying the breccia unit are beds of moderately indurated sands and gravels with clasts of both volcanic and sedimentary origin. These units are overlain by late Santa Fe to Recent pediment gravels which are underformed and appear to have been derived at least in part from the underlying unit.

Other moderately-indurated alluvial deposits are found on the east and north flanks of Polvadera Mountain, and appear to be undeformed. Considerable erosion has occurred, however, and these units are tentatively placed in the Tertiary. A small remnant of an alluvial-fan deposit at the base of the east face of a west-dipping hogback of Hells Mesa and Spears has a dip of 17 degrees to the west while direction of transport indicates the primary dip should be to the east. This change in dip direction from east to west is due to renewed faulting and subsequent tilting of the range.

QUATERNARY ROCKS

A sequence of semiconsolidated to unconsolidated pediment and bajada gravels and sands onlap upon both flanks of the eastern and western ranges of the Lemitar Mountains. These gravels are undergoing dissection from the major arroyos emerging from valleys and canyons in the Lemitar Mountains but the depth of dissection is somewhat limited. North of the map area near San Acacia and south of the map area near Nogal Canyon, the pediment gravels are considerably more dissected with several pediment surfaces evident. The pediment surface developed along the base of the Lemitar Mountains appears to be considerably lower than many pediments exposed to the north and south of the map area. Denny (1941, pp. 225-234) and Sanford and others (1972, p. 8) discuss the development of pediments in the Rio Grande Valley and have defined five surfaces by their present projected elevation above the Rio Grande flood plain. The projection of the pediment surface on the east slope of the Lemitar Mountains coincides exactly with the present elevation of the flood plain, indicating the pediment surface is very recent in age.

Other alluvial deposits of Quaternary age in the Lemitar Mountains consist of stream gravels, talus cones and alluvial fans forming at the base of cliffs and steep slopes. With the exception of a normal fault cutting the pediment gravels at the east end of Corkscrew Canyon, no deformation of Quaternary alluvium was found in the Lemitar Mountains.

STRUCTURE

General Statement

The regional structure of Socorro County indicates a complex history of tectonic activity concentrated in the Precambrian, late Mesozoic-early Cenozoic and late Cenozoic Eras. Major north-northeast Laramide structures have been overprinted upon a much older Precambrian fabric with a similar north to northeast trend. Late Cenozoic Basin and Range (rift) faulting was in turn superimposed upon older structural features, on one hand reinforcing the northerly structural grain of the region and introducing a later series of west-trending normal faults which intersect the older structural grain at nearly right angles.

Precambrian Structure

Precambrian structural features in the Lemitar Mountains consist of: (1) steep east-dipping beds, locally foliated and cut by a shear zone and faults in the Corkscrew Canyon sequence; (2) zones of shearing and foliation in the Lemitar sequence; and (3) weak foliation in the Polvadera granite stock.

The oldest Precambrian structural feature in the map area consists of steeply dipping bedding in the Corkscrew Canyon sequence. Bedding planes dip east from 25 to about 60 degrees, with dips increasing to the west. Crossbedding can be observed in a few beds and indicates that the beds are presently oriented in an upright position. However, a 40 degree rotation* in a clockwise manner around a north-trending axis to eliminate the effects of Tertiary deformation would re-orient dips to about 65 degrees east, increasing westward until the beds are overturned to the west. Near the common boundary of sec 1, T2S, R2W and sec 6, T2S, R1W westerly dips between the sedimentary rocks of Paleozoic age and the overlying Spears Formation of Oligocene age differ by about 15°. This indicates that the rotational effects of Laramide deformation were small. The steeply dipping to overturned beds of the Corkscrew Canyon sequence were probably developed through tight, possibly isoclinal, folding along a north-northeast-trending axis during a Precambrian orogenic event.

Mapping in mountains north and northeast of the Lemitar Mountains (Reiche, 1949; Stark, 1956; Mallon, 1966) has shown the existence of several tight north to northeast-trending folds. The limited exposures of the Corkscrew Canyon sequence in the map area does not show a complete fold, but the outcrops may form part of the western limb of a north-northeast-trending syncline whose axial plane dips steeply west-northwest.

Cutting across beds of the Corkscrew Canyon sequence near the western limit of Precambrian exposure is a broad shear zone about 200 feet in width. The shear zone has a northeast strike and does not continue into the Lemitar stock. Bedding has been destroyed and foliation consists of bands of quartz and feldspar contorted into ptygmatic and sheared-out isoclinal folds

*This value is derived from the average dip of 40° west of the rocks of Paleozoic age in Corkscrew Canyon.

(fig. 18 A and B). After re-orientation to eliminate the effects of Tertiary block faulting, the shear zone has a pronounced westward dip. The orientation and compressional nature of the shear zone suggest the existence of a Precambrian reverse fault with the direction of thrusting from the west-northwest. Similar shear structures have been described in the southern Sierra Ladrone Mountains by Headerle (1966, p. 49), the Los Pinos Mountains by Mallon (1966, p. 59) and the Manzano Mountains by Stark (1956, p. 30) and Reiche (1949, p. 1197). Development of the shear zone may be related to the same stress field that caused the folding, or to a later orogenic event, but predates the intrusion of the Lemitar stock.

North of Corkscrew Canyon, the Corkscrew Canyon sequence is more intensely deformed as the intrusive contact with the Lemitar stock is approached. Bedding tends to strike nearly east to northeast with steep southerly dips. Near the contact with the Lemitar stock, rocks of the Corkscrew Canyon sequence are sheared to the extent that bedding is obliterated. Increasing deformation north of Corkscrew Canyon is probably related to the intrusion of the Lemitar stock.

Foliation in the Corkscrew Canyon sequence is expressed by the preferred orientation of biotite. The foliation is irregular, sometimes paralleling bedding, often at steep angles to bedding and varies in intensity.

A series of northeast-trending, steeply dipping faults cut both sheared and unsheared portions of the Corkscrew Canyon sequence. Widths range from a few inches to about

Figure 18 - A.

Tight, ptygmatic folds in the sheared zone of the Corkscrew Canyon sequence.

Figure 18 - B.

Sheared-out isoclinal folds typical of the shear zone exposed in Corkscrew Canyon.

three feet, with fault breccia and gouge intensely silicified. Clockwise rotation re-orients the fault planes to a westward dip. No evidence of drag along the fault planes was noticed and relative movement across the faults is unknown. Lack of any compressional features associated with these faults indicate the faults may represent tensional block faults formed after the end of a compressional period of folding and thrusting. These faults cannot be traced into the Lemitar stock.

Northeast-trending schistose zones in the Lemitar stock dip steeply northwest and range from about 5 to as much as 20 feet in width. Megascopic foliation is well-developed and parallels the trend of the schistose zones. Cataclastic texture visible in thin sections, sharp contacts between the schistose zones and the stock rocks, and foliation parallel to the contact indicate that the schistose zones developed as shear zones. Lack of similar structures in the Polvadera granite leads to the conclusion that development of the shear zones occurred prior to or during emplacement of the granite.

The presence of a few folded quartz veins and mortar texture in some thin sections also indicate deformation of the Lemitar stock. Folded quartz veins occur as synforms and antiforms whose axial planes strike northeast and plunge northward. Foliation is generally absent in the stock rocks except near the shear zones and near the Polvadera granite where foliation parallels the contact.

The Polvadera granite displays a crude biotite foliation, poorly developed except near contacts with the Lemitar stock and the swarms of intrusive mafic dikes with which the foliation is parallel. Elsewhere, the foliation is irregular but trends generally northeast and may represent primary flow structure during emplacement as thin sections show no recrystallization. However, mortar texture visible in thin sections of granite indicate considerable crushing.

Intrusion of mafic dike swarms represent the last known Precambrian orogenic event. The dikes strike north to northeast with steep west to northwest dips and intrude older Precambrian rock units in the map area. According to Hills (1963, p. 371), the parallelism of mafic dike swarms indicate injection normal to the least compressive stress, which may be tensional at shallow depths.

Laramide Structure

The Laramide orogeny, a late Cretaceous to early Tertiary episode of folding and thrust faulting, has been recognized over a widespread area of the western United States (Eardley, 1951; Gilluly, 1963). Laramide structures composed mostly of broad folds and high-angle reverse faults have been mapped in many areas of exposed rocks of pre-Tertiary age in central New Mexico (Darton, 1928; Kelley and Wood, 1946; Reiche, 1949; Stark, 1956; Tonking, 1957; and Chapin, oral communication, 1973). Effects of Laramide faulting in central New Mexico can readily be seen by comparing thicknesses of Paleozoic and Mesozoic sedimentary sections exposed along the Rio Grande to the same section north or south of the horst. Stratigraphic throw across the faults is estimated to be as much as 650 feet across the southern fault and as much as 550 feet across the northern fault.

Reliable identification of Laramide structures within the map area can be made only when visible deformation of the Paleozoic section such as tilting of beds, drag along faults and structural offset can be traced to a contact with over-lying beds of Tertiary age. Where rocks of Precambrian age are exposed, fault zones of Laramide and late Tertiary age have a similar appearance: fault gouge contains chlorite and epidote in the Lemitar stock and hematite, sericite, and varying amounts of silica and calcite in the Polvadera granite. Other faults of Laramide age probably exist in the map area but may have been rejuvenated during late Tertiary rift faulting. Rejuvenated faults of Laramide age have been recognized in the Magdalena Mountains (Chapin, oral communication, 1973).

Erosion of mountains formed by the Laramide orogeny during early Tertiary time in central New Mexico deposited clastic rocks of the Baca Formation of Eocene age in the surrounding structural basins. The thinness of Baca outcrops on the ridge west of Polvadera Mountain, the absence of Baca on Polvadera Mountain and large differences in the thickness of the remaining Paleozoic section in the Lemitar Mountains may be interpreted to mean that the map area remained a structural high undergoing extensive erosion during much of Eocene time. Eventually, the region of the Lemitar Mountains was reduced to an area of topographically low to moderate relief with relatively thin Baca conglomerates and sandstones encroaching on the remaining highlands. Over this nearly beveled uplift, the volcanic-derived conglomerates and ash-flow tuffs of the Spears and Hells Mesa Formations were deposited in early Oligocene time.

Tertiary Structure

The Rio Grande rift zone (Bryan, 1938; Kelley, 1952; Chapin, 1971) transects New Mexico from south to north and continues into central Colorado. Bounded on the west by the Colorado Plateau and the Basin and Range province and on the east by the southern Rocky Mountains, the Rio Grande rift forms a wedge-shaped intra-continental lineament, narrow in the north, widening and bifurcating to the south. The rift in central New Mexico south of the Albuquerque basin consists of a series of semi-parallel north-trending grabens separated by several intra-rift horsts (Chapin, 1971; Sanford and others, 1972). Another series of en echelon southwest-trending basins intersecting the Rio Grande rift zone at the north end of the Socorro basin has been called by Chapin (1971, p. 199) the San Augustin lineament and may represent a weak bifurcation of the main rift structure. Paleontological data and K-Ar dates on the basal clastic and volcanic fill in the subsiding basins of the rift zone indicate the onset of rift faulting began at least 18 million years ago (Chapin, op. cit.).

Intra-rift horsts near Socorro, New Mexico, consist of the Magdalena, Socorro-Lemitar, and Chupadera Mountains. The

Lemitar Mountains are located near the axis of the rift and form an intra-rift horst between the Socorro basin to the east and the La Jencia basin (Snake Ranch Flats) to the west. To the south, the Lemitar Mountains merge into the structurally-related Socorro Mountains while the northern extent of the range is formed by the San Augustin lineament. Except for folding of Precambrian age, faulting has dominated the structural development of the Lemitar Mountains.

Recognizable faults of late Tertiary age in the map area are related to rift faulting and may be classified into two distinct structural groups: (1) north-trending en echelon system of normal faults with a steep eastward dip and (2) west-trending normal faults with steep to vertical dips.

The north-trending en echelon system of normal faults form the major rift structures on the west side of the Socorro basin. The fault system has stepped-down crustal blocks to the east, forming the two main ranges of the Socorro-Lemitar Mountains. Exposed fault zones range from about 6 to as much as 30 feet in width. Maximum vertical movement across the fault system may be estimated by comparing the elevations at the top of the Precambrian at its highest point of exposure in the Lemitar Mountains to the top of the Precambrian in the Socorro basin. Results of a gravity survey in central Socorro County (Sanford, 1968) place the top of the Precambrian basement approximately 12,000 feet below the surface of the valley floor, while the top of the Precambrian basement at its highest point in the Lemitar Mountains is about 6700 feet, or 2100 feet above the valley floor to the east. Total elevation difference is approximately 14,000 feet, of which probably no more than 3500 feet* may be attributed to Laramide faulting. Assuming about 10,500 feet for a minimum average vertical displacement across the fault system from Polvadera Mountain to the Socorro basin, only a small fraction of this figure is accounted for by faults exposed in the map area. Therefore, most of the fault system related to the formation of the western part of the Socorro basin lies buried beneath alluvium and late Tertiary rocks that form the graben-filling sediments east of the present range front. Evidence for the existence of buried faults may be seen in the numerous small scarps cutting pediment gravels east of the Socorro-Lemitar Mountains (Budding and Topozada, 1970; Sanford and others, 1972). Measurable displacement along rift faults exposed in the Lemitar Mountains varies from approximately 1100 feet at Corkscrew Canyon to as much as 3200 feet in the western range just south of Red Mountain.

West-trending normal faults cut or intersect the north-trending rift faults and, with one exception, are generally of small to moderate displacement. The most prominent fault system in this group truncates the north end of the Lemitar Mountains and forms the southern boundary of a downthrown trough that lies between the Lemitar Mountains on the south and the Ladron Mountains on the north. It is believed that

*This figure is derived by subtracting the maximum thickness of the Paleozoic section in the Lemitar Mountains from the average thickness of the Paleozoic-Mesozoic section east of Socorro, New Mexico.

this trough forms the easternmost extension of Chapin's San Augustin lineament. Displacement across this fault system varies from a maximum of at least 2500 feet in the northeast part of the map area and decreases westward. Drag along the north side of the fault system has re-oriented bedding in the A. L. Peak and Popatosa Formations to northwest to northeast strikes with northerly dips.

Several west-trending normal faults cutting the Lemitar Mountains form minor graben structures that cut across the two main ranges in a transverse direction, dividing the original north-trending rift structures into many smaller fault blocks which have since moved independently of each other. Displacement ranges from a few tens of feet in the south increasing northward to as much as 800 feet south of Red Mountain.

Structural blocks forming the transverse grabens have undergone a counterclockwise rotation about a south-to-north axis of as much as 40 degrees with respect to the bounding horst structures. Effects of tilting of north-trending blocks during initial uplift and rotation are cumulative with a maximum observed rotation approaching 90 degrees north of Corkscrew Canyon. Independent rotation of structural blocks may occur along gravity or normal faults if the dip of these faults decreases with depth (Hills, p. 191).

Tectonic Interpretation of Rift Structures

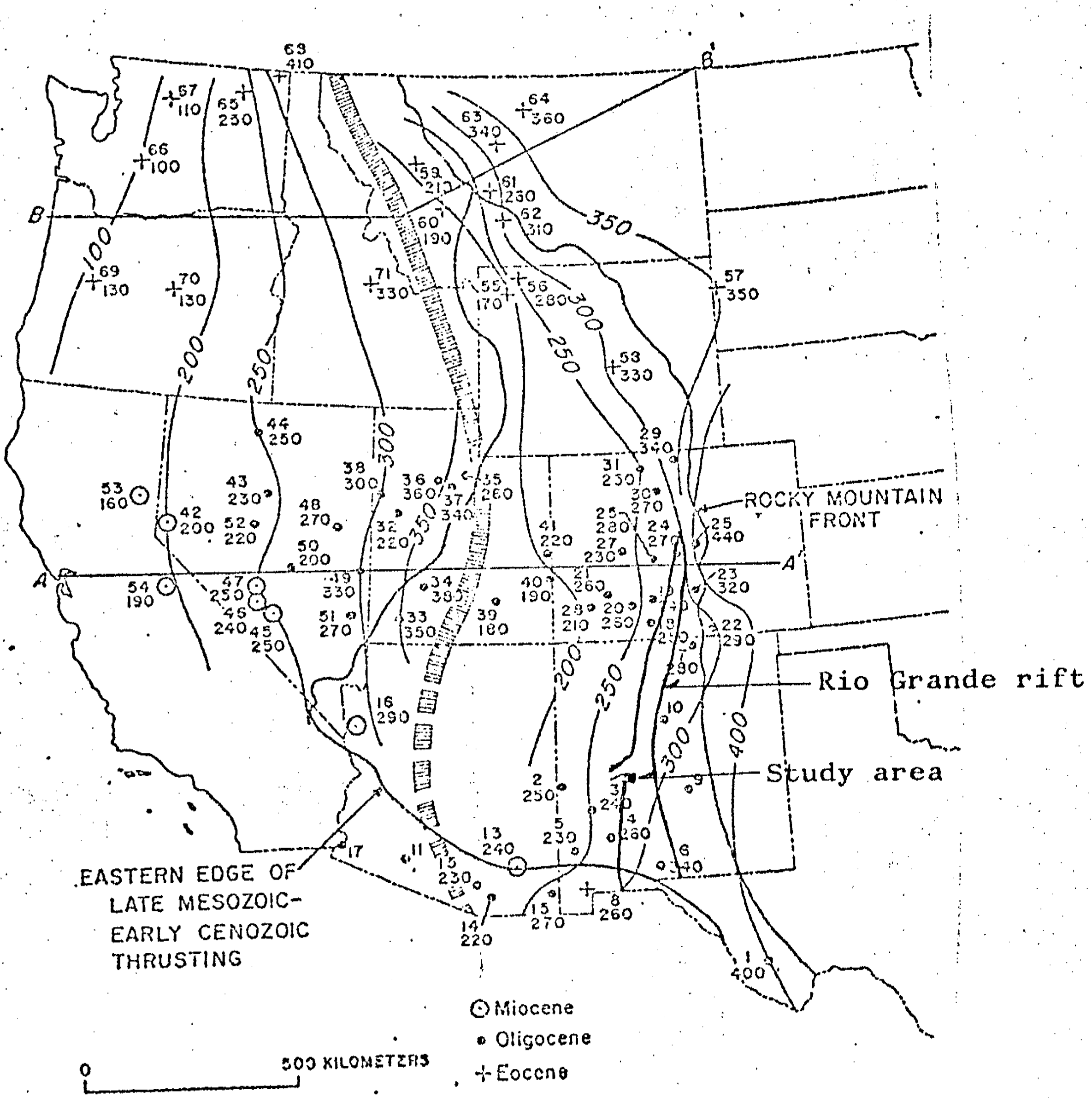
Development of the theory of plate tectonics over the past decade has resulted in a re-evaluation of many orogenic concepts (Dietz and Holden, 1967; Dickinson, 1970; Dewey and Bird, 1970). Regional extension and uplift of the western United States during late Cenozoic time as a result of a change in boundary conditions between the American and Farallon plates provides a better explanation of Basin and Range tectonics than previous interpretations (Eardley, 1951; Gilluly, 1963; Hamilton and Meyers, 1966; Atwater, 1970; Christianson and others, 1970).

The Rio Grande rift zone is characterized by the development of many subparallel graben structures oriented en echelon in a north to south direction, bifurcation and widening of the rift zone south of the eastern boundary of the Colorado Plateau, and tilting of the rift (and intra-rift) margins away from the axis of the rift zone (Bryan, 1938; Kelley, 1952, 1954, 1970; Chapin, 1971). Experimental production of graben structures by Cloos (in Hills, 1963) by arching clay cakes over balloons has reproduced quite accurately both regional and local structural patterns of major rift systems.

The existence of a gently dipping, imbricated subduction zone beneath the southwestern United States has been proposed by Lipman and others (1970, pp. 28-41) from a study of K_2O/SiO_2 ratios of early and middle Cenozoic volcanic rock types erupted in the western United States. Depth to the proposed subduction zone along the present axis of the Rio Grande rift zone ranges from about 230 km. to as much as 350 km. (fig. 19). The over-riding and subsequent destruction of the East Pacific rise along the western margin of the American plate began in

Figure 19.

Map of western United States showing location and depth to possible imbricated subduction zone utilizing K_2O/SiO_2 ratios of early and middle Cenozoic volcanic rock types (from Lipman and others, 1970).



ROCKY MOUNTAIN FRONT
Rio Grande rift
Study area
EASTERN EDGE OF LATE MESOZOIC-EARLY CENOZOIC THRUSTING
Miocene
Oligocene
Eocene
0
500 KILOMETERS

latest Oligocene to early Miocene time (McKensie and Morgan, 1969; Atwater, 1970), with the result that subduction of the Farallon plate beneath the western United States gradually ceased. After subduction stopped, the gradual rise of geothermal gradients would increase magma generation from the melting plate. Rising magma may be responsible for a linear arching and uplift along a north-trending axis above the edge of the subducted plate. Independent movement accompanied by a slight clockwise rotation of the Colorado Plateau crustal block, in addition to the linear arching and uplift due to subcrustal processes, may be responsible for producing the present Rio Grande rift structures.

Seismic activity (Sanford and Long, 1965; Sanford and others, 1972), high heat flow (Reiter, oral communication, 1973), and abundant scarplets cutting the Pliocene and Pleistocene surfaces (Budding and Toppozada, 1970; Sanford and others, 1972) indicate that the rift zone is active during the present time.

SUMMARY OF GEOLOGIC HISTORY

Precambrian History

Deposition of a thick sequence of interbedded quartz sandstones, feldspathic sandstones and arkoses overlain by a sequence of sialic to mafic volcanic rocks represent the oldest Precambrian event known in central New Mexico (Stark, 1956; Condie, oral communication, 1973). Radiometric dates from the subsurface rocks of eastern New Mexico and the exposures in central New Mexico indicate at least two periods of orogenic events to be tentatively recognized in central New Mexico, one at 1600 m. y. and one at 1350 m. y. (Muehlberger, 1966). Radiometric dates from rocks in central New Mexico are from high-grade metamorphic products (gneiss) or sialic igneous rocks (granite) and do not represent the metasedimentary-metavolcanic sequence cropping out in the Rio Grande Valley.

The Corkscrew Canyon sequence represents only a small part of the total metasedimentary-metavolcanic sequence. Thick beds of quartzite underlying the arkosic rocks are not exposed in the Lemitar Mountains nor are the overlying metavolcanic rocks that crop out in the Ladron Mountains (Condie, oral communication, 1973) and the Manzano Mountains (Stark, 1956).

The structural deformation of the metasedimentary-metavolcanic sequence of rocks followed by large-scale intrusion of sialic and mafic plutons and dikes is continuous throughout central New Mexico. Considering the widespread similarity of structural features, metamorphic grades and petrologic assemblages, a general setting of the Precambrian tectonic events may be developed and summarized:

(1) Deposition of quartz sands, followed by arkosic sands and gravels in a linear, northeast-trending basin. The change from quartzose to arkosic sediments indicates a rising granitic land mass near the edge of the basin.

(2) Widespread episode of volcanism ranging from rhyolitic to basaltic lave flows and ash-flow tuffs, possibly related to similar volcanic eruptions in Arizona (Yavapai Series and Pinal Schist)(Livingston and Damon, 1968).

(3) Mazatzal orogeny (Wilson, 1939; Muehlberger, 1966; Livingston and Damon, 1968) locally produced intense folding, thrust faulting from the northwest, metamorphism and intrusion of gabbroic to granitic plutons.

(4) Local relaxation of compressional stresses, intrusion of mafic dike swarms followed by a long period of erosion lasting into the Phanerozoic Eon.

Paleozoic History

Sedimentation resumed with the deposition of the Caloso Formation of Mississippian age and continued with minor epeirogenic interuptions through remaining Paleozoic time.

Mesozoic History

Deposition during the Mesozoic Era is restricted to upper Triassic terrestrial deposits and to Cretaceous clastic near-shore deposits. Deposition ended with the beginning of the Laramide orogeny in late Cretaceous to early Tertiary time.

Cenozoic History

The Lemitar Mountains were uplifted along reverse and vertical to high-angle normal faults of Laramide age to form a prominent structural highland during early Cenozoic time. The entire Mesozoic sedimentary section and most of the Permian section were eroded with the resulting sedimentation of clastic debris in nearby structural basins to form the Baca Formation of Eocene age.

By Oligocene time, the map area was eroded nearly to the level of the surrounding sediment-filled basins. Topography consisted of very low, rounded hills capped with rocks of Paleozoic age dipping to the west at low angles with metamorphic rocks of Precambrian age cropping out at the highest elevations. Baca sediments covered the western part of the map area to a depth of a few hundred feet.

During the Oligocene Epoch, the Lemitar Mountains were buried under an accumulating blanket of volcaniclastic sediments and interbedded ash-flow tuffs and andesite flows. Gradual uplift and subsequent erosion formed east-trending valleys in the Spears and Hells Mesa Formations which were later filled by successive andesite flows and ash-flow tuffs of the overlying A. L. Peak Formation. Continued uplift and erosion during the Oligocene produced sufficient topographic relief to restrict deposition of the ash-flow tuffs of the overlying Potato Canyon Formation to the southern part of the Lemitar Mountains.

Basin and Range faulting beginning in late Miocent time was marked by the deposition of fanglomerate and playa sediments in a broad structural basin (Bruning, in press). The map area was part of the basin and was buried under a thick sequence of volcanic conglomerates interbedded with andesite flows and playa deposits, all of which comprise the Popatosa Formation of Miocene age.

Near the end of the Miocene, present-day rift structures began with the formation of many north-trending normal faults creating the Socorro-Lemitar intra-rift horst. Popatosa beds in the Lemitar Mountains were tilted to the west. The uplift of the Socorro-Lemitar Mountains separated the La Jencia basin in the west from the Socorro basin to the east.

Bifurcation of the original rift structure truncated the Socorro-Lemitar intra-rift horst at the north end of the Socorro basin. Normal faults associated with the bifurcation formed several minor transverse graben/horst structures in the Lemitar Mountains. Continued uplift and rotation of fault blocks in the transverse structures along original rift faults deformed the older pediment gravels and eroded early alluvial deposits. During late Pliocene and Quaternary time, erosion of the Lemitar Mountains formed extensive pediments along both flanks of the Socorro-Lemitar range. These pediments are now being eroded and dissected by tributaries of the Rio Grande.

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