# STRUCTURE AND METAMORPHISM IN THE SOUTHERN SIERRA LADRONES SOCORRO COUNTY, NEW MEXICO



by

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of the degree of
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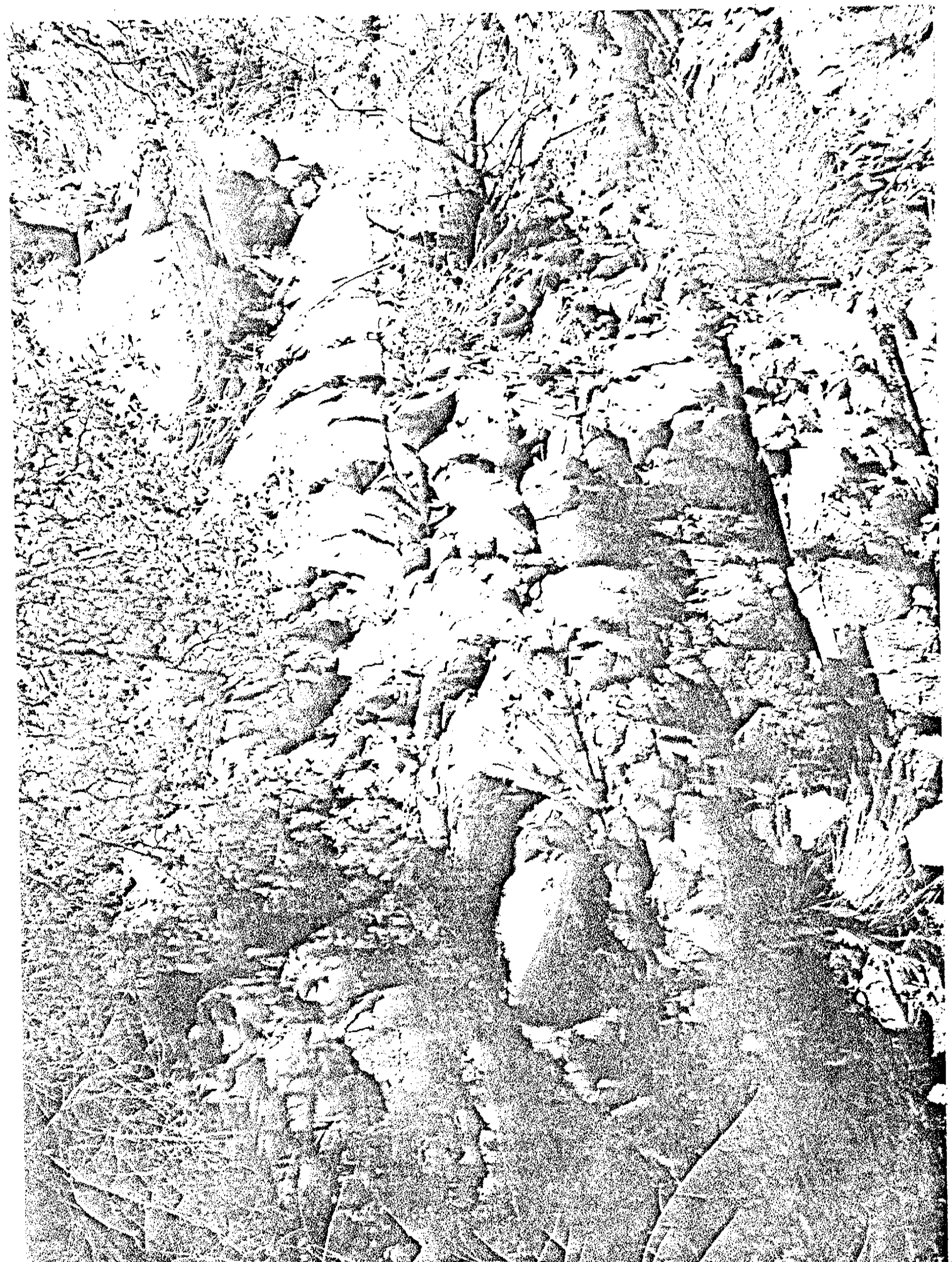
Frontispiece: Isoclinally folded thin quartzite bed (s) NE of Cerro Colorado. The synclines are faulted out (thrusts) leaving only anticlines. Looking approximately along fold axis. The anticlines are about 10 to 18 inches from limb to limb.



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# A B S T R A C T

The most commonly occuring rocks in the Southern Sierra Ladrones are of Precambrian age. They consist of metaquartzites, hornblende schists, quartz-hornblende gneiss, a grandioritic augen gneiss and two granodiorites. One of them is believed to have been formed by granitization during a period of regional metamorphism.

The metasediments have been classified as belonging to the almandine-amphibolite facies, except for the augen gneiss, which, together with the granodiorite, represent the most intense degree of metamorphism reached in the area.

Locally effects of retrogressive metamorphism are noted, produced by the development of chlorite from hornblende.

The Precambrian rocks are tentatively correlated with formations described by Stark (1956) from the South Manzano Mountains.

Foliation in the metasediments parallels bedding as defined principally by lithologic contacts. It is interpreted as axial plane foliation produced by deformational stresses acting in a direction approximately N 60° W. Isoclinal folding is thought to have been produced.

Ladron Fault, with possibly some strike slip movement, and Cerro Colorado Fault, the major fault of the Rio Grande Graben in this area, bound the uplifted block of the central part of Sierra Ladrones on the SW and SE respectively. These faults are believed to have formed during the Tertiary.

Other formations croppingout in the area are Mississippian and Pennsylvanian sediments, the Tertiary Popotosa formation and Quaternary pediments.

# A C K N O W L E D G E M E N T S

The writer wishes to express his gratitude to Dr. Clay T. Smith, Head of the Department of Geology, NMIMT, who was thesis advisor. His comments and suggestions are appreciated.

Acknowledgement is due Dr. A. K. Armstrong, formerly of Socorro, who suggested the problem and spent some time to familiarize the author with the area.

Special thanks are extended to Mr. Max E. Willard of the State Bureau of Mines and Mineral Resources, NMIMT. Mr. Willard's suggestions and assistance in theory and practice are greatly appreciated.

Dr. F. Kuellmer of the State Bureau of Mines and Dr. A. Budding, Professor in the Geology Department, NMIMT both spent a day in the field with the writer. I am indebted to both for helpful discussions.

Mr. Bob Price, draftsman in the State Bureau of Mines and Mineral Resources drafting office prepared the topographic map.

# I N T R O D U C T I O N

This report is based on the results of an investigation undertaken in partial fulfillment of the degree of Master of Science in Geology at the New Mexico Institute of Mining and Technology, Socorro, New Mexico.

The problem chosen was to determine the structure and metamorphism of the Precambrian rocks exposed in the southern part of the Sierra Ladrones.

Mapping was done on a topographic base map at a scale of 1:12000. This map was made by enlarging a portion of the U. S. Geol. Survey Riley 15 minute quadrangle from scale of 1:48000. For the sake of clarity only the 200 foot contour lines were retained on the base map.

Field mapping and collection of representative specimens was done from late fall of 1960 through summer of 1961 whenever weather and road conditions were favorable.

From the collected specimens thin sections were prepared and studied microscopically. Some of the very fine grained rocks had too small a grain size for definite identification by microscope alone. These were crushed, ground and screened. The fraction from 0.1 to 0.4 mm. was separated by a heavy liquid (Tetrabromoethane). The light fraction was pulverized and the minerals identified by x-ray diffraction methods.

During the author's employment as petrologist for the Cerro De Pasco Corporation, in La Oroya, Peru, the thin sections were re-examined. Results of this examination agree with the previous work and the results of the x-ray diffraction could be confirmed since the microscope available yields magnifications up to 2000 diameters.

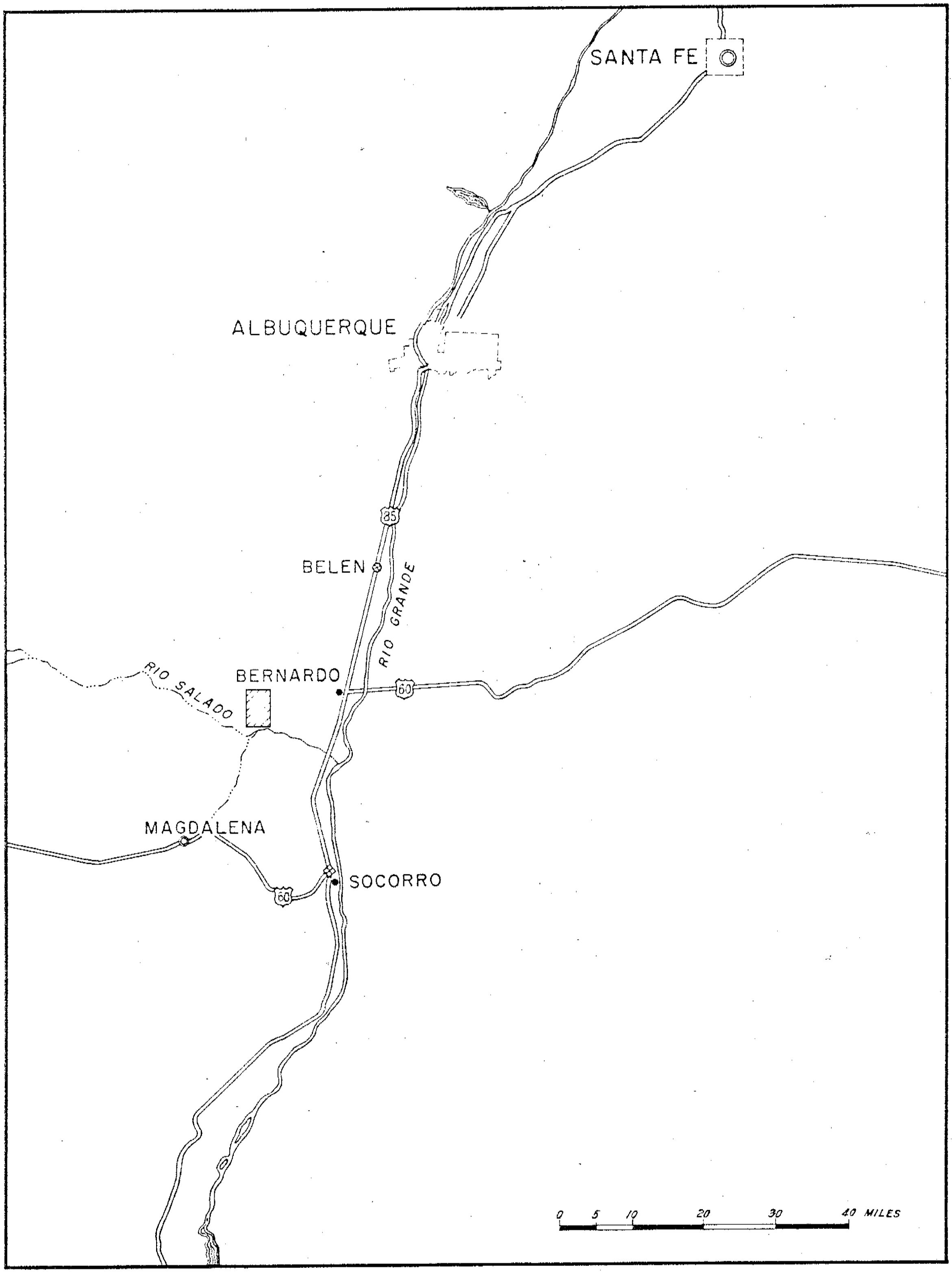


FIGURE I

INDEX MAP SHOWING FIELD AREA

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# Geography

## Location and Accessibility

The Sierra Ladrones is in central New Mexico on the western margin of the Rio Grande Valley, approximately 25 miles north of Socorro (Fig. 1).

The area studied is the southern part of the Sierra Ladrones and includes all or part of the following sections: 7, 17, 18, 19, 20, 29, 30, 31, 32 in T2N, R2W; parts of sections 5 and 6 in T1N, R2W, as well as part of the northwestern corner of the Sevilleta Land Grant.

The total area mapped is about 15 square miles.

Access roads are scarce, due mainly to the topography and to lack of settlements in the area. Dirt roads branch off the former US Highway 85 about 1/2 mile west of the junction of US Highways 85 and 60 at Bernardo, New Mexico. One of these dirt roads leads to the former "Lazy C Bar J" Ranch on the eastern flank of the Sierra Ladrones. Another road leads to the southern end of the mountains, where it passes through the Rio Salado and from there continues north as a "jeep trail". Both roads are nearly impassable in wet weather and are often deeply rutted and locally covered by drift sand.

## Topography and Physiography

The topography in the Sierra Ladrones is rugged. Ladron Peak in the west central part of the mountains rises to an elevation 9176 feet. Many of the smaller knolls and ridges are about 6500 feet. The elevation at the south end of the mapped area, approximately 6 miles south of Ladron Peak, is about 5300 feet.

In the central part of the Sierra Ladrones (north end of map area) steep walled canyons are numerous and rather deep. Toward the east the relief decreases and small hills and knolls become prominent. In the south the relief is low, except for Cerro Colorado which rises sharply about 1000 feet above the low ridges east of it.

The western part is characterized by a hogback of Mississippian and Pennsylvanian rocks. This hogback drops off steeply to the east and locally has vertical and overhanging cliffs as high as 20 to 30 feet. The west slope of the hogback is a dip slope, approximately 20 degrees.

The high ridges are generally outcrops of Precambrian quartzites, gneiss and granite. Areas of lower relief are underlain by schists of Precambrian age and by Tertiary sediments.

Physiographically the Sierra Ladrones belongs to the Mexican Highland Section of the Basin and Range Province. The Sierra Ladrones is, however, not a mountain typical of the Basin and Range Province, as it is isolated and separated from the Socorro-Polvadera Range by the water gap of the Rio Salado.

## Climate, Vegetation and Drainage

The climate in central New Mexico is characterized by warm days and cool nights. The average annual temperature is 58°F.

The four seasons, although well marked, are not rigorous. The January average daily maximum is 54°, the average minimum 23°. The average daily maximum for July is 95°, the average minimum 64°F.

Precipitation averages less than 10 inches per annum, most of it occurring during the summer months in the form of cloudbursts associated with thunderstorms. Occasionally up to 1-1/2 inches of rain may fall within one hour.

The relative humidity is very low, even after rainfalls.

Due to the seasonal precipitation natural vegetation is restricted to plants which require little water, or to such plants which can store water in their systems for a long period of time.

The predominant vegetation in dry washes and at low elevations (up to about 5600 feet) consists of mesquite, sage brush and creosote bush; some cedars are usually present.

The next higher faunal zone is comprised of cedar, yucca and several cacti, mainly tree cholla and "prickly pear". This zone also contains locally evergreen oak and some grasses (e.g. gramma grass). The approximate range of this zone is from 5600 to 6400 feet.

In the highest faunal zone represented, cedar is present and Ponderosa pine. Most of the latter were killed during the droughts of 1955 and 1956. Cacti occur only sparsely. White oak, pinon pine and "alligator juniper" were found locally, also some mosses in moist places.

Ridges of granite and quartzite support much less vegetation than areas underlain by schists and hornblende gneisses.

All of the streams in the mapped area are intermittent; they carry water only after rains and during a short period in spring when the snow melts. The streams are directly or indirectly (tributaries of the Rio Salado) tributaries of the Rio Grande. The Rio Salado which passes just south of the area mapped is also intermittent since in most years surface flow ceases for a short length of time.

# GENERAL GEOLOGY

Rocks in the Sierra Ladrones consist principally of Precambrian metasediments and two separately mapped granodiorite units. West of Ladron Peak are Carboniferous sediments, mainly limestones, sandstones and shales. Scattered outcrops of Pennsylvanian sediments also occur east of Cerro Colorado.

One of the granodiorite units has metamorphic affinities and has been intruded by the other granodiorite. The younger granodiorite shows cross cutting relationships with the metasediments in Cañon Hondo and now forms the eastern part of the Sierra Ladrones. The younger rock has been determined to be Precambrian in age (1.44 billion years) by Rb/Sr determinations (Wasserburg 1965).

The Tertiary Popotosa formation, a volcanic conglomerate, crops out along the southeastern front of the mountains. The overlying Santa Fe formation filling the Rio Grande Valley is present only east of the mapped area.

Quaternary pediment gravels are abundant along the south and southeast flanks of Cerro Colorado and to the east of it. At least two pediment surfaces can be recognized although they are not subdivided on the map (Plate 1). Quaternary alluvium is found in all valleys and canyons.

The early Precambrian metaquartzites (Lower Quartzites in this report) form Ladron Peak and a high steep ridge (Main Ridge) which extends approximately 3 miles south to southeast from the peak. These rocks occupy most of the NW quarter of the map area. Interbedded with the quartzites are minor amounts of micaceous quartzites, quartz-mica schists and quartz-hornblende gneisses.

Red granodioritic augen gneiss with interbedded, more or less feldspathic quartzites and some hornblende gneisses are well exposed on Cerro Colorado, about 5 miles south of Ladron Peak in the SW quarter of the mapped area (Plate 1). This augen gneiss exhibits only moderate foliation. Hornblende schists, hornblende-quartz gneisses and mica schists interbedded with some thin quartzite beds are mapped in a belt trending SW - NE. This belt lies in the valley directly west and north of Cerro Colorado and along the base of the Main Ridge. Intense deformation of these rocks is evident. Foliation and lineation are well developed in most of the hornblende-quartz gneisses and evidence of tight folding with possible faulting is found.

The quartzites interbedded with these hornblende schists appear to be much more strongly deformed than the quartzite beds on the Main Ridge. Folds of small amplitude are common and one outcrop directly north of Cerro Colorado shows tight, isoclinal folding of a massive quartzite. Only anticlines are present and the synclines appear sheared out along faults which are parallel to the fold limbs (Frontispiece). On the Main Ridge all measured orientations are more or less parallel and no definite evidence for isoclinal folding has been noted, except for the rapid northeastward pinching out of a wedge of micaceous and hornblende schists about 1 mile north of Loma de Silla.

Precambrian red granodiorite crops out in a N-S belt east of the Ladron fault extending from Cañon Hondo in the north to within 1 mile of Cerro Colorado. The same rock is believed to comprise the northern part of Loma de Silla west of the Ladron fault. Generally the granodiorite is massive and relatively homogeneous in composition; however, locally there are patches which are texturally and compositionally identical to hornblende schist.

A younger granodiorite, weathering generally buff colored, crops out in the northeastern mapped area. This rock shows intrusive contacts with the other Precambrian rocks. Xenoliths of Precambrian metasediments are locally quite numerous. Intrusive contacts are present locally; no effects of contact metamorphism are noted.

A few basic dikes, some too small to map, are scattered throughout the map area. They generally trend northeasterly; their mafic consituents are completely altered. A few lenticular, pegmatitic veins are restricted to the Cerro Colorado area.

West of Cerro Colorado a hogback of Carboniferous sediments extends north-south along the entire west side of the Sierra Ladrones. The Carboniferous beds are in depositional contact with the underlying, strongly folded and eroded Precambrian rocks, although good exposures are limited.

The southeastern part of the area is covered by the Tertiary Popotosa formation, a volcanic conglomerate which contains boulders as large as 2 feet across. This formation is in fault contact with Precambrian and Pennsylvanian rocks along the Cerro Colorado Fault.

Quaternary pediment gravels, consisting mainly of Precambrian and to a lesser extent of Carboniferous rock fragments are abundant in the southeastern and east central parts of the area. Alluvium is found in all dry washes and canyons.

# PRECAMBRIAN ROCKS

Rocks of Precambrian age in the Sierra Ladrones consist of: a sequence of metasediments, a granodioritic augen gneiss, a red granodiorite and a light buff granodiorite.

Foliation and lineation are developed to varying intensities, depending upon rock composition as well as intensity of metamorphism. Lineation can in most cases be detected only in thin sections. Both granodiorites are generally massive, however the red granodiorite displays foliation where the metasediments form a gradational contact with it. Where original bedding in the metasediments is still discernible foliation always coincides with it.

For the purpose of mapping the metasediments in the Sierra Ladrones have been divided into (1) Lower Quartzite, (2) Hornblende Schist, (3) Upper Quartzite, and (4) Massive Amphibolite.

It is believed that these units may correlate with the sequence established by Stark (1956) in the Manzano Mountains.

In some exposures, it is evident that folding has been very intense, and that faulting has played a significant role in the deformation. The rocks most affected are hornblende schists, quartz-hornblende gneiss and some thin quartzite beds within the hornblende schists. Ptygmatically folded veins of predominantly quartz and sodic feldspar are locally found in hornblende schist. Compositional layering in the hornblende schist is very well developed in some areas. Drag folds and chevron type folds were observed and mapped in these rocks.

45x, // nicols. Skeletal magnetite with hornblende (light grey mottled) and garnets (white, high relief); from amphibolite.

45, // nicols. Hornblende prisms growing from parallel fractures (cleavage?) into completely sericitized plagioclase (finely mottled).

45x, // nicols. Marginally sericitized plagioclase surrounded by hornblende.

45x, // nicols. Large crystal of garnet, anomalously anisotropic.

Fig. 2

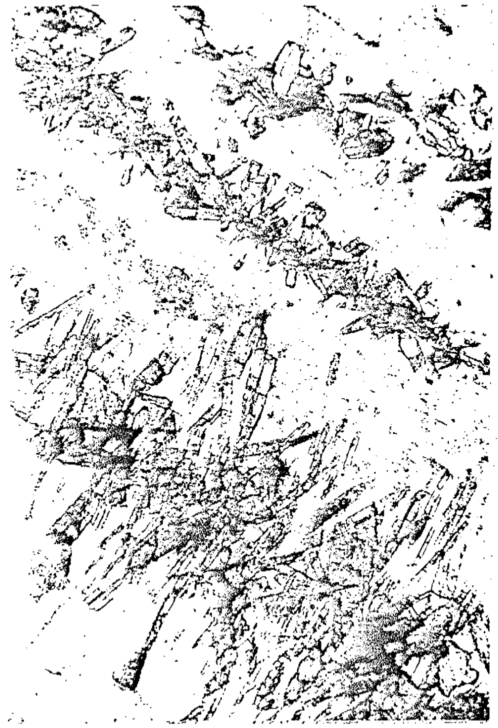

Fig. 3

Fig. 4

Fig. 5

## Lower Quartzite

A sequence of pure quartzite with an exposed thickness of 5400 feet, herein called the Lower Quartzite, extends from the base of the eastern flank of Main Ridge westward toward Ladron Peak. The rocks are confined to the north of Ladron Fault and continue northward for several miles. The Lower Quartzite is exposed over approximately 3 square miles in the map area.

The Lower Quartzite is massively bedded and strongly metamorphosed. In this sequence thin beds of quartz-muscovite schists and quartz-muscovite-andalusite schists are sparsely interbedded with the quartzite.

The Lower Quartzite is tentatively correlated with the Sais Quartzite which Stark (1956) describes from the South Manzano Mountains. The latter has a thickness of about 2,000 feet, and its descriptions agree fairly well with the Lower Quartzite.

The Lower Quartzite forms very prominent outcrops and supports scant vegetation.

### Structure and Lithology

The Lower Quartzite is massive, and few bedding features have been observed. Hematite and/or magnetite rich layers a few centimeters in thickness alternating with almost pure quartz layers are suggestive, but not conclusive proof of bedded structures. Thin conglomeratic beds are found, but they are usually lenticular and cannot be traced along the strike for any distance. Measurements of bedding attitude were taken only where such vague banding was present or at lithologic contacts between quartzites and some of the thin schistose interbeds.

The average strike of the Lower Quartzite is N30E with an average dip of 45° southeast. The dip steepens slightly to the north.

Jointing is present, but it is widely spaced and not prominent, and there is no preferred orientation. Foliation is present in quartzite units which are micaceous as well as in some of the thin interbedded schists. Foliation parallels bedding as defined by lithologic variations and boundaries.

The Lower Quartzite ranges from white to gray in color: shades of off-white, pinkish, light gray with darker bands, and medium gray are common. Sometimes the color is mottled or streaked in reddish or grayish tones. Weathered and fresh surfaces rarely differ in color although staining occasionally modifies the weathered surface.

The grain size within individual units is uniform. Small lens-like bodies of coarser material occur in finer grained surroundings. The grain size varies from 0.1 to 2 mm and at times reaches 10 mm in conglomeratic lenses.

Most of the quartzite beds are rather pure, containing up to 98% quartz. The minor constituents are magnetite, hematite, muscovite and sericite; apatite, zircon and tourmaline occur as accessories. Magnetite is, usually, xenomorphic, although occasionally, well formed octahedra are found. When muscovite, or very rarely, sericite, are present in a bed, they impart a foliation to the bed, even though their abundance may be as low as 5%.

Direct evidence of large scale folding is scarce in the Lower Quartzite. However, its presence may be inferred from indistinct drag folding near the schist-quartzite contact 1.5 miles north of Loma de Silla and along the quartzite-schist contact at the base of Main Ridge. Near these contacts the quartzites are somewhat contorted. In addition, a small fold 20 feet

45x, x nicols. Strongly elongated grain of quartz, containing many inclusions of other minerals (hornblende, muscovite, apatite) in fine grained surrounding of quartz, hornblende, biotite.

45x, x nicols. Elongated and strained, relatively coarse quartz.

45x, x nicols. Strained quartz in a "rod" in epidote.

45x, x nicols. Strained and elongated quartz surrounded by finer quartz and epidote.

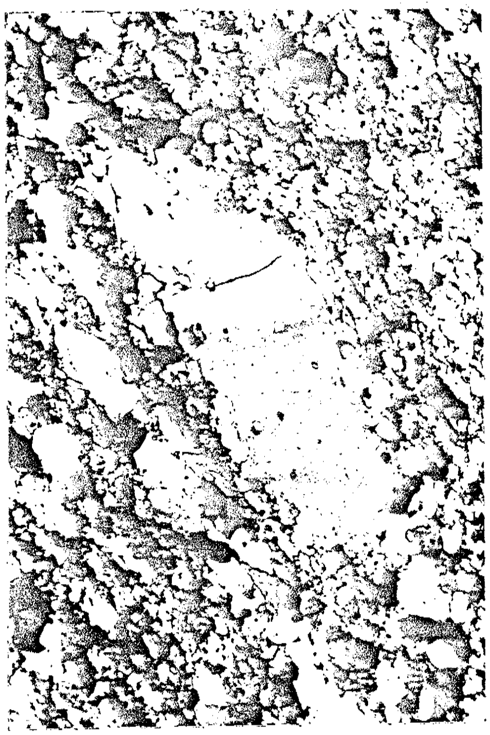

Fig. 6

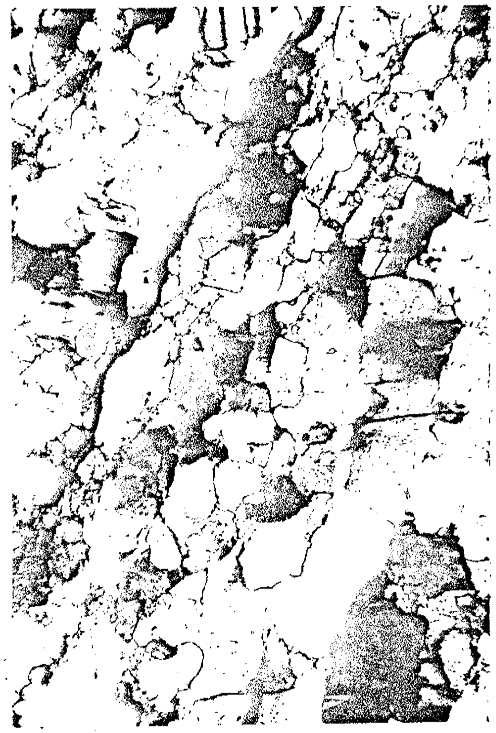

Fig. 7

Fig. 8

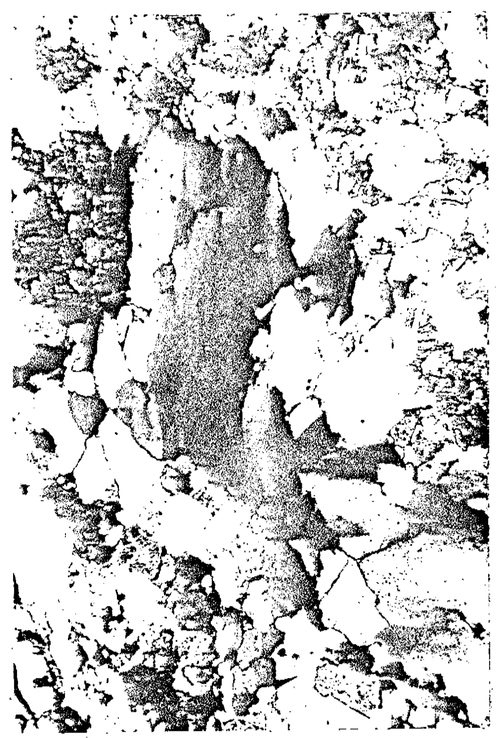

Fig. 9

from limb to limb was found in the upper part of Mule Springs Canyon.

Effects of Metamorphism

The effects of metamorphism are somewhat varied, depending on the original composition of the beds. Some layers are now dense and glassy and fractures are subconchoidal to conchoidal; in these, individual grains cannot be recognized even with the aid of a hand lens. In other coarser grained beds where individual grains can be recognized fractures still cut through the grains.

In conglomeratic beds the pebbles have been elongated slightly. Such elongation represents a lineation or foliation, depending on whether the pebbles were stretched into rod shape or flattened into more or less discoid shapes. Both types are found and where this elongation or flattening is pronounced measurements of the orientation were taken. It was found that foliation and bedding have the same orientation.

The most pronounced effect of metamorphism is the elongation of quartz grains which can only be seen microscopically. This effect is not present in all beds. Some quartz grains have a length to width ratio of 2 or 3 to 1 (Figs. 6 to 9). These grains are optically continuous and their long axes coincide with the foliation of the rock as expressed by aligned mica flakes. The elongated grains are considerably larger than the average for any particular rock and they show less strain than small grains. Strained quartz is quite common, not only in the quartzites but also in other rock types.

Since the quartzites are rather pure, their metamorphic facies is difficult to establish. Minerals found in some of the impure beds include plagioclase (composition not determinable), microcline, muscovite, biotite, hornblende and epidote. The assemblage quartz-microcline-plagioclase-biotite (muscovite-epidote) is typical for quartzo-feldspathic rocks in the staurolite-almandine subfacies of the almandine-amphibolite facies (Turner and Verhoogen). The Lower Quartzite is therefore tentatively assigned to this metamorphic facies.

Hornblende Schist

Stratigraphically above, and apparently in conformable contact with the Lower Quartzite is a unit mapped as hornblende schist. Near the base of the hornblende schist a 200 foot thickness of quartz-muscovite schists and quartz-muscovite-andalusite schists is prominent but too thin to map separately. Lithologically similar, thin beds (0.5' - 15') of quartz muscovite schist are interbedded with the Lower Quartzite, and these are described here to avoid repetition.

The upper part of the Hornblende Schist is comprised of essentially hornblende schists and hornblende-quartz gneisses with minor interbedded quartzites and muscovite schists. A maximum thickness of about 2,200 feet is present in the widest part of the outcrop belt east of Loma de Silla.

The outcrop belt extends SSW-NNE almost across the entire map area, from east of the Lower Quartzite in the north to the north of Cerro Colorado, where it is cut by the Ladron Fault. Another exposure is from west of Cerro Colorado to the Ladron Fault. One branch extends up Cerro Colorado where it pinches out. An isolated short, lens-like body, faulted off on one side is close to the crest of Cerro Colorado. Roof pendants, too small to be shown at the scale of the map in the Precambrian younger granodiorite consist also to a large extent of hornblende schists. A wedge-like body, comprised mainly of muscovite schist occurs about 1 mile north of Loma de Silla.

Outcrops are usually not prominent; the thin soil cover derived from weathering supports fair vegetation. A tentative correlation is made of the Quartz-Muscovite Schist and the Hornblende Schist with Stark's Blue Springs Schist from the South Manzano Mountains. The Quartz-Muscovite

Ptygmatically folded "vein"
of quartz and feldspar.

Composition banding in hornblende-
gneiss, north of Cerro Colorado.

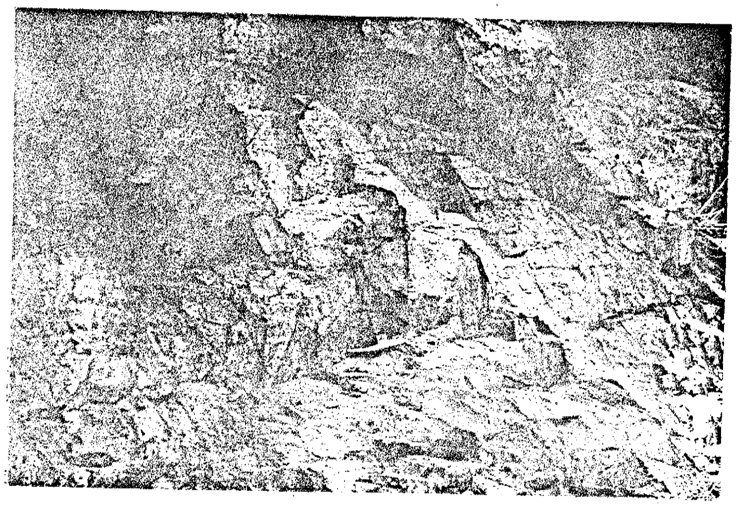

Fig. 10

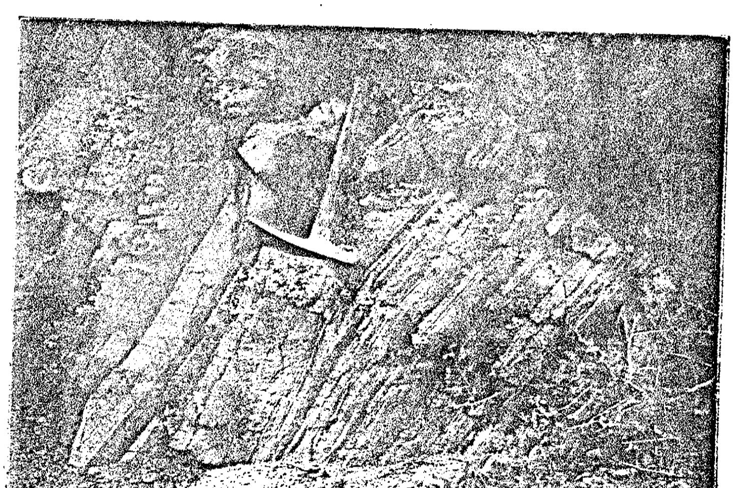

Fig. 11

45x, // nicols. Quartz-hornblende gneiss foliation is very well developed.

45x, // nicols. Chlorite porphyroblast, exhibiting pleochroism, in quartz hornblende schist. This rock is only moderately foliated.

Fig. 12

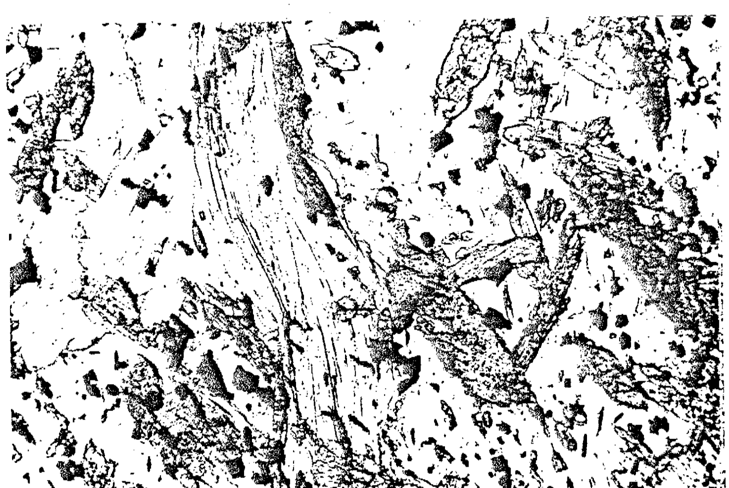

Fig. 13

Schist corresponds to the lower portion of the Blue Springs Schist while the Hornblende Schist of the Sierra Ladrones is correlated to the upper part. Lithologic similarities exist even though metamorphism in the South Manzano Mountains was less intense than in the Sierra Ladrones.

Structure and Lithology

Bedding features in the quartz-muscovite schist are completely obliterated by metamorphism. Measurable attitudes can be seen only at contacts with other, lithologically different, beds.

Foliation is well developed and macroscopically evident by the parallel arrangement of mica flakes and by porphyroblasts of andalusite. The latter lie in the plane of foliation, but without preferrential orientation of the prism axes. Foliation is also produced by a composition banding: quartz-rich layers alternate with muscovite-rich layers. The latter type of foliation is detectable only in thin section. The general trend of the foliation in the schists is much less uniform than in either the Lower Quartzite or the overlying Hornblende Schists. This is a natural result of the incompetence of these beds when undergoing deformation.

Dips as steep as 62° were measured locally, the average being about 50° to the southeast. The strike generally agrees with the regional trend. In most of the schists drag folds and crenulations on the plane of foliation are developed but only in small sizes (2 to 5 cm.). They vary somewhat in intensity.

The quartz-muscovite schists and also those containing andalusite vary from a light grey to a light olive green on both weathered and fresh surfaces.

The average bedding attitude in the Hornblende Schist generally parallels the regional trend. Foliation as well as lineation is present.

The foliation is expressed through a composition banding (Fig. 11) which is very distinct. Lineation is visible only in thin section, and is produced by a preferred orientation, often nearly perfect, of the hornblende prisms, (Fig. 12).

The rocks are usually a dark green to blackish green which grades to an olive green if appreciable amounts of epidote are present.

The hornblende schists are an unusual rock type containing predominantly hornblende and quartz, locally with epidote, but only little plagioclase. Locally, the texture is gneissic, in other places schistose, and no sharp demarcations exist. Due to the similarity of one bed with another, and due to the lack of continuity of outcrops no one bed could be picked as a marker and traced along the strike for any length.

East of Mule Springs Canyon near the red granodiorite contact a thin bed of chlorite schist is contorted into a multitude of chevron folds, about 5 to 10 mm high. Deformation is very intense in many places and most intense around Cerro Colorado. Drag folds are very common and evidence of more than one stage of deformation may be present. Locally, ptygmatically folded veins of granitic composition occur (Fig. 10).

The intensity of deformation is not everywhere equal as illustrated by figures14 through 17.

In Figure 14 ovoid shapes of quartz with sericitized plagioclase are embedded in a matrix of hornblende prisms. The ovoids produce a crude lineation and foliation by the orientation of their long axes and by their being arranged in layers. Figure 15 shows an almost identical rock. Here the ovoids are decidedly more stretched out and are best described as rods. The rock shows moderate foliation produced by composition banding or compositional layering. The rods have a length to width ratio of about 4:1. The hornblende prisms are aligned generally parallel to

About 3/4 nat. size. Ovoids of quartz and plagioclase in hornblende matrix. Moderate foliation and lineation.

About natural size. Composition identical to that of Fig. 14. Ovoids are stretched into rods which are arranged in crude layers producing foliation.

45x, / nicols. Almost perfectly parallel hornblende prisms and part of a quartz and plagioclase rod in quartz-hornblende schist. Note heavy mineral grains (high relief).

45x, / nicols. Cross-section of the "rods" of Fig. 16. Nearly all hornblende presents basal sections.

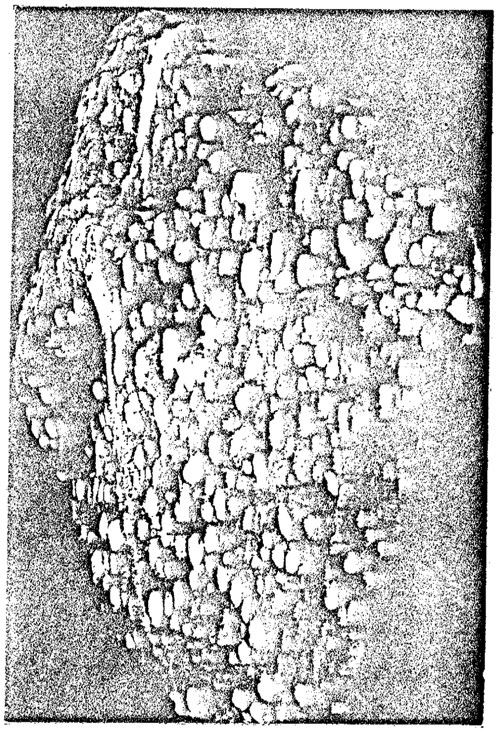

Fig. 14

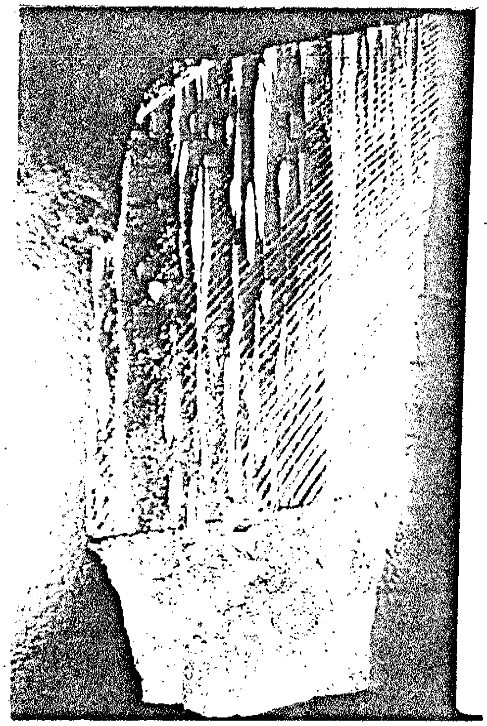

Fig. 15

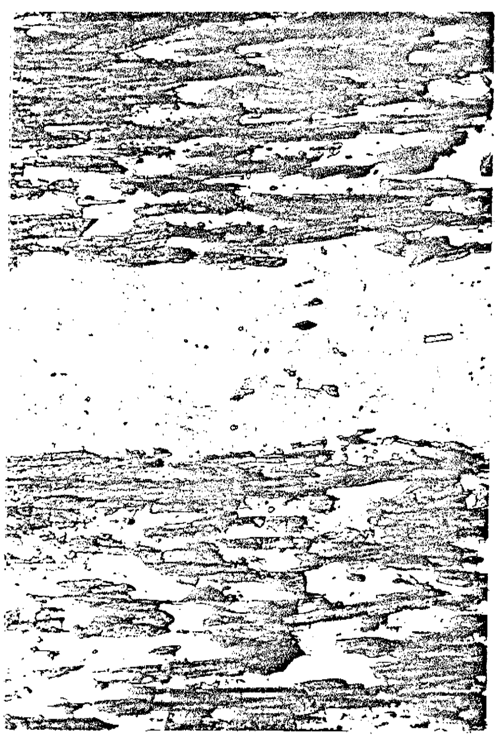

Fig. 16

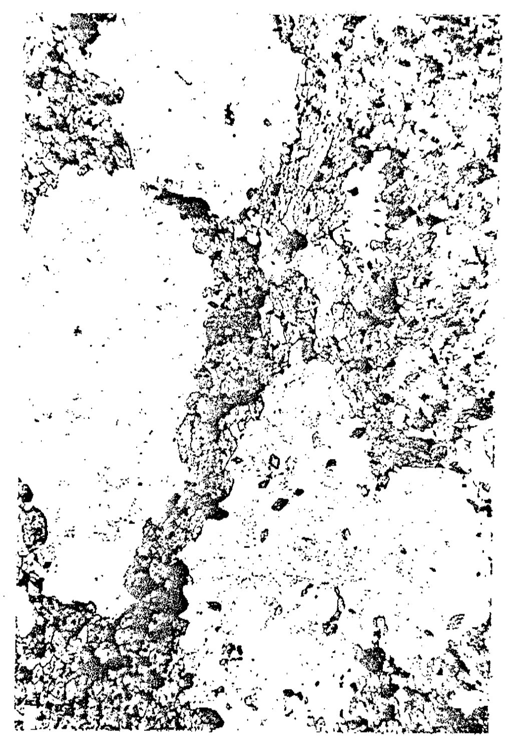

Fig. 17

the composition banding. Some elongation of quartz grains is present.

Figure 16 shows an extreme case. Compositional layering is very pronounced; bands of 50-60% or more hornblende alternate with quartz-plagioclase rods which now are "smeared out" and have a length to width ratio of 10 or 20 to 1. The parallelism of the hornblende prisms is very well defined. Quartz grain elongation is prominent.

Figure 17 is taken from a thin section cut at right angles to the foliation and lineation of the rock from which the thin section of figure 16 was prepared. More or less rounded or elliptical areas of quartz and plagioclase represent the cross section of a rod. These are completely surrounded by hornblende, about 97% of which are basal sections. In this thin section the quartz-plagioclase rods were examined to determine whether the quartz showed a preferred optical orientation. It was found that an unusually high precentage of the quartz occurs as basal sections. Thus the elongation of the quartz is along the c-axis.

The major constituents of the quartz-mica schists are quartz, muscovite and minor biotite. Magnetite and garnets occur as common accessories. Less common are apatite, zircon, rutile and tourmaline; frequently these are enclosed by quartz. Quartz is commonly anhedral, the smaller grains show much strain, while the larger, obviously recrystallized ones are frequently elongated and less strained. The long axes of the elongate grains lie in the plane of foliation as defined by alignment of mica flakes and by composition banding.

Andalusite, identified through its typical crystal form, birefringence, and parallel extinction may be locally as abundant as 10%. Much of it has been replaced by a very fine grained aggregate of chlorite and sericite. The porphyroblasts range from 4 mm to a maximum of 25 mm. One thin section showed an alternating fine and somewhat coarser grained layering which is cut by the foliation at an angle of about 15°.

Differences exist between the hornblende schists of the northern part and the southern part of the outcrop belt. In the north, epidote is a common constituent and locally biotite bearing hornblende schists are found. Chlorite is also a common constituent, but it is evident that the chlorite is a product of retrograde metamorphism because it replaces hornblende with the liberation of iron oxide, mainly magnetite. In the south, epidote is much less conspicuous. Grain sizes of quartz and plagioclase in the north are as small as 20 μ and seldom exceed 20 μ; the hornblende prisms are about 2 to 3 mm. in length. In the south quartz and plagioclase are 100 to 400 μ in size and the hornblende prisms up to 5 mm. in length. Chlorite is rare in the southern outcrops.

Foliation in the north is less well developed than in the south. It is produced by a crude compositional layering. Quartz rarely shows elongation. Chlorite orientation is random. Foliation is also due to alternating fine and coarser layers of quartz. In these layers the coarser grained quartz shows less strain than the finer grained. The coarser quartz grains enclose heavy mineral grains while in layers of finer grained quartz the heavy minerals are interstitial to the quartz grains.

Other constituents in the hornblende schists are magnetite, locally some muscovite and minor accessory minerals. Unusually high concentrations of detrital accessory minerals occur in some of the beds east of Main Ridge. Apatite, zircon, tourmaline and rutile at times reach 1/2 to 1% of the total volume of the rock. The grains are well rounded. Sphene was found locally, having been formed at the expense of ilmenite and/or rutile.

A specimen of hornblende schist taken from a 60 foot thick bed cropping out in Cañon Hondo contains 50% fine grained quartz ranging from 10 to 100 μ in size. Forty per-cent of the rock is hornblende in prisms up to 1 mm. in length; chlorite occurs as a replacement of hornblende, and shows very slight parallelism to the foliation. Magnetite and epidote in about equal amounts comprise the remaining 10% of the rock and are disseminated throughout. Foliation in the massive appearing hand specimen is defined by composition banding and alignment of hornblende prisms. The rock is designated quartz-hornblende schist and the chlorite is due to retrograde metamorphism.

A specimen of hornblende schist from northeast of Cerro Colorado, near the base contains the following constituents: Quartz, 50%; hornblende, 25 to 30%; biotite 15%; epidote 4 to 5%; magnetite 3%; very little plagioclase. Grain size from 10 μ to 1/2 mm. maximum. Biotite is green and pleochroic. Plagioclase is near $Ab_{83}$ in composition. Quartz is unstrained and slightly elongated. Well developed foliation results from composition banding, alignment of biotite shreds and hornblende prisms as well as a slight quartz elongation. The rock is designated quartz-hornblende-biotite schist.

Effects of Metamorphism

The quartz-muscovite schists have undergone far-reaching reconstitution and recrystallization of the original component minerals. Bedding is completely obscured by the foliation and the recrystallization. The presence of andalusite cannot be explained as the result of contact metamorphism, as no intrusive is known to exist to which it could be attributed. The data on stability fields of the $Al_2SiO_5$ polymorphs is conflicting and apparently all three polymorphs can occur in rocks produced by regional metamorphism.

On the basis of typomorphic minerals these schists are assigned to the kyanite-almandine-muscovite subfacies of the almandine-amphibolite facies. Turner and Verhoogen give 550° as minimum temperature and a possible maximum of 750°C; pressures range from 4000 to 8000 bars.

Deformation in the Hornblende Schist is variable, but appears stronger than in the Lower Quartzite. Drag folds, segregation banding, elongation of quartz-plagioclase rods, local gneissic textures and ptygmatically folded veins testify to the intensity of the deformation and differential movements.

Recrystallization has resulted in a revision of the mineralogy without much addition of material. The hornblende schists show idioblastic growth of quartz during metamorphism.

Classification of these schists is done on the basis of typomorphic minerals of the amphibolite facies (Turner and Verhoogen). The presence of chlorite, which replaces hornblende, is due to retrograde metamorphism. The assemblage most closely fitting is hornblende-plagiocalse-almandine-epidote (quartz-biotite) with only plagioclase missing, or being very low, in these hornblende schists under discussion. This assemblage belongs to the almandine-amphibolite facies, staurolite-almandine subfacies. Temperatures and pressures during metamorphism for this subfacies lie in the lower region of 550° to 750°C and 4,000 to 8,000 bars.

The presence of composition banding would allow the rock to be classified as a gneiss. According to Turner and Verhoogen, composition banding indicates higher-grade metamorphism than would be indicated by the above mineral assemblage. The gneissic phases of the hornblende schists

Fig. 18: Looking SW toward Cerro Colorado. The pattern of outcrop suggests strongly a bedded sequence. In the foreground typical vegetation of the lower faunal zone; tree cholla and creosote bush with occasional cedars.

Fig. 19: Two pediment surfaces in the southeastern part of the map area.

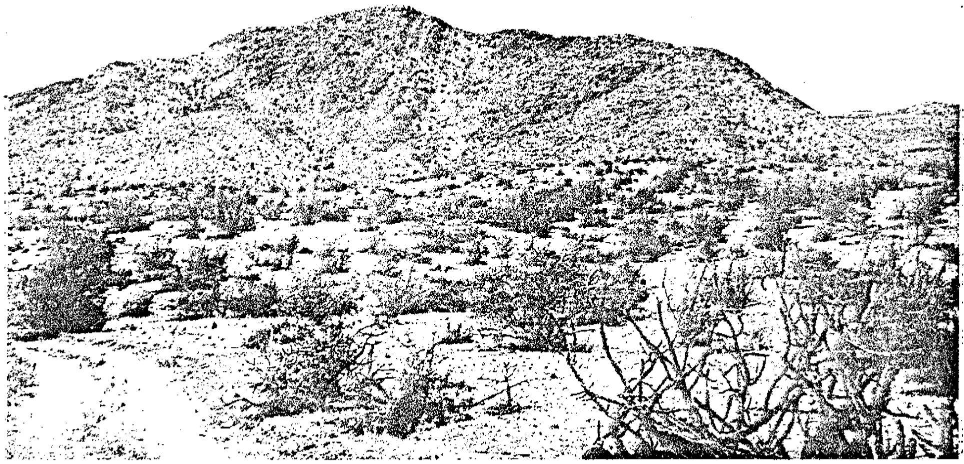

Fig. 18

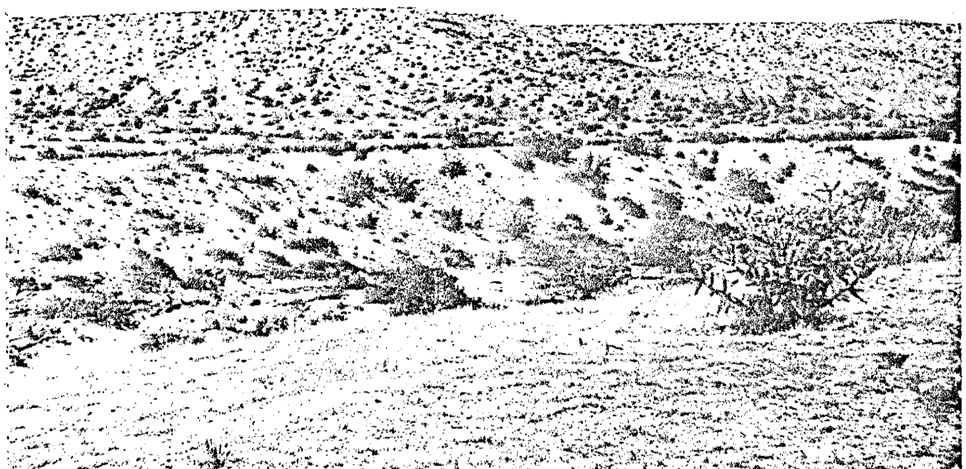

Fig. 19

might, therefore be the result of temperatures in the high portion of the range indicated above, i.e. about 650° to 750°C.

Upper Quartzite

The Upper Quartzite crops out on the southern Loma de Silla, on Cerro Colorado and at the southeastern contact of the red granodiorite.

The Upper Quartzite is distinguished from the Lower Quartzite by finer grain size, less purity and more interbedded muscovite and hornblende schists.

The contact with the underlying Hornblende Schist is not exposed, except south of Loma de Silla where it appears conformable. Outcrops are less prominent than those of the Lower Quartzite. In some of the roof pendants, principally east of the map area, bluish quartz grains with an opaline appearance occur.

The Upper Quartzite is correlated with Stark's White Ridge quartzite of the South Manzano Mountains. Correlation is made on the basis of the sequence of lithologically and mineralogically similar units. The exact thickness of the White Ridge quartzite is uncertain. The eastern flank of the main syncline in the Los Pinos Mountains contains a thickness of 3700 feet, believed to be due to repetition through faulting. The western flank of the syncline contains 200 to 500 feet, and Stark believes that erosion has taken place prior to the deposition of the next higher unit, the Sevilleta metarhyolite.

No attempt is made here to give a thickness of the Upper Quartzite.

Structure and Lithology

On southern Loma de Silla and on Cerro Colorado the average strike of foliation and bedding in the Upper Quartzite where recognizable, is northerly, with dips from 40° to 85°, the average being about 60° to the east. The area between the Cerro Colorado Fault and the older granodiorite is characterized by strikes of N45E with dips ranging 35° SE to

Fig. 20: Outcrop of intensely folded quartz-hornblende gneiss, NE of Cerro Colorado. The anticlines in the center of the picture plunge steeply east, and are the result of a later E-W deformation. Height of picture about 30 feet.

Fig. 20

vertical.

Foliation is fairly well-developed due to the micaceous nature of the beds. Foliation and bedding coincide, where the latter is recognizable, mainly at contacts of different beds. The grain size is much finer than in the Lower Quartzite and there are compositional differences as well. Some of the units in the Upper Quartzite are arkosic, and some of the beds have well-developed gneissic texture.

The major constituent is quartz; however, microcline, plagioclase, muscovite, biotite and epidote occur in significant amounts in some of the beds. A specimen from the crest of Cerro Colorado had the following characteristics (thin section): Quartz (75%), mainly in grains from 50 $\mu$ to 0.5 mm., occurs with about equal amounts of microcline and plagioclase (total 24%). Biotite shreds (1%) are disseminated throughout and outline a feeble foliation. The foliation is strongly expressed by an alternation of finer and coarser grained layers. Elongation of quartz parallel to this foliation is marked. Fracturing parallel to the foliation is evident, the fractures being filled with secondary limonite.

Another specimen from the same general area as the one described above exhibited the following:

Strongly strained quartz (predominant) is intergrown with minor feldspar and epidote in a very fine grained texture, exhibiting a marked foliation. Quartz varies from about 50 $\mu$ to 0.5 mm. and the intergrowth between grains is serrate. Some of the larger grains show a definite elongation. A layering of the constituents in bands of finer and coarser grain sizes produces a distinct foliation. Small quartz grains have a cloudy appearance, while the coarser ones are clear. This suggests recrystallization, because overgrowths are not detectable.

Effects of Metamorphism

At the northern end of Cerro Colorado several thin quartzite beds crop out which are believed to be part of the Upper Quartzite. These beds may be near the contact between the Upper Quartzite and the underlying Hornblende Schist. These beds exhibit the strongest deformation seen in the area (see Frontispiece). Several antiforms are seen in one outcrop; the width from limb to limb is somewhat variable, but averages about 1-1/2 feet. Intense deformational stresses have produced parallel shears which separate the antiforms from one another. No synforms are present.

Recrystallization is common in thin sections of these beds; quartz in general is most strongly affected, but other constituents are also involved. The larger grains of microcline and plagioclase are of metamorphic origin, as is also epidote.

The assemblage quartz-microcline-plagioclase-biotite (muscovite-epidote) which is found in the Upper Quartzite is the typical one in quartzo-feldspathic rocks of the staurolite-almandine subfacies, almandine-amphibolite facies of Turner and Verhoogen. The temperature at which metamorphism of these rocks occurred may have been approximately 600° and up to a possible maximum of 700°C.

Northwest of Cerro Colorado a group of rocks has been mapped as Upper Quartzite, however, these rocks have a fine grained gneissic texture and they grade northward almost imperceptably into non-foliated, medium to coarse grained, red granodiorite. The Upper Quartzite mapped on Cerro Colorado grades southward into granodiorite Augen Gneiss.

45x, // nicols. Schist exhibiting segregation banding: biotite-rich layer between quartz-rich layers.

45x, // nicols. "Fluidal" texture produced probably by recrystallization under effects of a shear

45x, // nicols. Possible indication of shear planes, slip cleavage, in quartz-muscovite schist.

45x, // nicols. Local concentration of epidote parallel to foliation in quartz hornblende schist.

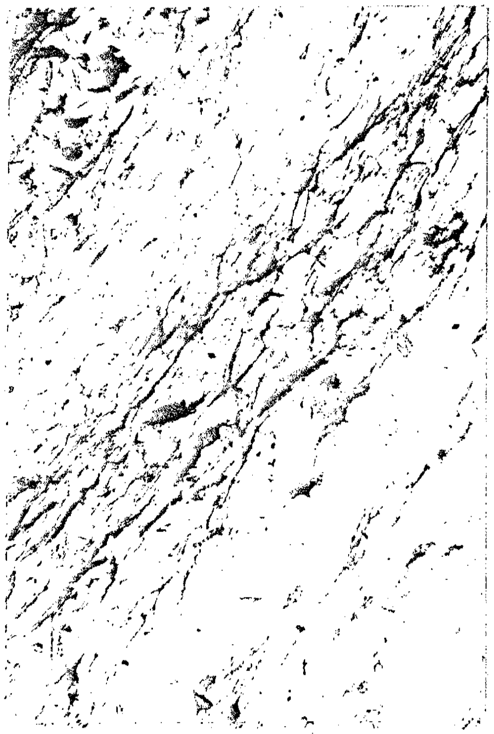

Fig. 21

Fig. 22

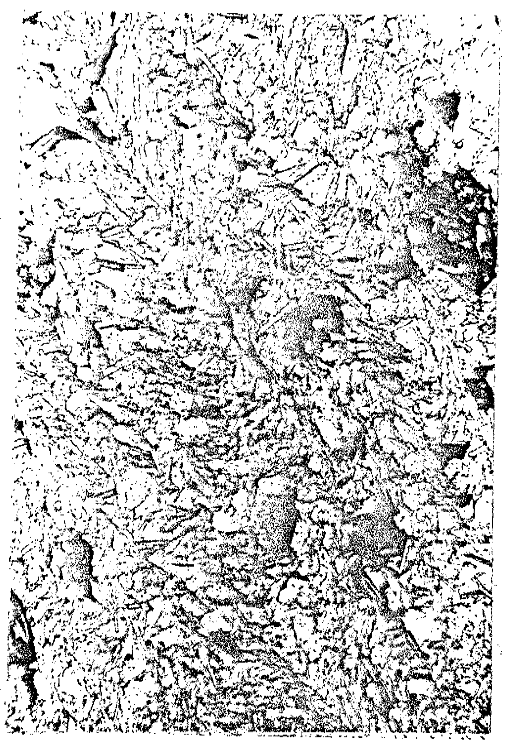

Fig. 23

Fig. 24

Massive Amphibolites

There are two areas of amphibolite outcrops. The northwesternmost is approximately 400 feet thick and is known to extend over one mile along the strike.

The other is massive, and is found about 1/2 mile southwest of Loma de Silla. The area in which the latter crops out is roughly 500 by 1500 feet. This rock is believed to be partly covered by the overlying Mississippian beds to the west. It is unique in that it contains garnets which are visible macrospically, the only significant occurrence in the area.

Small bodies of amphibolite are found as roof pendants in the younger granodiorite; these bodies were too small to be shown on the map.

Structure and Lithology

Amphibolites on the whole appear massive and lacking foliation, even microscopically. The dominant color of these rocks is dark green to almost black and they contain occasional, irregularly distributed light grey to white spots. Constituents are hornblende, in random orientation, and plagioclase. Epidote, garnet and magnetite are present as minor constituents.

On of the roof pendants in the younger granodiorite contains an amphibolite bed, about one foot thick, which is folded into a tight, almost isoclinal fold, the axis of which is near horizontal.

A specimen from the outcrop southwest of Loma de Silla is massive and coarse grained with individual grains up to 5 mm. in diameter. The plagioclase (30%) is oligoclase and intensely sericitized. Green hornblende, in well developed idiomorphic grains amounts to 60% of the rock.

Some garnets are present, and these are anomalously anisotropic. Minor epidote (var. pistacite) occurs. Magnetite, often in clusters, is disseminated throughout the rock and shows some skeletal growth (Fig. 2). An interesting feature is that plagioclase contains fractures, which follow crystallographic directions, along which hornblende crystals have grown, penetrating into the sericitized feldspar (Fig. 3). Alteration of the hornblende to chlorite is very minor.

Ilmenite occurs in varying amounts in the amphibolites. A common alteration of the ilmenite is to sphene. Ilmenite grains are surrounded by a rim of sphene, which may vary in thickness; sometimes only sphene is present, all of the ilmenite having been replaced.

Effects of Metamorphism

Formation of sphene from ilmenite in the amphibolite has occurred during metamorphism. Forster (1948) and Dal Vesco (1953) report the occurrence of sphene reaction rims about ilmenite and rutile from the Locarno region of Switzerland. In many cases the reaction there has gone so far as to leave only a relic of rutile or ilmenite enclosed by sphene. This formation of sphene is reported from many types of metamorphic rocks containing rutile and/or ilmenite, especially Ca-rich eclogite-amphibolites, plagioclase-amphibolites, garnet-amphibolites and biotite-amphibolites (European terminology).

The alteration texture is most readily explained by the chemical reaction:

$$\underset{\text{Ilmenite}}{FeTiO_3} + CaO + SiO_2 \longrightarrow \underset{\text{Sphene}}{CaTiSiO_5} + FeO$$

According to Turner and Verhoogen the assemblage: Hornblende-plagioclase-almandine-epidote is typical of the staurolite-almandine subfacies of the almandine-amphibolite facies. This assemblage is also typical for having been derived from basic igneous rocks. According to them, "co-existence of a medium plagioclase ($An_{25}$ to $An_{45}$) with epidote is common in these rocks and indicates high load pressure...". In the specimen examined plagioclase was found to be oligoclase. Due to intense sericitization a precise determination of the percent anorthite in the feldspar could not be made.

Turner and Verhoogen conclude that for the almandine-amphibolite facies, temperatures range between 550°C and 750°, and pressures range between 4,000 bars and 8,000 bars. The staurolite-almandine subfacies corresponds to the lowest grade of metamorphism in the almandine-amphibolite facies; therefore, the lower figures given above are the more likely ones. It is also pointed out that the presence of hornblende and muscovite indicate that high water pressures prevailed.

### Granodiorite Augen Gneiss

A coarse grained, red augen gneiss is exposed over much of the southern half of Cerro Colorado, in what would normally be the stratigraphic position of the Upper Quartzite. A gradational lateral contact between these two rock types is present.

Some contacts between the Augen Gneiss and quartzite beds are knife edge-like, with no evidence of faulting causing such abrupt relationships.

The relative resistance to weathering of the Augen Gneiss and the related Upper Quartzite makes Cerro Colorado a prominent topographic feature.

#### Structure and Lithology

The foliation in the Granodiorite Augen Gneiss is less well developed than that in the Upper Quartzite. The few measurable outcrops accord with the regional trend. In this southern part of the map area the strike of the foliation is generally within a few degrees of due north. Lenses of interbedded or infolded hornblende schists represent a later, E-W stage of deformation.

Bedding as defined by lithologic variation in the gneiss cannot be recognized. However, the foliation in the gneiss is parallel to contacts with quartzite beds. Several faults are exposed, but their displacements are indeterminate and they could not be traced.

The augen gneiss consists of approximately 20% quartz, 20% biotite and chlorite, the latter being an alteration product of biotite, and 60% combined microcline and plagioclase. Both feldspars occur in somewhat varying amounts but are usually equally abundant. The color of the augen is pink to light red and this gives the whole rock a reddish tone. Quartz is generally milky white to colorless; the biotite and chlorite are dark brown to greenish brown, depending on the amount of chlorite.

The augen consist of aggregates of microcline and oligoclase, individuals reaching 5 cm. in length and 2 to 3 cm. in width; the average size is about 4 by 2 cm. Many of the augen contain broken feldspar grains. Small fragments of feldspar are commonly concentrated near the ends of the augen (in "eddies"), in a typical mylonitic texture. Quartz grains and augen are elongated and parallel and define a foliation. Biotite and chlorite are fine grained and they envelop quartz and feldspar in a fluidal texture (Similar to Fig. 22).

Lenses of pegmatitic material are found within the augen gneiss; these are parallel to the foliation of the gneiss and reach a maximum length of about 300 feet. Their width is variable from a few inches to nearly 2 feet. No foliation is found in the pegmatites. They are coarse grained and consist of pink feldspar and milky to colorless quartz. The composition is essentially that of the gneiss except the mafic constituents are completely lacking. The augen gneiss in contact with the pegmatites does not show any higher content in mafics.

Effects of Metamorphism

The composition of the augen gneiss and its stratigraphic position indicate that it is the equivalent of the Upper Quartzite, or at least part of it. Some beds of the Upper Quartzite are arkosic in composition, and through metamorphism and mylonitization were converted to the Augen Gneiss. The more siliceous beds, fairly clean sandstones, reacted to the same conditions with the development of mica and recrystallization of quartz. Pure quartzite beds and augen gneiss layers are interbedded occasionally, and the knife edge contacts show no evidence of faulting or intrusion.

Gneiss is considered the product of deep seated, intense regional metamorphism, without metasomatic activity being necessary. The granulite facies, to which gneisses belong, has been subdivided into a pyroxene-granulite subfacies and a hornblende-granulite subfacies (Turner and Verhoogen). Pelitic and quartzo-feldspathic assemblages in the hornblende-granulite subfacies are quite similar to those in the almandine-amphibolite facies. Temperatures of formation are given as between 700°C and 800°C, the lower figure being more likely for the hornblende-granulite facies. Turner and Verhoogen believe that even with high partial pressures of $H_2O$ pyroxene will be formed, rather than amphibole, if the temperature is sufficiently high.

Since the Augen Gneiss is not strictly a granulite, the possible temperature reached during metamorphism may have been around 700°C or slightly below. The close spatial association of the hornblende schists with their gneissic texture and the augen gneiss suggest fairly high temperatures for their formation. A possible maximum of 700° to 750°C may have been reached.

Red Granodiorite

A red granodiorite crops out in a N-S trending belt about 3 miles long in the eastern part of the map area. The width of exposure varies from about 400 feet in the northernmost part to about 4,000 feet in the central and southern parts.

The western contact is with the Hornblende Schist, and the contact is parallel to the foliation of this schist. In the east the contact is of an intrusive nature formed by the younger granodiorite. The southwestern boundary is formed by the Ladron Fault, which brings granodiorite in contact with Hornblende Schist. In the southeast the contact is much obscured but it seems to parallel the foliation in the Upper Quartzite.

Another outcrop area of granodiorite is on the northern portion of Loma de Silla and is gradational with metasediments mapped as Upper Quartzite. Interbeds of hornblende schist extend well into the non-foliated granodiorite.

The red granodiorite weathers readily, producing arkosic, coarse sand which blankets most of the area except for the steeper slopes. Vegetation is more abundant than over quartzites but not as abundant as over hornblende rich rocks. The general color of the rubble is similar to that of the fresh rock. Some limonite staining is present. The color of the rubble has been used to map approximate contacts where outcrops were lacking.

Structure and Lithology

The granodiorite has a predominant reddish color which is produced by the red color of microcline feldspar. Quartz is white to colorless, as is plagioclase. The mafic constituents are low in abundance; biotite is most common, but hornblende has been noted; muscovite occurs sparingly. Chlorite is a common but not abundant product of alteration of the mafic constituents. The grain size is fairly uniform, about 3 to 8 mm., and no evidnece of porphyritic texture has been observed. Foliation is nonexistent except for a few local occurrences.

Inclusions have been noted in the belt of granodiorite east of the Hornblende Schist; these consist principally of hornblende schist or similar basic rock types, and they do not show evidence of alteration. Inclusions are also found in the Loma de Silla area.

Effects of Metamorphism

The contact between the Upper Quartzite and the Red Granodiorite on Loma de Silla is almost imperceptably gradational.

Some of the fine grained, relatively pure quartzite beds extend north into the granodiorite outcrop area. Grain size in these units remains fairly constant as the contact zone is approached. Other, micaceous and arkosic units show an increase in feldspar and biotite, and coarsening of grain size as the contact is approached and these cannot be traced once they are within the granodiorite outcrop area. Interbeds of hornblende schist in the southern part of Loma de Silla can be traced northward and they persist undisturbed within the granodiorite. A few of the beds are locally mylonitized and they grade northward into coarser grained rocks.

This rock cannot be classified into a metamorphic facies; but since all of the rocks enclosing it are of the staurolite-almandine subfacies, almandine-amphibolite facies the red granodiorite is assigned to the same facies.

## Younger Granodiorite

The eastern margin of the map area south to the Cerro Colorado Fault is occupied by an intrusive, granodioritic in composition. This intrusive extends northward for several miles and also eastward for a short distance and the outcrop pattern is elongated north-south.

### Structure and Lithology

The younger Granodiorite is medium to coarse grained and has a seriate (4-8mm.) texture. The contact on the west is an intrusive one with the red granodiorite and metasediments. Roof pendants are small but numerous, and where foliated rocks of Precambrian age are included a partial assimilation produces foliation in the intrusvie. Generally, however, the contacts are quite sharp and little evidence exists for assimilation. No effects of contact metamorphism have been observed in the Precambrina metasediments. Xenoliths are present in some areas,not in others.

The granodiorite is light grey to buff to almost white; mafic constituents are minor. Principal constituents are microcline, oligoclase and quartz, with muscovite being more abundant than biotite. Zircon, tourmaline and apatite occur as accessories.

Locally dike-like bodies or irregular patches of slightly lighter color than the main mass of the intrusive may be either aplitic or slightly pegmatitic. The margins of these bodies are usually not well defined, norcan they be traced for any large distance.

The granodiorite weathers to typical well rounded forms, and locally, spheroidal weathering is prominent. The weathered rock is quite friable and solid samples for thin sectioning are difficult to obtain.

Jointing in the granodiorite is common but definite sets of joints were not mapped.

# PALEOZOIC ROCKS

## Mississippian

The oldest of the Paleozoic sediments are rocks belonging to the Caloso formation and Kelly formation. These occur west of Cerro Colorado (Armstrong, 1958), where the Caloso formation rests with disconformable contact on Precambrian amphibolite. It consists of a basal bed, about 2 to 4 feet thick, of arkose and quartz sandstone, overlain by reddish shales, grey and brown sandstones and a dense, finely crystalline limestone. The total thickness is about 30 feet.

Overlying, with apparently slight unconformity, is the Kelly formation, consisting of crinoidal and locally medium crystalline limestones with chert stringers. This formation has a maximum thickness of about 50 feet; this small thickness is partly due to erosion prior to deposition of the Pennsylvanian beds.

## Pennsylvanian

The prominent hogback in the western part of the map area is made up principally of rocks belonging to the Magdalena group.

The lower part, the Sandia formation, rests unconformably over the Kelly formation and consists of sandstones, shales and limestones. The upper part, or Madera limestone, consists of bluish-grey, thick bedded and massive limestone. Box Canyon, formed by the Rio Salado cutting through this sequence, affords a good exposure. A total thickness of about 2,800 feet is present there (Armstrong, personal communication).

East of Cerro Colorado, on the west side of Cerro Colorado Fault are some scattered outcrops which may be correlative with the Sandia formation.

Permian

No rocks of Permian age are exposed in the Sierra Ladrones. It is believed, however, that they may be present in the downthrown block east of Cerro Colorado Fault.

Richter (1950) describes approximately 1500-2000 feet of Abo, Yeso and San Andres formations from the western part of the Riley Quadrangle. This area is immediately west of the map area.

# MESOZOIC ROCKS

No Mesozoic deposits are exposed in the Sierra Ladrones. Tonking describes these from the Puertecito Quadrangle, where approximately 3,400 feet are present. These belong to the Triassic Chinle formation and the Cretaceous Mesaverde group (Dakota ss., Mancos sh., La Cruz Peak fm., Crevasse Canyon fm.).

The author believes that these rocks may also be present in the down-thrown block of Cerro Colorado Fault.

# C E N O Z O I C   R O C K S

## Tertiary? Basic Dikes

Many small basic dikes cut the younger granodiorite, and other Precambrian rocks. Their length along the strike is usually too short to be shown on the map.

### Structure and Lithology

The dikes post-date the intrustion of the younger granodiorite. Their borders are chilled, but interpretation is difficult because of the intense alteration of the dikes themselves.

The predominant strike of the dikes is northerly to northeasterly with dips steeply east to nearly vertical.

The dikes were probably basaltic in composition; they consist now of plagioclase and calcite with minor disseminated magnetite. All of the former mafic constituents are altered although a diabasic texture is recognizible. .

## Tertiary Popotosa Formation

In the southeastern part of the map area the Popotosa formation (Denny, 1940) is exposed. It is in fault contact with Precambrian and Pennsylvanian rocks along the Cerro Colorado Fault. To the east it is partly covered by overlying pediment gravels.

### Structure and Lithology

The Popotosa formation is a volcanic conglomerate, predominantly of dark red to purple color. Boulders up to 2 feet in diameter are enclosed in a dominantly sandy matrix. Practically all of the material is of volcanic origin. Bedding is ill defined; sparse sandy or silty interbeds, in the form of lenses, determine the attitudes. The strike is northerly and dips vary strongly, from about 35° to 68° to the west.

The outcrops in the mapped area cover about 2 square miles and an approximate thickness of 3,000 feet is indicated, unless duplication by faulting has occurred. To the east of the map area outcrops of the Popotosa formation continue for a few miles, but the exposures are partly concealed by overlying pediment gravels.

## Quaternary

Pediment gravels are found along the slopes of Cerro Colorado, overlying the southern end of the Tertiary granodiorite and covering part of the Popotosa formation. Material in the gravels is of mixed origin. In the gravels of Cerro Colorado Precambrian fragments dominate. Following up toward the slopes of Cerro Colorado the percentage of Precambrian rock fragments increases until it becomes impossible to differentiate between the pediment gravel and rubble.

In the area of the Popotosa formation two definite pediments are present (Fig. 19). The surface around Cerro Colorado lies topographically higher and may possibly represent yet another surface. The other possibility is that since the formation of these pediments movement along the Cerro Colorado Fault has produced the difference in elevation.

Alluvium is present in practically all of the canyons and washes. The thickness is variable but does not exceed about 15 feet.

# STRUCTURE

## Faults

Two major faults occur in the mapped area, Cerro Colorado Fault and Ladron Fault. Both are high angle normal faults with relatively large displacements. Cerro Colorado Fault is believed to be still active. Some faults of small displacement are also present.

A strong lineation was noticed on the aerial photographs through the younger granodiorite. Checking in the field revealed that a fault zone is a possible interpretation, but that the same pattern could be produced by tightly spaced joints. Some few slickensides were found on the fracture planes but because the feature was observed only in the younger granodiorite, no displacement was detectable.

## Cerro Colorado Fault

Cerro Colorado Fault is marked by an abrupt change in strike where Ladron Fault joins it. North of the junction it trends NE, and to the south it strikes southerly.

The block lying to the east of Cerro Colorado Fault has moved down in relation to the block to the west. The throw is believed to be more than 15,000 feet.

Cerro Colorado Fault is one of the main faults of the western border of the Rio Grande Graben. Precambrian and Pennsylvanian rocks are in fault contact with the Tertiary Popotosa formation. Other faults may exist further east of Cerro Colorado Fault but they are not readily identifiable in the Popotosa formation.

The continuation of Cerro Colorado Fault is obscured south of the Rio Salado and to the east of the map area.

Assuming that Paleozoic, Mesozoic and Cenozoic rocks described from surrounding areas (Denny, 1940; Richter, 1950; Tonking, 1957;) continued across the Sierra Ladrones prior to the uplift of the Sierra Ladrones horst, throw along Cerro Colorado Fault is on the order of 12,000 feet. If the difference in elevation between the outcrop of the fault and Ladron Peak is added (about 4,500 feet) the structural relief is at least 16,500 feet.

Dr. A. Sanford (personal communication) has run several gravity profiles across the Rio Grande depression to determine the depth to the Precambrian basement. His observations are that the western part of the depression is sharply faulted and the eastern part step-faulted.

Differences in elevation on pediment surfaces on either side of the fault suggest that movement has taken place since these pediments were formed. This is best illustrated in the central area. North of Cerro Colorado Fault some pediment remnants are between 6,000 and about 5,900 feet, south of the fault elevations are 5,700 - 5,600 feet. Thus an approximate 200 feet difference in elevation has occured along Cerro Colorado Fault since formation of the pediments.

An epicenter for an earthquake in summer 1960 was tentatively located (Sanford and Holmes, 1961) in the vicinity of Cerro Colorado Fault, and suggests that this fault is still active. These epicenters may be in error because of horizontal refraction of the seismic waves. The writer checked at that time in the field for possible evidence of displacement visible in the zone of the Cerro Colorado Fault but could not find any. This, however, does not rule out that a displacement had actually occured on Cerro Colorado Fault.

Ladron Fault

Ladron Fault extends from its junction with Cerro Colorado Fault in a northwesterly direction. In most of the mapped area, Precambrian rocks are on either side of the fault. To the northwest Pennsylvanian sediments are brought in fault contact with Precambrian. Both dip slip and strike slip components are recognized with the eastern block moving up and south with respect to the western block.

Evidence for the vertical displacement is found 1/2 mile north of Loma de Silla where drag in Pennsylvanian beds indicates the relative displacement. The apparent throw is at least 1,300 feet, calculated from the differences in elevation of the base of the Carboniferous and Ladron Peak.

The apparent strike slip is about 9,000 feet, as determined from the Precambrian red granodiorite offset, although the easterly dipping contact between the Red Granodiorite and Hornblende Schist can produce the same offset with only vertical movement along Ladron Fault.

A few faults crop out which can be followed for short distances along the strike, and whose displacements could either not be determined or are small. Some of these are shown on the map, other, too small to be plotted, are omitted.

In the outcrop shown on the Frontispiece shearing parallel to axial planes is conspicuous. Such faulting and the preserving of antiforms is related to strong deformation during regional metamorphism.

Folding

Large scale folds have not been seen in the map area, only effects of them. Drag folding is common in hornblende schists and was measured where it was strongly developed. Contorted layering in the quartzites is present near contacts with other units but orientations of the almost-drag folds could not be determined accurately. Chevron type folds of small scale are found in a greenschist lens east of Mule Springs Canyon near the Hornblende Schist - Red Granodiorite contact. Strong folding is found just north of Cerro Colorado, where the photographs were taken shown in figure 20 and the frontispiece.

The exposed lithologic units on Main Ridge suggest a continuous sequence striking about N30E and dipping SE, however the 5400 feet of Lower Quartzite is suggestive of repetition of beds by folding and/or faulting.

The wedge of muscovite schist which lies within the Lower Quartzite north of Lome de Silla pinches out rapidly northeasterly and may be either a tight, plunging anticline or is faulted off at a small angle with the bedding along its eastern contact.

The long septum of hornblende gneiss immediately east of the crest of Cerro Colorado is possibly a tightly folded unit.

# M I N E R A L I Z A T I O N

No mineralization related to the Precambrian red granodiorite has been found.

Scattered thin veinlets carrying mainly galena are found in the Precambrian red granodiorite on Loma de Silla. These are not of economic value. Lead isotope dating (Austin, personal communication) has determined these to be of possible Laramide age.

The Juan Torres Mine, in Precambrian red granodiorite supposedly was worked at the beginning of this century. Galena, fluorite and amethystine quartz were the principal minerals present. At the time of mapping this mine was inaccessible.

In the same general region several small prospect pits were found. These had been dug where some faint copper stains (malachite) were evident along fractures in the rocks.

# D I S C U S S I O N

Strained quartz occurs commonly in rocks which have undergone deformation, be it through faulting, folding or dynamometamorphism.

In the Sierra Ladrones all rock types containing quartz exhibit this feature. Examination of thin sections revealed that in any one rock the finer grained quartz (0.02 to 0.05 mm. approx.) is more strained than the coarser grained quartz (0.5 to 1.5 mm. approx.).

A study was made then, measuring how many degrees the microscope stage had to be turned in order that an "extinction front" would traverse a unit distance. This was done on several thin sections containing both fine and coarser grained quartz. Measurements were always taken at right angles to the "extinction front".

Approximately 30 to 50 grains of both grain sizes of quartz were measured in each thin section.

The following result was obtained:

In the coarser grained quartz the stage had to be turned 1° in order that the "extinction front" traversed the unit distance, while in the finer grained quartz the stage had to be turned 10° to traverse the same distance.

This indicates that the finer grained quartz is under considerably more strain than the coarser grained quartz, which has recrystallized.

Recrystallization of the coarser grained quartz is further substantiated by detrital accessory mineral grains being enclosed by it. In the finer grained quartz, on the other hand, the detrital accessory mineral grains occur interstitially to quartz.

Since recrystallization tends to eliminate strain the strain in the coarser grained quartz are probably due to later occurring deformational stresses.

Overgrowths of quartz are not present which suggests that the grain size of quartz was originally small.

The Lower Quartzite consists of beds or layers of predominantly quartz with minor magnetite and/or hematite, muscovite, sericite, apatite, zircon, sphene and tourmaline. Thin quartz-muscovite schists are interbedded or possibly infolded. On the basis of typomorphic minerals found in some of the less pure beds or layers the Lower Quartzite is assigned to the staurolite-almandine subfacies of the almandine-amphibolite facies.

Grain size is fairly uniform, but recrystallization has occurred and quartz-grain elongation is locally prominent. A faint cross-bedding-like feature was observed in several outcrops. Whether it is cross-bedding or due to fracture cleavage is uncertain.

The high quartz content (up to 98%) and the apparent well sorted character suggest that the Lower Quartzite was derived from quartz sands which were probably deposited on a stable shelf area.

The lower 200 feet of what is mapped as Hornblende Schist consists of quartz-muscovite schist and quartz-muscovite-andalusite schist. These beds contain quartz, muscovite, some biotite and locally andalusite. Accessories include magnetite, apatite, zircon, rutile and tourmaline. A few garnets are present but it cannot be ascertained whether these are of detrital or metamorphic origin.

The mineral assemblage is typical for that of pelitic sediments having undergone regional metamorphism; they are classed as belonging to the almandine-amphibolite facies.

A striking feature in the Lower Quartzite is the pinching out of a quartz-muscovite schist; within about 2500 feet this bed thins from almost 1,000 feet to nothing. This may be due to a fault which nearly parallels the bedding, or to a tight and plunging fold.

The Hornblende Schist proper is a series of predominantly hornblende schists and quartz-hornblende gneisses with minor interbedded muscovite schists and quartzites. Dominant minerals are quartz, hornblende and locally epidote with zircon, apatite, tourmaline and ilmenite. Sphene has been derived from ilmenite during metamorphism. Chlorite is a product of retrograde metamorphism.

The outcrop pattern suggests a layered body. It could originally have been an intrusive sheet, but the presence of detrital, accessory minerals rules out the igneous origin and confirms sedimentary origin. No individual bed or layer was so significantly different from the enclosing rocks that it could have been useful as a marker bed. Part of the total thickness exposed may be the result of repetition of beds due to their incompetence.

The quartz-hornblende schists are unusual rocks and a search of the literature has not revealed rocks of similar mineralogical composition. The original rock may have been a ferruginous, quartz rich sediment. On the other hand metasomatic processes may be responsible for the unusual mineralogy.

Hornblende schists have locally a definite gnessic texture, which could be called a pencil gneiss. The rods or pencils consist of quartz and plagioclase. In some areas the varying intensity of stretching of these rods is remarkable. Compressional forces alone could hardly have produced a texture of this kind. Shearing which produced a "rolling" effect could account for the "pencils"; Craig (1960) has explained a pencil gneiss to have been produced by "rolling" in the Red Mountain Area, Connecticutt.

All of the rocks mapped as Hornblende Schist belong to the staurolite-almandine subfacies of the almandine-amphibolite facies. The rocks having gneissic texture reflect probably somewhat higher temperatures and pressures of formation.

The Upper Quartzite is a series of quartzites with interbedded mica schists. Some of the quartzite units are arkosic and in general finer grained than the Lower Quartzite. The predominant constituent is quartz; however microcline, plagioclase, muscovite, biotite and locally epidote occur in fair amounts. The presence of micas produces a distinct foliation in most units and locally a gneissic texture becomes evident. The latter is especially prominent on southern Loma de Silla, where a gradational contact exists with the red granodiorite and on Cerro Colorado where Upper Quartzite grades into Augen Gneiss.

Some thin quartzite beds just north of Cerro Colorado are folded into tight isoclinal folds and shearing parallel to the axial planes has taken place. This testifies to the intense deformation that has occured.

The Upper Quartzite is placed in the staurolite-almandine subfacies of the almandine-amphibolite facies. The gneissic texture occuring locally suggest higher temperature and pressure of formation. Mylonitization which is also present in some places suggests intense deformation.

The Amphibolite consists of plagioclase and hornblende with minor magnetite, ilmenite, epidote and garnet. From the outcrop pattern an intrusive origin is suggested, as is also from the mineralogical composition. The outcrop in the northwest of the map area appears sill like in the Lower Quartzite while the outcrop southwest of Loma de Silla may be a discordant body which cuts the Upper Quartzite.

A period of regional metamorphism and strong deformation occured after these above sediments had been deposited and intruded by the rock which is now amphibolite. Foliation is strongly developed and parallels what appears to be bedding, as defined by lithologically different layers. Foliation strikes northeasterly and is most easily explained as flow cleavage produced by stresses acting in a northwesterly direction.

Isoclinal folding on a small scale is present in an outcrop just north of Cerro Colorado; shearing occuring parallel to axial planes is also prominent there, and this suggests that isoclinal folding has also been active on a large scale. The excessive thickness of the Lower Quartzite is also indicative of isoclinal deformation. The quartz-muscovite schist wedge north of Loma de Silla might be a tight, plunging isoclinal fold or be the result of a shear cutting it at its eastern contact with the Lower Quartzite.

Drag folds are common in hornblende schists, and along the Lower Quartzite-Hornblende Schist contorted layering in the quartzite is present. Chevron type folds of small magnitude occur in a greenschist east of Mule Springs Canyon. This area is interpreted as synclinal, because M. Willard's observation (Personal communication) is that chevron folds are commonly found in axial zones,whereas drag folds are commonly found on limbs. Drag folds are not abundant enough to be useful for a statistically valid structural analysis.

Drag folds in the northern part of the mapped area plunge southerly and southeasterly, in the Cerro Colorado area the dominant direction of plunge is easterly and northeasterly. These two areas are separated by the Ladron Fault and the area just north of Cerro Colorado may have been affected by movement along this fault.

The Granodiorite Augen Gneiss contains microcline and plagioclase, quartz and biotite. Some of the biotite is altered to chlorite which indicates retrograde metamorphism because of textural relationships. The Upper Quartzite crops out in the northern part of Cerro Colorado and toward the south the gneissic texture becomes more strongly developed. The southern part of Cerro Colorado is predominantly augen gneiss, however, some thin interbedded quartzite units still do occur. Contacts of these with the Augen Gneiss are sharp and appear not to be faults.

Near the ends of the augen many small grains of feldspar occur, indicating that mylonitization has occurred, and that therefore deformation has been intense.

Hornblende schists occur probably as infolds. These beds together with the Upper Quartzite form a feature which appears like a layered sequence and can be seen from a distance (Fig. 18).

The Augen Gneiss has been classified as a hornblende-granulite, the highest metamorphic rank evident in the mapped area.

Within the Augen Gneiss a few pegmatitic short sills are present. These pegmatites contain microcline, plagioclase and quartz. No enrichment of mafic minerals is present in the host adjacent to pegmatite sills, which indicates that they were not formed by metamorphic differentation in situ. Nevertheless this process may have occured at depth with subsequent injection along the path of least resistance, i.e. parallel to the foliation.

The bedded or layered sequence and the infolds of hornblende schists rule out an igneous origin for the augen gneiss; and the gradational contact from Upper Quartzite to Augen Gneiss strongly supports a sedimentary origin for these rocks.

The Upper Quartzite is believed to have been a series of arkosic sandstones, or arkoses.

This author does not agree with Slingerland's (1950) interpretation of Cerro Colorado as consisting of a foliated granite.

The Red Granodiorite contains reddish microcline, and white to colorless plagioclase and quartz. The mafic minerals are sparsely distributed, biotite is most common, but hornblende was noted. Muscovite is quite rare in this rock. Chlorite occurs locally in minor quantity as an alteration product of the mafic constituents.

The granodiorite has a seriate texture, is massive, and lacks foliation except on Loma de Silla where sediments, Upper Quartzite, grade into it almost imperceptably. A few hornblende schist layers extend from the Upper Quartzite into the Red Granodiorite. In the adjoining Hornblende Schist east of Main Ridge no impregnation of the Hornblende Schist is evident, nor are there veinlets of quartz and/or feldspar in the Hornblende Schist near the contact with the granodiorite. The contact between Hornblende Schist and the Red Granodiorite appears comformable, i.e. parallel to the foliation in the schists. Effects of contact metamorphism have not been noticed. Locally a few inclusions are found in the granodiorite; these, however, may be remnants of layers not granitized, such as the hornblende schists extending into the granodiorite on northern Loma de Silla. Mylonitization is believed to have been active and probably responsible for breaking up some of the hornblende schist layers which then became assimilated, at least in part. The outcrop area east of Main Ridge is believed to be eroded to a deeper level than the outcrop area on Loma de Silla. This is deduced from the relative movement on Ladron Fault. In the deeper portion homogenization was more complete than in the shallower portion, which leaves a continuous layer of hornblende schist in the Loma de Silla outcrop whereas in the outcrop east of Main Ridge only few inclusions remain.

The Red Granodiorite shows a gradational contact with metasediments mapped as Upper Quartzite; the latter is arkosic in parts, and close to the contact has a gneissic texture.

Granitization is a subject of many, and often, strong controversies. Much has been written and argued pro and con by the different schools of thought. The term granitization itself is not well defined and is used with different meanings. Evidence which is used by a "transformist" as indication for granitization in situ may be used by a "magmatist" as proof for intrusive origin. What a "magmatist" may call xenoliths are often termed skialiths by a "transformist".

The best argument is undoubtedly that by R. Chapman in Gilluly (1948 pg. 128-129):

"The transformists regard granitization as a deep-seated process, one which is, in effect, ultrametamorphism.....some results of this process are gradational boundaries between granite and wall rock, lit-par-lit gneisses, ptygmatic folds, relics of wall rocks

> in the granite, and "basic fronts". Granitization, however, can conceivably take place only at great depth when temperatures and pressures are high. .... Instead, in the upper levels, the magma ... will intrude the country rock and leave such telltale evidence along its boundaries as apophyses, inclusions, sharp contacts, and chilled borders".

Is there actually any necessity to believe in only one or the other theory of granite origin? Definitely not! The author does not wish to be classified as a "transformist" merely because of the interpretation in this report. There are definitely granites and granites, and depending on their contact relationships, on the environment in which they were emplaced or in which they were formed they should be classified as of intrusive or metamorphic origin, provided, of course, that sufficient evidence is available to do so.

In this report granitization is used to describe a process which occurred during a period of regional metamorphism. Originally sedimentary rocks which were arkosic underwent recrystallization, after possibly extensive prior mylonitization, and possibly suffered some metasomatism to produce a rock which has now the appearance of a granite (in the widest sense). Whether or not remelting occurred cannot be determined. The author is convinced, however, that a liquid phase must have played an important role, as diffusion in a completely dry system is rather slow, and a liquid phase would aid considerably. A liquid phase, predominantly water, contained by the sediments, would also lower considerably the melting range of silicates (Tuttle and Bowen, 1958) and bring it within the range of temperatures suggested by the metamorphic facies represented in the area of the southern Sierra Ladrones.

The area occupied by the granodiorite has been interpreted as a synclinal zone. This agrees with field observations that synclines were faulted out and that these were necessarily at greater depths that anticlines. The same has been reported in several instances that granitization occurred mainly in synclinal zones, but occasionally also in anticlines.

Interpretation of folded amphibolite layers in phacoliths depends on whether the geologist happens to be a "magmatist" or "transformist". Buddington (1959) explains these as xenoliths and the granite as magmatic. Stevens (in Buddington, 1959) interprets skeletal folds outlined by layers of hornblende gneiss near Northgate, Colorado, as relics residual in quartz monzonite of granitization origin. The latter would be properly classed as skialiths.

Metamorphic facies present in the vicinity of the granodiorite suggest that temperatures during metamorphism were sufficiently high to have produced at least a partial remelting of some rocks. Experimental data by Tuttle and Bowen indicates that the lowest temperature at which a granitic rock may crystallize in a "wet" melt is around 650°C. Temperatures as high as 700° to 750°C may have been reached in this area, and melting, therefore, would have been possible, with a sufficiently high $H_2O$ pressure. It is the author's contention that the water enclosed by these sediments was sufficient to achieve this.

To recapitulate in short: granitization occurred during the period of regional metamorphism, recrystallizing, and possibly remelting, arkosic sediments with possible minor additions through metasomatism. Mylonitization may have been produced in these sediments prior to the recrystallization - evidence for this exists in the augen gneiss which has essentially the same composition as the granodiorite. Mobilization of the granitized mass did not occur. The bordering Hornblende Schist has a contact with the granodiorite which is concordant to the foliation of the schist and parallels the regional trend of foliation. The granodiorite is feebly foliated in the zone of gradational contact with the gneissic metasediments but massive away from this contact. Some hornblende schist interbeds extend into the granodiorite and show little effects of assimilation.

The Younger Granodiorite consists of quartz, microcline and oligoclase with minor muscovite and biotite. It is in intrusive contact with Precambrian metasediments and the Red Granodiorite. In the northeastern part of the mapped area, just south of Cañon Hondo a small hill has a Red Granodiorite capping whereas the lower part of this hill is Younger Granodiorite. Small roof pendants of metasediments in the Younger Granodiorite are also present in the same general area, and north of Cañon Hondo. This suggests that, at least in this area, the erosion surface must be close to the original top of this intrusive.

The metasediments in the roof pendants show no effects of contact metamorphism, this may indicate that the intrusive was emplaced while the terrain was still relatively warm from the regional metamorphism.

Age dating by G. Wasserburg has established an age of 1440 million yrs, supposedly from samples of this younger granodiorite.

# CONCLUSION

During Precambrian times, clean, well sorted quartz sands with a few, thin, shaly interbeds were deposited on a stable shelf area. Then a thin sequence of pelitic sediments and a somewhat thicker one of possibly fine grained ferruginous sandstones and a later sequence of quartz sands and arkosic sands accumulated during a period of transgression and possible uplift of a land mass, from which these sediments were derived. After the accumulation of these rocks basic sills and dikes intruded the sequence. Sedimentation must have continued for some time after this event, evidence for later rocks existing in the South Manzano Mountains.

A period of regional metamoprhism accompanied by intense deformation produced tight isoclinal folding and strong foliation in the deeply buried rocks. Temperatures and pressures reached sufficient intensity to reconstitute arkosic sediments to form Augen Gneiss and Granodiorite. Sometime later granodiorite also intruded the terrain and this appears to terminate the activity of the Precambrian.

A long period of erosion began, which was terminated by sedimentation, beginning in Mississippian times.

During Tertiary times the Rio Grande depression began to be formed and sediments derived from the neighboring hills filled the valley. The fault on the western boundary of the depression, Cerro Colorado Fault in the Sierra Ladrones, is believed to be still active.

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