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Geology of the South Manzano Mountains, New Mexico

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Abstract

The South Manzano Mountains in central New Mexico form a unit of the easternmost of the Basin Ranges and are structurally continuous with the Los Pinos to the south and the North Manzano and Manzanita Mountains to the north. Precambrian metaclastics of the area consist of the basal Sais quartzite overlain by the Blue Springs schist and White Ridge quartzite in conformable sequence, followed by 5,000 ft of rhyolite flows and intercalated basic sills. A small outcrop of granite in the northwest part of the area is similar to and correlated with the Ojito stock of the North Manzano Mountains, which intruded metaclastics older than the Sais quartzite. In the south, the Priest granite and associated pegmatite and aplite dikes intrude all older formations. Vein quartz ranging from thin stringers to massive quartz reefs over 1,000 ft thick are prominent throughout the range and represent several periods of intrusion.

Three periods of Precambrian orogeny are recognized: (1) Early folding of the metaclastics and metarhyolite into an asymmetric syncline, its axis striking northeast across the north trending range and the steeper eastern limb overturned, with the axial plane dipping steeply to the southeast. At this time, regional cleavage was developed paralleling the axial plane, with small drag folds on the flanks of the syncline. (2) Later, cross-folding, faulting, and small crenulations were developed on the older schistosity. (3) Finally, granites were intruded, with associated dikes and quartz veins, across preexisting structure.

A later disturbance, probably Laramide, formed three major thrust-fault zones, the easternmost bringing Precambrian formations against Paleozoic sediments. A normal fault in Tertiary time is responsible for the block tilting of the range with respect to the Rio Grande Valley on the downthrown side. Small scarps in Quaternary gravels of the Tio Bartola pediment indicate recent normal faulting.

Introduction

GENERAL STATEMENT

The steep western escarpment of the South Manzano Mountains, a familiar landmark to travellers in the Rio Grande Valley in the vicinity of Belen, affords an unusually extensive exposure of the Precambrian or basement rocks of this region. Not only do these rocks appear for a distance of 19 miles along the front, but the 3,000 ft of vertical exposure in ridges and steep-walled canyons provides a particularly favorable opportunity for viewing the structure of these rocks in a third dimension as well. In view of this favorable situation, as well as the interest of the oil industry in the nature of the Precambrian basement, or "granite," as it is commonly called, it appeared that a careful study of the South Manzano Mountains was especially in order. Furthermore, the North Manzano Mountains had been mapped by Reiche (1949), and the Los Pinos Mountains to the south had been mapped by Stark and Dapples (1946), so that this study completes the continuity of geologic information along the entire front south of Sandia Mountain. The study was confined essentially to the Precambrian rocks, and only their structural relations to the overlying Pennsylvanian rocks was noted.

Though the Precambrian rocks are moderately to thoroughly metamorphosed, a large part may be interpreted as having been a sequence of clastic sedimentary beds, with some sills of basic igneous rock; still another part is interpreted as a series of rhyolite flows. Of especial interest in this area are large masses of quartz, here called quartz reefs, which are interpreted as of intrusive or vein origin. Several masses of granite have intruded the Precambrian rocks and are regarded as of Precambrian age. No mineral deposits of any consequence have been found associated with the quartz reefs, but large quantities of quartzite are excavated and crushed for railroad ballast from extensive pits on the south side of the Atchison, Topeka and Santa Fe Railway tracks at the south end of the area.

LOCATION AND EXTENT

The South Manzano Mountains extend between latitudes 34°27' and 34°44' N., from the pass of the Atchison, Topeka and Santa Fe Railway in Arroyo Abo northward to the broad valley of Comanche Canyon. The area of Precambrian rocks ranges in width from 4 to 6 miles for the entire length of 20 miles. They disappear under the pediment gravels on the west and are thrust against Paleozoic sediments on the east.

FIELD WORK

During the summer of 1950, the author and two assistants, William Basham and James J. Dorman, spent June and July in the field studying

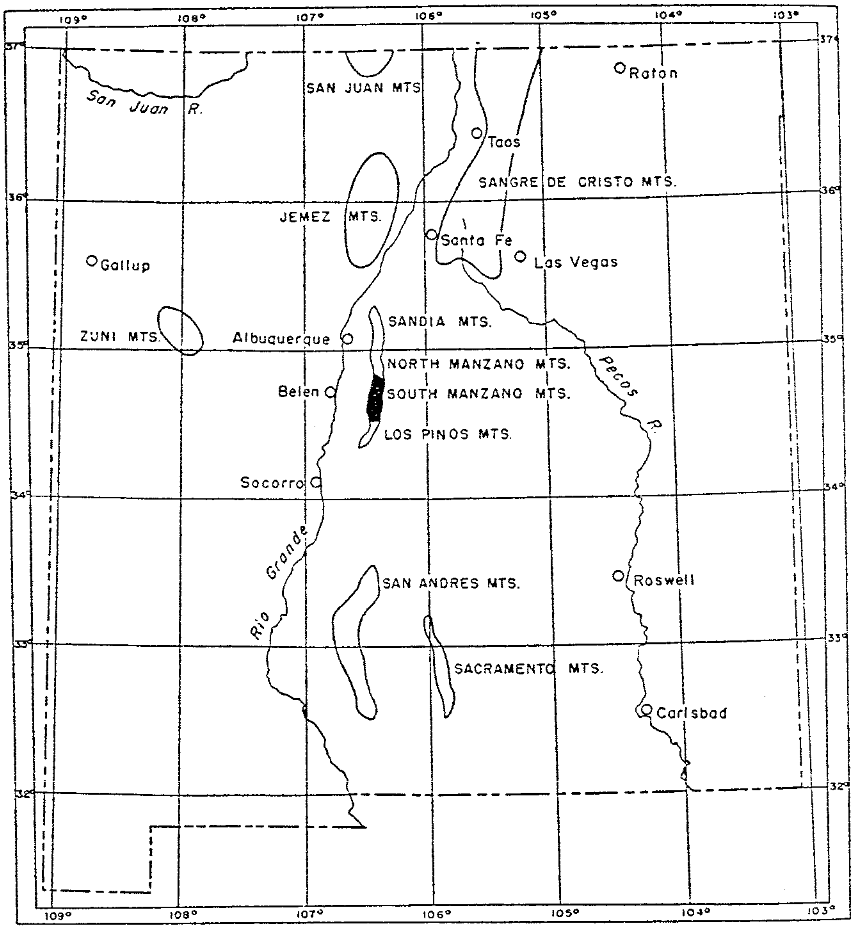


Figure 1

SKETCH MAP OF NEW MEXICO SHOWING LOCATION OF THE SOUTH MANZANO MOUNTAINS.

the Precambrian structure of the South Manzano Mountains. Aerial photographs (scale 1:31,680) were used for plotting outcrops, and planimetric sheets (scale 1:31,680) from the U. S. Soil Conservation Service, were used for the final base map (pl 1). Altitudes were determined by traverses across the range, using Paulin altimeters. Numerous temporary benchmarks, established by the U. S. Geological Survey on the western pediment, were used for check points.

ACKNOWLEDGMENTS

Mapping of the Precambrian geology of the South Manzano Mountains was a project of the New Mexico Bureau of Mines and Mineral Resources, under the supervision of Dr. Eugene Callaghan, director. Thanks are expressed to Dr. Callaghan for his helpful suggestions both in the field and in the office. The author wishes to acknowledge the assistance of William L. Basham and James J. Dorman, both of whom obtained material for M.S. theses, Mr. Basham on the structure and metamorphism of the metaclastics, and Mr. Dorman on the tectonics of the Priest granite. The results of their studies have aided materially in writing the present report. Laboratory work was carried out at North-western University, where helpful criticism was received from Professors E. C. Dapples and A. L. Howland. Thanks are due Mr. R. E. Miller, on whose property the party camped, and who was extremely helpful in his knowledge of the region and in recording hourly barometer readings at the base camp. Permission was cordially granted by Messrs. Aguayo, Crisp, and Sedillo to use private roads across their ranches. Mr. E. W. Cotton, forest ranger at Mountainair, supplied maps and information on roads and trails.

Physiography

TOPOGRAPHY

The Sandia, Manzano, and Los Pinos Mountains form the north-easternmost block-faulted range of the Basin and Range province. The range is topographically asymmetric, with a steep western front and a more gently sloping eastern flank. The contact of the pediment gravels with Precambrian formations along the western front of the South Manzanos has an average altitude of 5,700 ft. The average altitude of the crest of the mountains is 8,800 ft, with a maximum elevation of 9,400 ft on Manzano Peak. Lower crest elevations from 7,000 to 7,500 ft pre-dominate in the southern 6 miles.

In the northern part of the area, eastward dipping Paleozoic sediments give a cuesta aspect to the eastern flank, from Comanche Canyon to Capillo Peak. Along the southern 6 miles of the eastern slope, the steeply dipping Pennsylvanian limestone forms hogback ridges. Along the central part of the eastern flank, low ridges formed by the rock layers are less conspicuous. The steep western front of the range is probably a fault-line scarp. A series of small, recent scarps in the pediment is conspicuous.

DRAINAGE

The principal streams cut the regional structures at nearly right angles, and tributaries are developed along the strike of the formations. This general pattern is reversed in Comanche Canyon at the northern boundary of the area, where the streams are approximately parallel to the strike of the formations, with tributaries perpendicular to the main valley. The canyon follows the trend of a normal fault throughout most of its length and, apparently, is controlled by erosion along the brecciated zone.

In the area underlain by the Priest granite, a radial and dendritic pattern is characteristic; in general, the terrain is more mature topographically than that in the surrounding area.

Precambrian

GENERAL STATEMENT

The central mass of the South Manzano Mountains consists of a sequence of Precambrian metaclastics, rhyolite flows, intercalated basic sills, two separate granitic stocks, associated pegmatite and aplite dikes, and vein quartz. In the Los Pinos Mountains, immediately to the south, five mappable units of the Precambrian are recognized (Stark and Dapples, 1946, p 1127): (a) the Sais quartzite at the base; (b) Blue Springs schist, originally composed of shales and siltstones; (c) White Ridge quartzite, a thick series of quartzose beds containing many gradations into argillaceous silts; (d) Sevillita metarhyolite, surface flows approximately 4,500 ft thick in the Los Pinos area; and (e) the Priest granite. These five units have been traced northward into the South Manzano Mountains, maintaining with a few exceptions much the same lithologies and variations as in the region to the south (see Appendix).

In both the Los Pinos and South Manzano Mountains, the metaclastics contain numerous intercalated sills, now largely altered to amphibolite and chlorite schists; many pegmatite and aplite dikes; and vein quartz. The quartz veins, which are well represented in the southern range and commonly show gradations into quartz-microcline pegmatite, become increasingly important in the South Manzano Mountains, both in number and size. Small quartz pods, lenses, and stringers are so abundant in many parts of the Blue Springs schist as to form nearly 50 percent of the outcrops. Quartz reefs, ranging from a few feet to more than 1,000 ft in thickness, form a striking feature in the Precambrian metaclastics, extending across many canyons as wall-like partitions. In addition to the Priest granite, which apparently is a facies of the Los Pinos granite to the south, a more basic granitic mass crops out on the western slope of the South Manzano Mountains. It is thought to be closely related to the Ojito stock mapped by Reiche (1949, p 1192) 8 miles to the north. One other difference in lithology between the Los Pinos and South Manzano rocks is the increasing amount of basic schist intercalated in sill-like intrusions in the metaclastics and the rhyolite flows in the northern mountains.

The Sais quartzite and Blue Springs formation have been traced northward into the North Manzano Mountains, where they have been mapped by Reiche (1949, pl 5). A series of older metaclastics, unconformably beneath the Sais quartzite, does not extend into the South Manzano Mountains proper; they are shown on Plate 1 essentially as mapped by Reiche, and are a part of the northwest limit of a large syncline which forms the central part of the South Manzano Precambrian rocks.

SAIS QUARTZITE

The basal Precambrian formation of the South Manzano Mountains is continuous with the Sais quartzite of the Los Pinos area to the south and with the basal member of the upper metaclastic series of the North Manzano Mountains (Reiche, 1949, p 1190). This quartzite crops out from Abo Pass, near the Atchison, Topeka and Santa Fe Railway, north-ward for 1 1/4 miles, where it is bounded on the west and north by the conformably overlying Blue Springs schist, and on the east by the Montosa thrust fault. It forms a belt 12 miles long and from 1/10 to 2 miles wide, between latitudes 34°30' and 34°38'. This belt is discontinuous because of covering by pediment gravels and the intrusion of the Priest granite. The outcrop area is bounded on the west in its southern 2 miles and northern 5 miles by the White Ridge quartzite (Paloma thrust) and Blue Springs schist respectively. On the east side for 3 miles in the southern part, the quartzite is bounded by the Priest granite, and in the northern 9 miles by Pennsylvanian sediments. An outcrop 2 miles long occurs on the west slope of the range, immediately north of Comanche Canyon. This outcrop lies properly in the North Manzano Mountains and was so mapped by Reiche (1949, pl 5).

The Sais quartzite has an exposed thickness of approximately 2,000 ft in a $1/_2$-mile-wide outcrop just north of the Priest granite, sec. 30, T. 3 N., R. 5 W., where dips average 50 degrees. Here, the base of the quartzite is covered by the Montosa thrust fault, which brings up the Precambrian granite against Pennsylvanian limestone. In outcrop, the quartzite thins to the north. Immediately north of Comanche Canyon, the quartzite rests unconformably on the lower metaclastic series and is conform-ably overlain by the Blue Springs schist (Reiche, 1949, pp 1189-1190); the thickness is only 400 feet.

In southern outcrops, the Sais quartzite ranges from nearly white through light to dark gray. Greenish facies occur locally. Farther north, the quartzite is darker gray, with reddish and purplish beds characterizing many of the outcrops. Quartz, sericite, biotite, and, in one locality, kyanite are recognizable in hand specimens. The grain size is rarely more than 1 mm in diameter; in many beds, it is too small to be recognized megascopically. Near the base of the Sais formation, conglomerate occurs in thin beds from 1 to 2 in. thick and with pebbles as large as 5 mm in diameter.

The basal beds are characterized by lieseganglike banding, which in some places extends across bedding planes and in others appears to be truncated by them. Gently dipping crosslaminations indicate the normal attitude of the beds. Massive beds, averaging from 3 to 4 feet thick, alternate with thinner bedded zones which are commonly sericitic, suggesting argillaceous beds in the original sandstone.

In thinsections, the quartz grains show wide variation in shape and size, ranging from .05 to 0.97 mm. The grains are interlocking, with serrate borders and numerous small quartz inclusions, indicating recrystallization, but without any conspicuous dimensional orientation. Near the borders of the Priest granite, orthoclase is present, with irregular, interpenetrating contacts with the quartz. Laths of biotite and sericite parallel the bedding planes. Euhedral and irregular grains of magnetite are scattered widely throughout the thinsections.

North of Comanche Canyon, where the quartzite overlies the lower metaclastics, quartz forms 99 percent of the thinsections, with only traces of intergranular sericite, magnetite, and apatite. Secondary enlargement rims surround many of the quartz grains. A few grains, now entirely altered to white mica, appear to be altered feldspar. The quartzite north of Comanche Canyon appears to be a coarse-grained orthoquartzite, with typical secondary enlargements on original grains, modified by a slight amount of granulation. In contrast, quartz grains in the closely folded quartzite of Estadio Canyon (lat. 34º31') are very fine to medium and show much recrystallization; no original surfaces are evident.

BLUE SPRINGS SCHIST

The Blue Springs schist is exposed in discontinuous belts in the South Manzano Mountains (pl 1). The southern belt is traceable continuously from the Los Pinos area to latitude 34°29' N., 1 ½ miles north of Abo Pass. In the Los Pinos Mountains, the belt is bounded on the west by the White Ridge quartzite. One and one-quarter miles north of Abo Pass, the contact between Blue Springs schist and the White Ridge formation is depositional and gradational. To the east, the southern belt of Blue Springs schist is thrust against Pennsylvanian sediments (Montosa thrust fault). The northern boundary of this belt is formed by the Priest granite.

The central belt of the Blue Springs schist extends from latitude 34°32' N., longitude 106°29' W., northward for 5½ miles, where it widens to 1 ¼ miles. North of here, the schist is cut out by the Paloma thrust.

The northern belt of the Blue Springs schist extends for 11 miles between latitudes 34º35' and 34 °44', averaging 2½ miles in width. On the west, it is bounded by overlying pediment gravels, except for 2 miles in the southern part, where the Monte Largo stock intrudes the schist, and for 2 miles north of Comanche Canyon, where the schist is bounded by the overlying Sais quartzite. The east boundary, for the entire length of the northern belt, is the overlying White Ridge quartzite, except for the northernmost 3 miles, where it is in contact with the Pennsylvanian rocks.

Intense and repeated folding in many outcrops of the Blue Springs schist makes thickness determination difficult. Based on an average dip of 50 degrees at the head of Marker Canyon (pl I), where the schists are less folded, a maximum thickness of 2,040 ft is indicated; even here, the thickness may be less.

The Blue Springs schist changes from place to place, owing to differences in original composition and intensity of metamorphism. Three main types are recognized: siltstones, phyllites, and sericite-chlorite schists.

Fine-grained siltstones are the most distinctive and easily recognized facies of the Blue Springs schist. They are characterized by their pink, gray, and greenish-gray color, fine grain, and thin laminations. In general the siltstones are complexly folded, commonly with fine crenulations. For the most part, the siltstones are only slightly metamorphosed and probably represent the original rock from which most of the highly metamorphosed sericitic, chloritic, and porphyroblastic schists were derived. Excellent exposures of the siltstone occur on the western slope of the mountains, 2 miles north of the Atchison, Topeka and Santa Fe Railway, in Monte Largo and Salas Canyons and, to a lesser extent, in Comanche Canyon.

In thinsections, mineral percentages of the siltstones average: quartz, 80%-90%; oligoclase-andesine, 2%-10%; biotite, 1%-5%; epidote, 1%-5%; garnet, 2%; sericite, 1%; magnetite, less than 1%. The quartz grains are irregular, varying in size from .02 to 0.2 mm. Other minerals are of comparable size.

The phyllite shows excellent cleavage, uncrinkled surfaces, and a silvery sheen of sericite on its cleavage surfaces. Phyllites were seen on all traverses across the Blue Springs schist. They are especially well exposed near the head of Comanche Canyon, but they are never as abundant as the siltstones or the sericite-chlorite schists. Megascopically recognizable minerals are sericite, chlorite, and extremely fine-grained quartz. The phyllite is, in general, much less quartzose than the siltstones.

The sericite-chlorite schists range from dark gray to light greenish gray, and are common throughout the Blue Springs schist. They range in composition from sericite schist to chlorite-quartz schist. Outcrops are characterized by thickly crowded lenses, pods, and stringers of quartz ranging in size from paper thinness to 1 ft or more in width, and from one-half inch to several feet in length (pl 7-A). They are oriented parallel with the schistosity. In many outcrops, the quartz lenses make up nearly 50 percent of the rock. Extremely quartzose pegmatites, containing small amounts of pink microcline, are common at many places. Quartz veins, although particularly prominent in the sericite-chlorite schist facies, are not confined to these schists, but occur in all parts of the Blue Springs formation. Sericite-chlorite-quartz schists are well exposed in Monte Largo, Salas, Kayser, and Comanche Canyons. Intense shearing, small drag folds, and fine crenulations across the regional schistosity are characteristic of most outcrops.

Megascopically recognizable minerals are sericite, chlorite, quartz, and rarely magnetite. Mineral percentages average: quartz, 65%-75%; sericite, 25%-45%; chlorite, 1%-10%; magnetite, less than 1%. Apatite and zircon are present in widely scattered grains. The quartz grains range in size from .01 to 0.5 mm, averaging .05 mm. Larger grains appear to have been introduced or to have resulted from recrystallization of smaller clastic grains. In the quartz lenses, the grains are much coarser than in the enclosing schists, ranging from 0.5 to 16 mm in diameter. Chlorite and sericite appear to have been derived, in part at least, from original material in the siltstone or shale.

BORDER FACIES

Muscovite schist with flakes from 1 to 5 mm in diameter characterizes the Blue Springs schist adjacent to the Priest granite. A schist outcrop, ¼ mile east of Muir reservoir, near a granite, contains randomly oriented mica flakes. In other places near the granite (just north of the Atchison, Topeka and Santa Fe Railway), the muscovite flakes are developed parallel to the regional schistosity.

Around the borders of the Priest granite, sillimanite schists are common in the Blue Springs formation, with sillimanite crystals ranging from small needles to laths ¼ x 2 in.

WHITE RIDGE QUARTZITE

The White Ridge quartzite crops out in two belts. The eastern belt extends discontinuously from the Los Pinos Mountains, across Arroyo Abo, to as far north as latitude 34°41'. Its width averages ½ mile in the central part and narrows at both the northern and southern ends. The eastern boundary of the quartzite, south of Abo Pass, is formed by the Paloma thrust fault. Two miles farther north, the quartzite rests conformably on the Blue Springs schist and is intruded by the Priest granite. The quartzite emerges from under the pediment gravels at Muir reservoir and continues northward to latitude 34°41', where it is crossed by the Capillo Peak road. Along this latter stretch, the eastern boundary of the quartzite shows successively from north to south a thrust contact against the Sais quartzite, depositional contact with the Blue Springs schist, a fault contact against the Blue Springs schist, and a fault contact against the Sais quartzite. The western boundary of the eastern belt is formed by the overlying Sevillita metarhyolite.

The western belt of White Ridge quartzite extends continuously from the pediment contact, latitude 34°35', to a point ¼ mile southwest of Capillo Peak. The belt ranges in width from 250 to 600 ft. On the west, the quartzite is in depositional contact above the Blue Springs schist, and on the east, it is overlain by the Sevillita metarhyolite.

Along the west belt on the west limb of the central syncline, where the White Ridge quartzite is not repeated by folding, the thickness ranges from 200 to 500 ft. On the east limb of the syncline, repeated folding has widened the outcrop, and the actual thickness is determined less accurately. Near the central part of the eastern belt, where no folding is evident, the quartzite may be as much as 2,600 ft thick. A much greater thickness was measured in the Los Pinos Mountains, ranging from 3,700 ft in the central part of the Los Pinos, to 900 ft near Sierra Montosa (Stark and Dapples, 1949, p 1133). The differences in thickness were thought to be due to erosion before the quartzite was covered by rhyolite flows. Similar erosion may account for thinning in parts of the South Manzano Mountains; in other places, the quartzite belt is narrowed in outcrop by the intrusion of the Priest granite and by the thrust faulting.

The White Ridge is dominantly a white, massive-bedded quartzite. Gray, pink, red, and purple facies occur locally. Many thinner and less quartzose beds are now sericite-quartz schist. Throughout the formation, bedding planes commonly show reflecting surfaces of white mica. The grain size of the quartzite proper ranges from very fine to coarse sand. A prominent feature near the top of the eastern belt is an arkosic and conglomeratic facies. These arkosic beds contain grains of blue quartz from 2 to 15 mm, and plagioclase crystals from 0.5 to 3 mm, in diameter. There is much evidence of shearing, elongation, rotation, and granulation of the larger grains. The arkosic quartzite is characteristically schistose, as is the overlying basal Sevillita metarhyolite. Flakes of sericite are molded around lenses of fractured grains of quartz and feldspar. Along the strike, the arkose varies considerably in thickness. Near the central part of the eastern belt, it has a maximum thickness of approximately 2,000 ft, farther south, it thins to 300 ft. In the lower half of the arkosic layer, quartzite beds become increasingly numerous. The clastic character becomes less prominent toward the top of the arkosic layer, owing to recrystallization of the feldspathic sand and the development of feldspar porphyroblasts. Intercalated sills of rhyolite near the top are difficult to distinguish from the recrystallized sediment.

Many thinsections of the White Ridge quartzite show a high degree of purity, ranging from 95 to 99 percent quartz. Near the zones of thrust faulting, recrystallization and granulation of the quartzite is accompanied by the development of well-oriented sericite. Differences in composition of the metamorphosed beds appear to be due largely to differences in original composition. In the more schistose beds, epidote, biotite, chlorite, magnetite, and zircon are present. In places, sericite forms as much as 40 percent of the formation.

The gradation from relatively pure-white quartzite, through sericitic and arkosic quartzite and sheared conglomerate beds, into rhyolite flows raises a question as to the origin of the feldspathic quartzite. The underlying quartzite is typical of the stable shelf type of tectonic environment (Dapples, Krumbein, and Sloss, 1950). The great thickness of 2,000 ft is suggestive of a less stable condition. A nearby source of granitic material seems necessary for the accumulation of 2,000 ft of arkosic conglomerate.

Staatz and Norton (1942, p 62) suggest that material was added to the quartzite from rhyolite sills intruded into the upper part of the White Ridge quartzite, or possibly from the overlying flows, to form the feldspathic quartzite. There is little evidence in the South Manzano Mountains as to whether the intercalated metarhyolite beds in the upper member of the White Ridge quartzite were originally sills or flows. The presence of large pebbles of blue quartz suggests that there was a definite change of depositional and source environment. Such changes may have been accompanied by earth movements which exposed a nearby granitic terrain to erosion. Inclusions of granite and aplite in one of the rhyolite flows described in the section on the Sevillita metarhyolite give evidence for the presence of an older granite.

The White Ridge quartzite is conformable above the Blue Springs schist along the entire western outcrop belt, and on the east, along the 1-mile-long contact north-northeast of Abo Pass (pl 1). Between latitudes 34°30' and 34°38', the White Ridge quartzite is thrust over older Precambrian rocks along the Paloma thrust. The overlying Sevillita metarhyolite flowed over an eroded surface cut into the White Ridge quartzite.

SEVILLITA METARHYOLITE

The Sevillita metarhyolite flows crop out in a northeast trending belt across the central part of the North Manzano Mountains, averaging 1½ miles wide and attaining a maximum width of 2¼ miles near the middle portion. The metarhyolite occupies the center of a large syncline and is bounded on both sides by the White Ridge quartzite. At the southwest end, the flows disappear under pediment gravels; at the north-east end, 1 mile south of Capillo Peak, they are overlain by Paleozoic sediments. The contact here strikes into the north trending Montosa thrust fault, where rhyolite and Pennsylvanian limestone are in juxtaposition.

The rhyolite flows and intercalated basic sills are approximately 5,000 ft thick in the central part of the outcrop. Reiche (1949, p 1191) mapped an outcrop thickness of 12,000 ft of rhyolite flows in the Manzanita Mountains, and suggested that the great thickness might represent repetition in a syncline. Stark and Dapples (1949, p 1134) mapped 4,500 ft of westward dipping rhyolite flows in the northern part of the Los Pinos area, overlying the White Ridge quartzite. These flows disappeared under pediment gravels to the west, and are undoubtedly on the overturned east limb of the North Manzano syncline. The synclinal structure is clearly established, and the measured thickness of the rhyolite is in accord with the thicknesses recorded above. Easily recognized rock types are banded rhyolite, sericite schist, garnet schist, chloritoid schist, and hornblende-rich rhyolite.

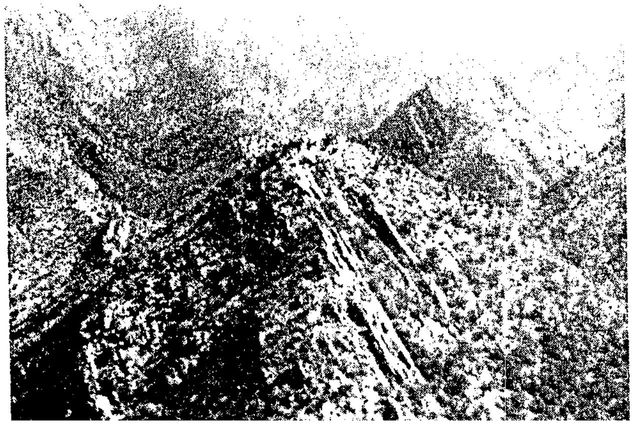
The typical rhyolite is a pink to gray, brittle, blocky-fracturing porphyritic aphanite (pl 2-A). The individual flows are as much as 20-30 ft thick; in general, however, the tops and bottoms are not readily discernible, as a result of shearing and fracturing. Closely spaced flow lines are evident on weathered surfaces. Textural variations range from de-vitrified glassy to aphanitic and aphanitic prophyritic. Phenocrysts range in size from 1 to 4 mm and are most commonly of quartz and/or pink feldspar. In Monte Largo Canyon, the lowest flows show abundant feldspar phenocrysts, but quartz is not visible megascopically. Above this is approximately 1,000 ft of rhyolite containing phenocrysts of feldspar and quartz. Still higher in the section, the flows show only quartz phenocrysts. The expected reversal of this textural sequence does not occur as the axis of syncline is crossed, suggesting that the texture differences have only local significance.

Mineral percentages in the rhyolite average: orthoclase, I5%-25%; albite, 10%-20%; quartz, 50%-60%; biotite, 1%-10%; magnetite, less than 1%; with scattered grains of apatite and zircon. Much of the feldspar is altered to masses of white mica, quartz, and epidote. Euhedral phenocrysts of quartz and feldspar make up from 5 to 10 percent of the banded flows. Quartz phenocrysts are commonly embayed. In the groundmass, the grain size averages .005 mm and is composed of quartz and untwinned feldspar. In many sections, the cloudy, patchy mottling of the matrix is suggestive of devitrification.

Locally, the rhyolite is metamorphosed to thinly laminated sericite schist in which the larger quartz grains form residual knots, with the sericite molded around them. Mineral percentages of the highly sericitized metarhyolite average: quartz, 60%; sericite, 25%; saussuritized oligoclase, 10%; magnetite, 2%; biotite 1%; with scattered traces of apatite.

In Monte Largo Canyon, latitude 34°36', the sericite schist contains well-rounded to oval inclusions of granite, aplite, quartzite, and vein quartz (pl 2-B). The inclusions are smoothly rounded, range from ½ in. to 2 ft in diameter, and superficially appear to be sheared pebbly conglomerate. The zone of rounded inclusions is approximately 20 ft thick and grades above and below into rhyolite, leaving no doubt as to the original igneous nature of the schistose matrix. The inclusions may represent fragments from older formations through which the magma passed to reach the surface, or possibly pebbles from a gravel bed. The former seems more likely, because of the extremely smooth surfaces of many of the inclusions. The oval inclusions are partly rotated to agree with the schistosity of the matrix. Small drags in the schistose metarhyolite indicate that the flow may be overturned.

The Sevillita metarhyolite contains numerous sill-like bodies of basic schist. These range in size from a few inches to a maximum thickness of 2,580 ft. These bodies thin and pinch out laterally; a thick layer at one place may be represented a few thousand feet away by numerous thin layers. At many places near the contact between the basic schist and the metarhyolite, the basic rock is changed to chlorite schist, and the rhyolite to sericite schist. In places, the alteration so completely masks the contacts that the relationship appears gradational. In most outcrops,

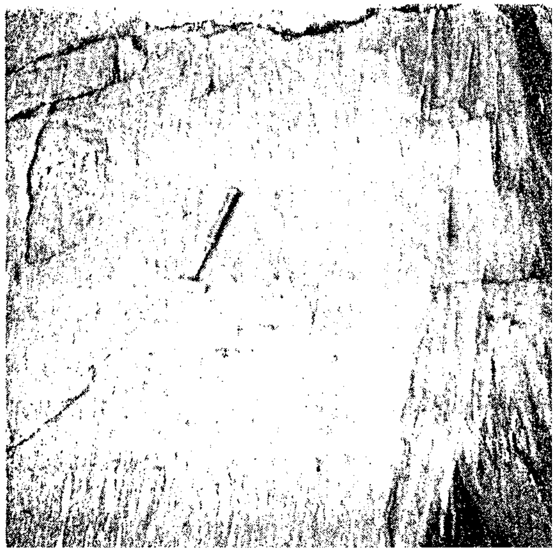


A. METARHYOLITE DIPPING STEEPLY NORTHEAST. MONTE LARGO CANYON

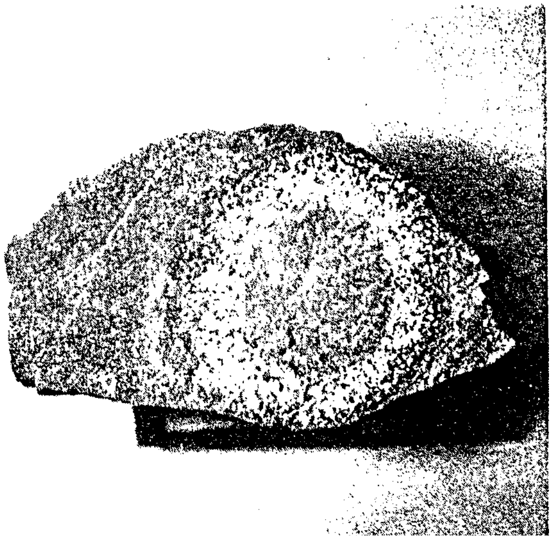
B. ROUNDED INCLUSIONS OF GRANITE, QUARTZITE, APLITE, AND QUARTZ IN RHYOLITE FLOW. MONTE LARGO CANYON

Plate 2

SEVILLETA METARHYOLITE



A. BASIC SCHIST WITH ELONGATE INCLUSIONS OF METADIORITE



B. ZONED AUGEN WITH EPIDOTE CORE SURROUNDED BY PLAGIOCLASE AND HORNBLENDE RINGS, IN BASIC SILL.

ABOUT 1 X ½

Plate 3

BASIC SILLS

however, the sill-like character of the basic schists, chilled borders, and intrusive apophyses is unmistakable.

Schistose metarhyolite adjacent to the basic sills varies from light-green sericite schist to porphyroblastic sericite schist, with zones of garnet, chloritoid, and, more rarely, magnetite. Garnetiferous schists are widely distributed; chloritoid zones are restricted to schists adjacent to the thicker basic sills. In a few outcrops, both garnet and chloritoid occur. The porphyroblasts range from small specks to garnets ¼ in. in diameter and chloritoid in columnar crystals over 2 in. long.

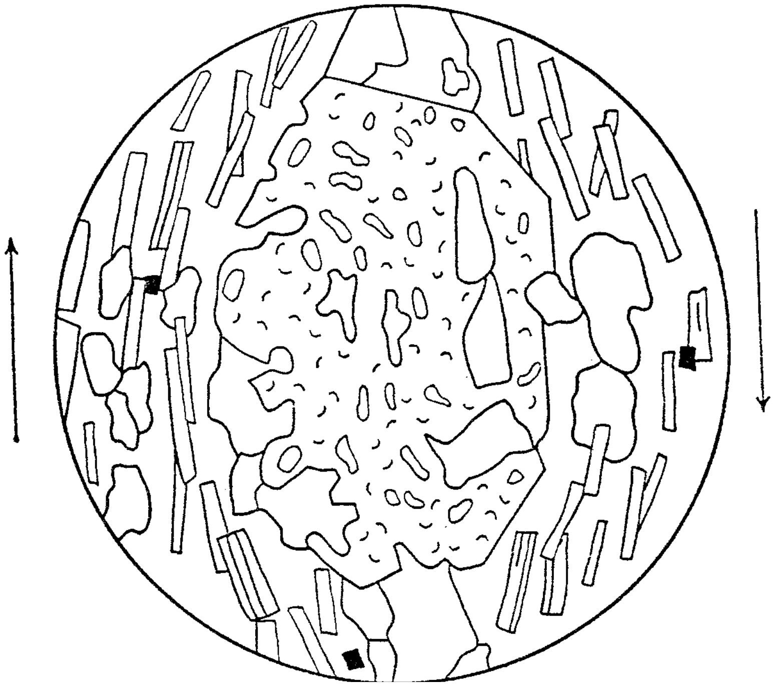
Average mineral percentages in the typical garnet schist are: quartz, 60%; sericite, 25%; garnet, 10%; biotite, 5%. In thinsections from Estadio Canyon (lat. 34°31'), the garnets appear to have been rotated 180 degrees during growth. Quartz inclusions in the garnets show S-shaped arrangement (pl 4-A). Sericite flakes are molded around garnet masses, which are commonly oval in shape and elongated parallel to the schistosity. Crystalline quartz in the pointed ends of these ovals, and a poikilitic chloritoid lath in the same thinsection appear undisturbed by rotation, suggesting a later development than the garnets. In contrast to the rotated garnets, thinsections from the schist north of Estadio Canyon show poikilitic chloritoid with no evidence of rotation (pl 4-B). Small quartz inclusions form straight lines through the garnets parallel to the regional schistosity. Porphyroblastic growth in the garnet schist of Estadio Canyon apparently occurred while deformation was still in progress, whereas in the schists to the north, the porphyroblasts developed after the folding had ceased.

In the chloritoid schist, the chloritoid forms plates and laths from 1/16 to 2 in. long. Quartz averages 65, sericite 25, and chloritoid 10 percent of the rock. Garnet and chloritoid schists are commonly interlayered, although flows containing both garnet and chloritoid are unusual. Reiche (1949, p 1188) describes chloritoid pseudomorphs, now chlorite and magnetite, in the lower metaclastics of Comanche Canyon.

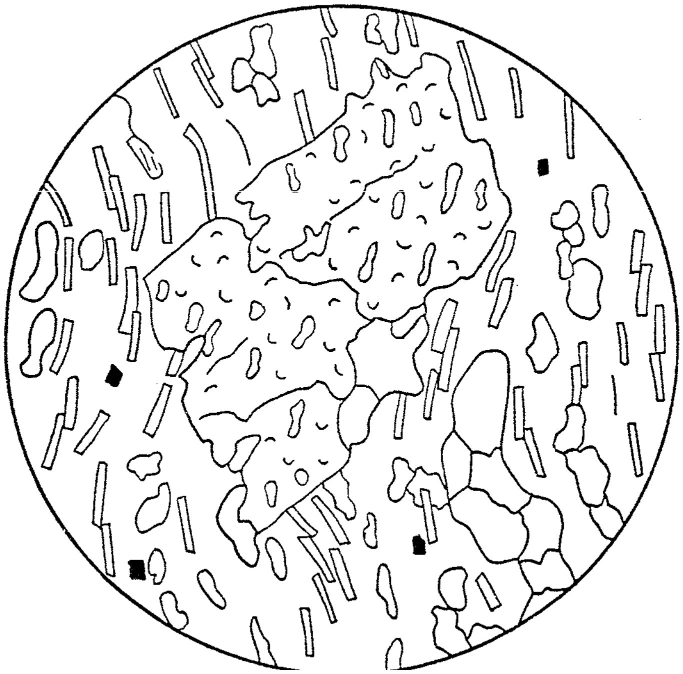
In Marker Canyon and the valleys to the north and south, metarhyolite inclusions in the black schist, or thin slablike masses of rhyolite from 2 in. to 2 ft thick and commonly 3 or 4 ft long, contain zones of thickly spaced reticulated hornblende porphyroblasts. The hornblende-rich zones are from 1 to several inches wide, and the individual crystals range from extremely fine needles to ½ in. long.

The metamorphosed hornblende-rich rocks show all variations from a few hornblende crystals to rocks containing 15 percent of hornblende. In the extremely hornblende-rich facies, the feldspar is labradorite. Mineral percentages average: quartz 4%; labradorite, 20%; epidote, 20%; hornblende, 5%; with small amounts of biotite, garnet, magnetite. The hornblende is sievelike, with many inclusions of quartz and epidote. The epidote is more or less uniformly distributed, except in areas rich in hornblende and labradorite.

Plate 4
SEVILLITA METARHYOLITE



A. GARNET CRYSTAL IN SCHISTOSE METARHYOLITE, SHOWING CLOCKWISE ROTATION (180°) OF THE GARNET PORPHYROBLAST. FROM ESTADIO CANYON. SKETCHED FROM THINSECTION. X 30.



B. CHLORITOID CRYSTALS IN SCHISTOSE METARHYOLITE, FROM SAME THINSECTION AS ABOVE. TRAINS OF QUARTZ INCLUSIONS PASS UNDISTURBED THROUGH THE CHLORITOID PORPHYROBLAST, INDICATING THAT ITS DEVELOPMENT POSTDATES THE SCHISTOSITY. X 30.

BASIC SCHISTS

Sill-like bodies of basic schist occur in all the Precambrian formations of the South Manzano Mountains, with the exception of the Sais quartzite and the granites. These intercalated bodies are especially abundant in the Sevillita metarhyolite. The schist zones range from a few inches to nearly ½ mile thick. Along the Capillo Peak road and in the south fork of Monte Largo Canyon, 25-30 sill-like bodies are mapped in less than ¼ mile of rhyolite flows. Many of the thicker masses of basic schist lense out laterally into a number of thinner masses. Chilled borders, parallelism of contacts with the flows, and apophyses into the metarhyolite characterize the intrusive nature of the basic schists.

In the Los Pinos area (Stark and Dapples, 1949, pp 1135-1136), basic schists occur in sill-like relation to all the Precambrian metasediments and metarhyolite, and in a few outcrops crosscutting dikes were found. In the Los Pinos area, primary igneous textures, vesicules, and amygdules were recognized in several outcrops; at three separate horizons, ellipsoidal structures suggested tops of flows. In none of the basic schists of the South Manzano Mountains were any of these features recognized, although special search was made for them. In general, basis schists of the northern area are much more sheared, and in many outcrops the schistose border zones are so completely altered that primary igneous structures, if they were ever present, are now completely destroyed. On the other hand, many outcrops show fine-grained borders and stringers of basic schist into the enclosing rocks, so that little doubt exists of their sill-like character.

The total thickness of the basic sills varies considerably from section to section. The combined thickness of the basic schists in Canyon Monte de Abajo is more than 1 mile, however, some of this thickness may be due to repetition by folding. The thickest measured sill (Canyon Monte de Abajo) is approximately 2,600 ft thick. In the canyon immediately to the south, the thickest sill is only 1,590 ft thick, but numerous smaller sills on both sides, separated by intercalated rhyolite flows commonly less than 50 ft thick, suggest that the larger sill to the north is divided into numerous small sills to the south. This pattern is repeated in all traverses across the metarhyolite. Commonly a sill will pinch out completely along the strike. Such lenses are well exposed in the north fork of Monte Largo Canyon.

The basic schists show extreme variations in texture and composition. Some of the larger sills appear to be composites in which finer grained rock has intruded the coarser grained. The common facies of the black schist are:

1. Metadiorite. The central portion of the thick sill in Canyon Monte de Abajo is a coarse-grained rock composed largely of saussuritized feldspar and fibrous hornblende. It grades into finer grained border zones averaging from 50 to 100 ft in width, which become pro-

gressively finer grained as the contact with the enclosing metarhyolite is approached. On both sides of the sill, the border zones are of thinly foliated chlorite schist. Both the chlorite schist zones and the coarser central parts of the sill are cut by fine-grained basic material of the same composition as the sill. The coarse-grained center has a blocky fracture and ranges from dark greenish gray to black. The feldspars, largely saussuritized, are surrounded by a felty matrix of chloritized hornblende needles ranging from 2 to 10 mm in length. There is complete gradation from the coarse-grained metadiorite to a fine-grained schistose border.

2. Lenticular feldspar schist. Many of the black schist sills show lens-shaped feldspars from 2 to 6 mm long, oriented parallel with the schistosity of the chloritized hornblende. These sills range in thickness from 1 to 400 ft and are the most common type of black schist.

3. Basic gneiss. In border zones of several of the thicker sills, the schist is foliated with bands of feldspar, 1 in. wide, alternating with hornblende-rich bands. The hornblende crystals become increasingly abundant toward the top of the bands in several outcrops.

4. Basic schist with oval inclusions. In Canyon Monte de Abajo and valleys to the north and south, several sills contain oval pods and drawn-out lenticular inclusions of coarse metadioritelike schist in a fine-grained matrix of chlorite and hornblende (pl 3-A). The majority of the pods range in size from 1 x 2 to 3 x 5 in. Some of the most elongated are 1 in. wide and from 6 to 10 in. long.

The smaller pods range from sharply bordered ellipsoids filled with coarse andesine crystals (2 mm) and quartz grains to vaguely outlined pods containing fine-grained plagioclase (.05 mm). Fibrous sheaves of hornblende wrap around the augenlike centers. The matrix is of fine-grained quartz, plagioclase, hornblende, magnetite, chlorite, and epidote. The pods are evenly distributed throughout the sills, with no noticeable concentrations near tops or bottoms, as might be expected if they were amygdules.

The larger augen have a higher feldspar content and are coarser grained than the matrix. They appear similar to inclusions of plagioclase porphyrite in metabasalt described by Sederholm (1923, p 37), who interpreted them as being due to fragments detached from subsurface plagioclase porphyrite and brought to the surface by rising magma. Such an origin seems highly probable for the augen schists of the South Manzano Mountains.

A rarer type of augen is shown in Plate 3-B. An epidote-rich center, 1 ½ in. in diameter, is surrounded *by* an altered plagioclase shell, which is in turn bordered by hornblende crystals 2 mm long. The plagioclase is altered to a fine granular mass of epidote, quartz, and calcite.

Hornblende of the basic schists makes up from 10 to 80 percent of the rock. It is highly pleochroic, with x = green, y = olive green, and z = blue. Staatz and Norton (1942, p 78) found optically positive pargasite in the basic schists of the Los Pinos Mountains, but in all sections from the South Manzanos the hornblende is optically negative. It occurs in fibrous, poikilitic crystals ranging from .005 to 30 mm in length, and appears identical with the hornblende of the hornblende-rich metarhyolite. Andesine is the predominant feldspar, ranging from .005 to 1 mm in diameter. Labradorite is rarely present. In general, the feldspar is altered to fine-grained epidote, quartz, and calcite. Epidote occurs also in veins and distinct grains, and forms as much as 10 percent of some thinsections.

Quartz is present in a number of the sills, apparently as primary grains and in veins. In a few sections, it averages 5 percent. Magnetite occurs in euhedral grains scattered indiscriminately throughout all other minerals, ranging from 1 to 3 percent and averaging 2 mm in diameter. Traces of apatite are present, and small amounts of biotite occur in the more highly sheared zones.

MONTE LARGO STOCK

A small stocklike mass of granite, quartz monzonite, and diorite, approximately 1½ miles square, crops out between the mouths of Monte Largo and West Bartalo Canyons in parts of secs. 26, 27, 34, and 35, T. 5 N., R. 5 E. The exposure is bounded on the south, east, and northeast by Blue Springs schist, by quartz reefs and Sais quartzite on the north, and by the overlying pediment gravels on the west. In outcrop and hand specimens, the rock appears similar to the much larger Ojito stock mapped by Reiche (1949, pl 5) 7 miles north of the Monte Largo exposure, and described by him as intrusive into the lower metaclastic series and greenstone complex. There is no reason to think that the two surface outcrops are not continuous at depth, but in the absence of any positive evidence, the southern exposure is called Monte Largo, from its outcrop at the mouth of this canyon.

The Monte Largo stock is coarse to medium coarse grained, and is composed almost entirely of saussuritized feldspar, quartz, and chloritized biotite and hornblende. It shows a schistose structure, schist inclusions more or less parallel to the schistosity, and numerous short, lens-shaped, quartz-filled vugs, which average 2-4 in. long and 1 in. wide.

Under the microscope, mineral percentages vary considerably from specimen to specimen, the rock grading from granite to quartz monzonite and quartz diorite. The feldspar is altered almost completely to masses of white mica. Remnants of twins in the saussuritized plagioclase indicate albite-oligoclase. Orthoclase, microperthite, and clear rims of orthoclase (?) surrounding plagioclase centers average 30-40 percent in the less altered specimens. In many sections, however, recognizable orthoclase is subordinate to the plagioclase. Quartz varies from approximately 25 percent in the granite to 20 percent in the more basic facies. The primary basic minerals are altered completely to chlorite, ranging from 15 to 20 percent, and to epidote, ranging from 2 to 3 percent. Out-lines of chlorite masses suggest that the chlorite may have originated from primary biotite. Calcite, apatite, tourmaline, and sphene are present in varying amounts. Much of the sphene is altered to opaque, yellow-stained leucoxene.

Shearing, apparently unrelated to the general schistosity of the stock, becomes increasingly marked as contacts with Blue Springs schist, quartz reefs, and Sais quartzite are approached. Directly at the contacts, the rock is a crumbly sericite schist, with quartz grains forming small knots. Near the center of sec. 26, T. 5 N., R. 4 E., a massive reef of vein quartz separates the sheared sericitic granite from the Blue Springs schist. The reef pinches out to the south, bringing the sericitic granite schist into contact with the highly sheared chlorite-sericite-quartz schist of the Blue Springs schist. Where the granite schist is in contact with the reef quartz, the relationship is one of shearing and molding of the schist against the quartz. Direct contact of the granite with the overlying Sais quartzite is obscured. Sericitic schists, oriented parallel to the contact, are only a foot or two from the quartzite, and show no evidence of being intruded; the relationship between the two appears to be one of shearing.

Near the western border, the Monte Largo intrusive becomes finer grained and more basic in character. Intrusive stringers of the coarser central granite cut this fine-grained border facies. The absence of such a border zone on the east and north supports the idea that the contacts at these places are probably faults and not intrusive contacts. The diorite border facies is fresher than the main mass of the intrusive. In thinsections, mineral percentages average: oligoclase, 50%, hornblende, 35%; orthoclase, 5%; quartz, 2%, magnetite, 1%, with traces of apatite. The plagioclase is almost entirely saussuritized; the hornblende is only slightly changed to chlorite and epidote.

Planar structures in the West Bartola Canyon exposure of the Monte Largo stock strike northeast and dip steeply southeast. Inclusions are subparallel to this structure, and quartz-filled vugs and thin epidote veins are oriented at right angles to it. Continuous quartz veins are not present, and the vugs are probably related to late consolidation stages of the intrusion.

The stock crosscuts the Sais quartzite (pl 1). A few hundred feet north of Monte Largo Canyon, apophyses from the main mass intrude the Blue Springs schist. On the north, the nature of the igneous-metaclastic contact is obscured by shearing. Strata overlying the stock are arched. Drag folds in the Blue Springs schist indicate that this arch plunges 45° NE. It was not determined, however, whether this structure is the result of roof arching by intrusion of the stock, or by later cross-folding, which is apparent in other parts of the area. Intense shearing has occurred everywhere along the borders of the stock. The structural features suggest that the stock was intruded into the Sais and Blue

Springs formations before or during the early folding of the Precambrian rocks.

PRIEST GRANITE

The Priest granite forms a lens-shaped outcrop, which underlies rugged central ridges of the extreme southern part of the South Manzano Mountains. It extends from latitude 34°28' northeast for 6 miles, with an average width of 1½ miles near the center, and narrowing at both ends.

The southern boundary is an intrusive contact with the Blue Springs schist and White Ridge quartzite. On the southwest, the granite is over-lapped by pediment gravels for 1 ¼ miles, as far as Muir reservoir. From here northeastward for 2 2/3 miles, the granite is in intrusive con-tact with the Sais quartzite. At the north, the granite intrudes Sais quartzite and Blue Springs schist. The eastern boundary is the Montosa thrust fault, except for a ¾-mile stretch at the south end, where the thrust passes into the limestone. Here, deeply weathered granite is over-lain by arkosic sandstone and quartzite of the basal Pennsylvanian.

The main mass of the Priest granite is a coarse-grained biotite-quartz-feldspar phanerite, with large phenocrysts or porphyroblasts of light-pink microcline. The granite is light red on fresh surfaces, but in most outcrops it is deeply weathered to a gray rock which readily crumbles. A younger facies of the granite is darker red, appears much fresher than the gray facies, and forms a border zone on the east, sending numerous apophyses and dikes into the gray granite. The younger granite is composed of dark-red feldspar, quartz, and biotite. Euhedral microcline crystals from ½ to 3 in. in diameter are common in both facies. At places, the red granite is sharply distinguished from the gray one; in other places, the two facies appear gradational, but the intrusive relationship of the red granite into the gray is generally evident. Epidote veins occur in both facies and are especially common along contacts of red granite. Irregular and gradational pegmatite bodies, from a few inches to a few feet in length and a foot or two wide, characterize the gray facies. Inclusions of schist and schlieren of partially digested schist occur in both the gray and red granite, but are especially numerous in the former. Roof pendants of schist and quartzite, from 1 in. to 50 ft long and from thin stringers up to 20 ft wide, occur in the gray granite near the central part of the outcrop.

Inclusions of schist and quartzite are numerous near the contact with the metaclastics, and in places abundant pegmatite and aplite dikes and quartz veins characterize the border zones. In many outcrops, thrust faulting has produced wide zones of fracturing and brecciation. A finer grained border facies is not evident except in a few places. Where finer grained border facies do occur, they are narrow, grading from coarse-grained granite to aplite in 4 or 5 in. Sills and dikes of granite from 1 to 200 ft thick intrude the metaclastics.

Mineral percentages in the granite average: total feldspar (including orthoclase, microcline, and albite [Ab_{92}]), 63%; quartz, 30%; biotite, 5%; epidote, 1%; with small amounts of magnetite, apatite, hematite, zircon, and allanite. Euhedral crystals of microcline, from 0.5 to 30 mm in length, are slightly altered to kaolin and sericite. Some albite crystals show rims of clear orthoclase. The albite is largely saussuritized to fine-grained masses of epidote, quartz, and white mica. Quartz grains range from 0.1 to 10 mm in diameter and form irregular patches, commonly poikilitic with biotite. Biotite varies considerably; much of it is associated with remnants of schlieren, where it forms as much as 15 percent of the rock. Much of the biotite is altered to chlorite and epidote.

A syenite facies of the gray granite occurs at its contact with the White Ridge quartzite on the crest of the ridge separating Marker Canyon from Estadio Canyon. The syenite crops out in a knob on the south slope of the ridge, approximately 50 by 200 ft, and is separated from the typical gray granite on three sides by covered areas 150 ft wide. Except for the absence of quartz, the syenite appears identical with the normal gray granite.

STRUCTURE OF THE PRIEST GRANITE

A structural analysis of the Priest granite was made by J. J. Dorman for his M.S. thesis at Northwestern University (1951). The following section is taken from Mr. Dorman's thesis.

The structural analysis identifies four main fracture directions that show a definite correlation with the flow structure. Some of these fractures are filled with late magmatic differentiates, and some are unfilled. In addition, four joint directions are identified as expressions of post-Permian regional deformations. One joint direction bears no clear relationship to other structures.

The structural interpretation of the Priest granite is based upon the orientation of various structural planes and directions determined from patterns of contoured point diagrams. These preferred orientations were examined in relation to each other and to the structures of the other Precambrian rocks in an attempt to reconstruct the deformational history of the granite.

A summary of the significant structural features of the granite stock is given in Plate 5.

The areal variation map of the joints (pl 6) illustrates that some sets of joints are developed only locally in the granite, but that other joint sets are persistent. These joint patterns do not seem to correlate in any way with the other structures of the granite.

The inclusions in the Priest granite are of quartzite and schist. They usually have a platy shape, with the shortest dimension perpendicular to the schistosity or bedding of the fragment. At places, the shape is pencillike. The schlieren are streaks of dark mineral concentrations having gradational borders with the granite. The schlieren are either platy or prismatic. Figures I -d and 3-d of Plate 6 show the similarity of the orientation patterns of schlieren and inclusions. This similarity is so close that the writer assumes that the schlieren in this case are the remnants of partly digested inclusions. Therefore, inclusions and schlieren jointly are referred to as flow structure, and no distinction is made between them in considering their structural significance.

However, there is an angular divergence of about 20 degrees between the average strike of the platy flow structure and the average strike of the metasediments which surround the granite, as is seen by comparing Plate 5, figure 5-d, with the geologic map, Plate I.

It appears that the granite was emplaced by injection, and that its inclusions and schlieren are fragments of the country rock carried along in the flowing mass.

Many surfaces of the granite present a rudely schistose weathered appearance, which is due to small, closely spaced, parallel cracks. Polished surfaces of the granite show no dimensional grain orientation, but minute parallel cracks from 2 to 10 mm apart are visible and correlate in direction with the fracture foliation in the country rock.

The irregularly shaped pegmatite segregations range from 1 to 2 ft wide and from 10 to 15 ft in length. Their borders are not sharp and clearly defined, like the walls of dikes, but are gradational both as to grain size and as to mineralogy of the rock. The pegmatites commonly are elongated or platy and have a preferred orientation.

The orientation of the inclusions and schlieren (pl 5, points N and O) shows that the strike of the flow planes in the granite is N. 5° E.

The preferred orientation becomes weaker away from the contact. There is no reversal of this deviation slope west of the Montosa thrust contact. The writer believes, therefore, that the Montosa fault did not break the granite in the immediate vicinity of its eastern intrusive con-tact, but left a considerable portion of granite concealed on the down-thrown fault block. Further evidence for this contention is the relatively greater abundance of inclusions near the intrusive contact than near the Montosa fault contact.

For satisfactory results, an analysis of the fracture pattern of a granite should be controlled by correlation with flow lines (Balk, 1937, pp 27-33). The primary fractures of the Priest granite bear a systematic relation to its flow structure; hence, the primary fractures can be identified with considerable assurance.

Cross fractures are identified as those preferred fracture planes whose poles show a subparallel relation to the flow lines, point P (pl 5, fig 3-a). This structural role is assumed by the aplite and pegmatite dikes, and the joints represented by points I, J, and A respectively. The cross fractures are probably tension phenomena.

The term longitudinal fractures is applied to the sets of primary fractures in igneous intrusions that are oriented perpendicular and contain the flow lines. Plate 5 shows that in the Priest granite this structural role is assumed by the fracture foliation, the epidote dikes, and a small number of pegmatite dikes. These planes are subparallel to the platy flow structure. The summary chart (p15) shows that the angle between the average planar flow structure and the average plane of fracture foliation is only 5 degrees. This is regarded as strong evidence that the fracture foliation is primary.

Horizontal joints in the Priest granite are not mineralized but they are distinguished by their perpendicularity from cross fractures and longitudinal fractures. These joints are represented by point B (pl 5).

The epidote dikes, point M (p1 5), probably occupy primary diagonal fracture planes. They make an angle of 66 degrees with the prominent set of longitudinal epidote dikes. According to Balk (1937, p 37), diagonal joints are not common but are developed sometimes to relieve lateral stresses in intrusives which are not free to lengthen by the injection of very thick cross dikes. This is probably the reason for their development in the Priest granite.

No mention has been made of the numerous joints which show no approximate parallelism to any of the sets of primary fractures. Most of these, instead of being scattered at random over the point diagram, are grouped into other highs. This is accepted as sufficient evidence that they have been formed by later crustal deformation. Points C, D, E, F, and G (pl 5) give the average orientations of these sets of secondary joints. Set E is the most prominent direction in the entire granite. Not only are there large numbers of joints of this orientation but they are also widely distributed. In contrast to this wide distribution are orientation points C and D. These highs represent joints which are developed only in the extreme southern tip of the stock and therefore appear only in Plate 6, figure 1-c.

In the Priest stock, the writer has correlated four of the joint directions mentioned above with other deformation features. Points C and D represent two sets of joints which clearly show a complementary relationship to each other with respect to an assumed horizontal compressional stress acting in the direction N. 45° W. These two planes intersect at an angle of 82 degrees, the bisector of the acute angle being approximately horizontal. The axis of least stress, therefore, is vertical, and the axis of intermediate stress is horizontal. This configuration of stresses corresponds closely to that which must have caused the Montosa thrust fault. The localization of these joints, close to the Montosa fault, lends weight to the conclusion that they are an expression of the same disturbance. The Montosa fault can be regarded as a member of fracture set C.

The above stress configuration is significant for another reason. Points E and F represent two other joint sets which are approximately symmetrical with the Montosa fault, except that in this case the stress magnitudes are interchanged. The intermediate axis is vertical with respect to these joints. The acute angle opens to the northeast, suggesting that the greatest stress axis was in that direction, and that the least stress axis was in the northwest direction. Actually, the axis of symmetry of this pair of joint sets is N. 61º W. rather than N. 54° W., a divergence of only 7 degrees. These joints bear a striking similarity in orientation to Tertiary basalt dikes cutting the Permian sediments of Chupadera Mesa, 20 miles to the southeast. The geographical relation of Chupadera Mesa to the Manzano Mountains is shown on the index map (fig 1). The similarity in orientation is strong evidence that the above-mentioned joint sets of the Manzano Mountains and the fractures of Chupadera Mesa, if not the basalt intrusions themselves, are results of the same deformational episode. Fracturing of this kind is equivalent to the formation of transcurrent faults, as defined by Anderson (1942, p 13).

One set of fiat joints represented by point G bears no clear relation-ship to the structures discussed above.

PEGMATITE AND APLITE DIKES

Irregular areas of pegmatite from a few inches to a few feet wide, and rarely more than 5 ft long, are common in most outcrops of the gray Priest granite. Their boundaries are gradational rather than sharp. Large pink microcline crystals from 1 to 2 in. long are common in the pegmatite and appear identical with the large feldspars in the normal granite. The porphyroblasts of pink feldspar in the schist inclusions are similar to the large pink microcline crystals in the granite, which suggests that the crystals in the granite may be porphyroblasts.

More typical dikelike pegmatites, ranging from thin stringers to several feet in width, cut all the Precambrian metaclastics and rhyolite. Near the Priest granite, the pegmatites are dominantly of quartz, micro-cline, feldspar, and biotite. Away from the granite contacts, the dikes become increasingly quartzose, with only small amounts of microcline and no dark minerals. Several such dikes grade into veins composed entirely of quartz.

Pegmatite and aplite dikes are numerous near the border of the granite, cutting both the metaclastic and the igneous rock. These range in thickness from stringers to 20 ft and commonly show chilled borders. Aplites are also numerous in the central part of the Priest granite. Their abundance, together with increasing numbers of small schistose inclusions and larger inclusions of schist and quartzite suggestive of roof pendants, is thought to indicate nearness to the roof of the granite stock.

QUARTZ VEINS AND REEFS

Cutting all the Precambrian formations are numerous quartz veins and vein-dikes which range in size from thin lenses to reeflike masses over 1,300 ft thick. The smaller veins are particularly abundant in the highly contorted Blue Springs schist, where they form elongated and oval pods from paper thinness to several inches wide, and from a fraction of an inch to several feet long. The quartz lenses appear to have been de-posited before the last folding of the schist. They are squeezed and pinched into sinuous layers conformable with the schistosity. A still later period of disturbance is indicated by cross fracturing. Locally, in Comanche, Jaramillo, and Trigo Canyons, the quartz lenses form nearly 50 percent of large outcrops of the Blue Springs formation.

One of the most striking features of the South Manzano Mountains is the large reeflike masses of quartz, which are commonly more than 1,000 ft thick. They form partitionlike ridges, some 600 ft in height, one reef in Trigo Canyon being traceable in continuous outcrop for 3 miles. The largest reefs are confined to the Sais and White Ridge quartzites and Blue Springs schist. They are particularly prominent on the west slope of the range, from Monte Largo Canyon northward, extending into the North Manzano area. The reefs pinch and swell; they are in many places conformable to the enclosing formations, and in other out-crops show crosscutting relations to schistosity and bedding (p1 7-A, B).

A prominent reef in the south wall of West Bartola Canyon occurs between the Blue Springs schist on the east and the sericitized schistose border of the Monte Largo granite on the west. In a distance of 2 miles southward to the mouth of Monte Largo Canyon, the reef narrows and pinches out completely several times. Schistosity of the enclosing rocks is parallel to the walls of the reef.

Followed along the strike, the massive reefs show both abrupt endings against the schist and a pinching out parallel to the schistosity in the Blue Springs formation and to the bedding in the quartzites. At places, the boundaries of the quartz reefs are gradational; at other places, laminae of the Blue Springs formation project into the reef. Although the reefs appear most commonly in the Sais and White Ridge quartzites, they also occur throughout the Blue Springs schist and between the schist and the Monte Largo granite.

Thin, irregular streaks and stains of manganese oxide and specular hematite are common in the quartz reefs. Structurally, they show shearing and distorted planar structures suggestive of the zone of flow. Quartz veins, probably in tension fractures, cut these planar structures. Imposed on these earlier structures are jointing, fracturing, intense brecciation, and development of slickensides that are related to later movements, probably the Laramide thrusting. The lenses, pods, and stringers of quartz in the Blue Springs schist may be much older than larger cross-cutting veins and the massive reefs.

All the quartz is Precambrian in age except the silicification of the fault breccias, which is partly contemporaneous with, and partly later than, the Laramide thrusting. The vein quartz and massive reefs, so abundant in the old metaclastics, do not extend into the overlying Paleozoic formations. In the vicinity of Capillo Peak, where the uncon-

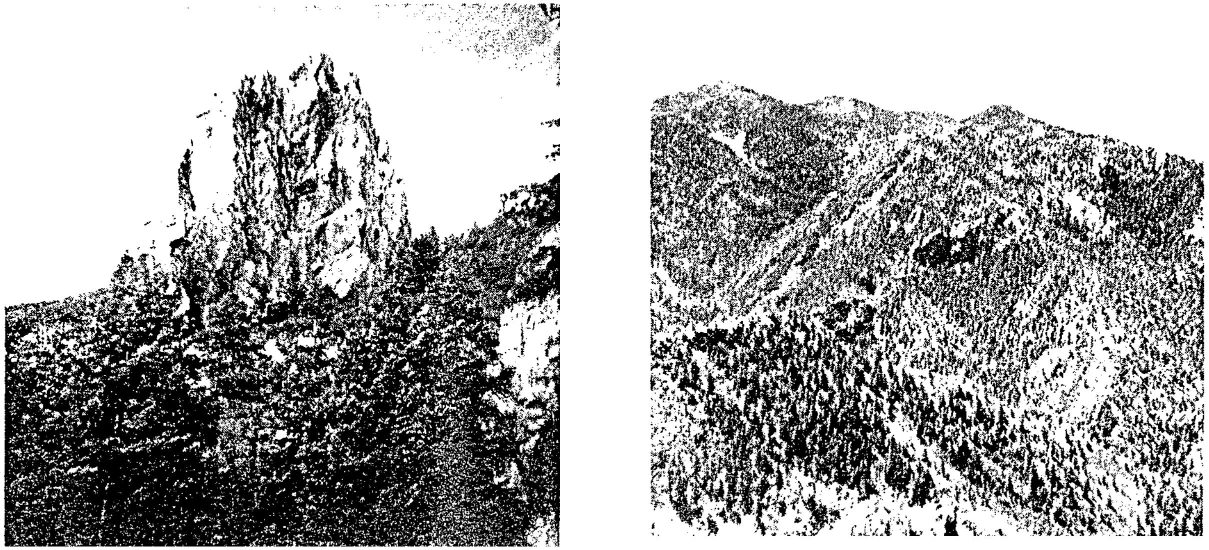
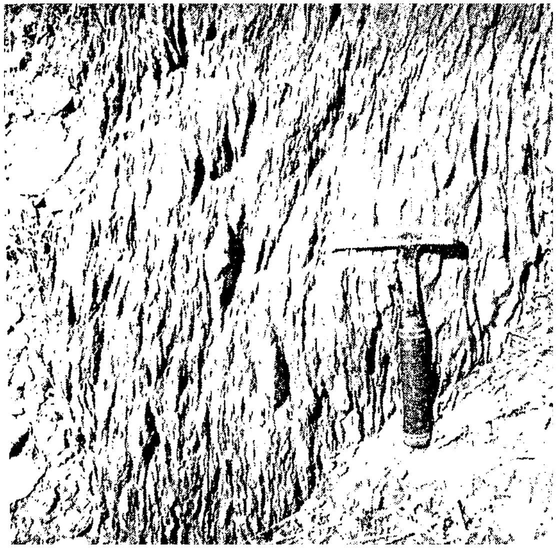
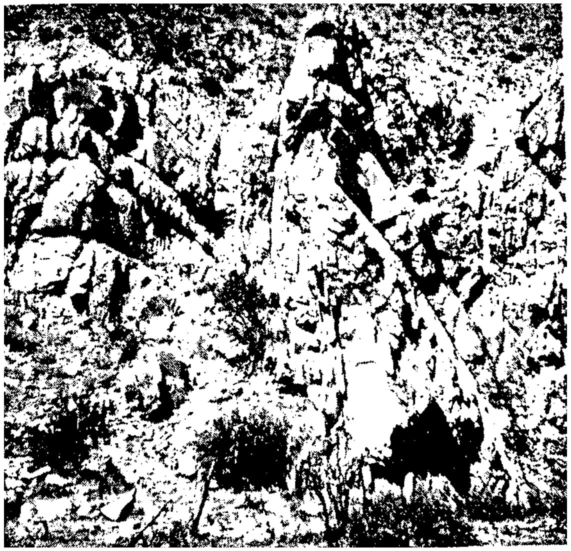


Plate 7

QUARTZ REEFS



A. PODS AND STRINGERS OF VEIN QUART IN BLUE SPRINGS SCHIST, COMANCHE CANYON.



B. LARGE DRAG FOLDS IN SAIS QUARTZITE. THE ANTICLINE TO THE RIGHT HAS BEEN SHEARED OVER ANTICLINE TO THE LEFT, OBLITERATING THE INTERVENING SYNCLINE, ESTADIO CANYON.

Plate 8

SECUNDARY STRUCTURES IN PRECAMBRIAN METACLASTICS

formity is well exposed in vertical sections for several miles, the quartz reefs end abruptly below the basal Pennsylvanian sandstone.

The origin of the quartz reefs has been interpreted differently. According to Keyes, they represent sandstone lenses metamorphosed to quartzite. Describing quartz reefs in Tijeras Canyon, along U. S. High-way 66, Keyes (1920, pp 240-241) states:

> The quartzite beds which stand at high angles are commonly mistaken for immense quartz reefs, and under such misconception they are extensively prospected for gold. Microscopical examination in thin slices demonstrates conclusively that the rock has a clastic origin, and that it is an old sandstone indurated by the interstitial deposition of silica disposed in optical continuity with the separate sand grains.

Ellis (1922, p 28), working in the same area, recognized that the origin was not so simple. He writes of the quartz reefs in Tijeras Canyon:

> This ridge may then be said to be a series of quartz schists, embodying some phases of massive quartz, almost pure, resembling quartzite. Whatever its origin may have been, it does not now present the aspect of an ordinary bed of quartzite, such, for instance, as occurs among the Algonkian rocks of the Lake Superior region. Its position as related to other rocks; the absence of clastic structure; the frequent pinching out of the ledge; the decidedly schistose structure intervening between the quartz layers, and the presence of shear planes between these layers; the plications of pure quartz layers running parallel with the general direction of schistosity of the series; the absence of any indication of bedding planes — these are some of the peculiar features presented in this ’quartzite' ridge.

Reiche (1949, p 1188) believes that much of the vein quartz in the lower metaclastic series is secondary. He speaks of the formation as being strongly silicified in the upper few tens of feet: ". . . and for 3 to 4 feet at the unconformity there has been essentially complete replacement by massive milky quartz." Of the schists correlated with the Blue Springs formation, he states (1949, p 1190) that "they are crowded with small lenses of vein quartz." In the same paragraph, however, he implies a sedimentary origin of the large quartz reefs: "Lensing reefs of buff, massive, saccharoidal quartzite, which weather to narrow hogback ridges, are conspicuous in this part of the section."

The quartz reefs of the South Manzano Mountains are a southward continuation of the "lensing reefs" described by Reiche. Their prominence is shown on the geologic map (pl 1), where the definite crosscutting relations of many reefs are clearly evident. Structurally, they resemble the reefs in Tijeras Canyon described by Ellis and similar reefs, smaller in size and less numerous, which occur in the Los Pinos Mountains. They pinch and swell, paralleling the enclosing metasediments in some places, and transgressing them in others. They cut all the Precambrian formations, and are particularly abundant in the Sais and Blue Springs formations of the northern part of the South Manzano Mountains and along the contact of the Monte Largo stock and the schist. In all out-crops, it is evident that the reefs shared in folding and metamorphism of the host rock. Although some of the quartz ridges may represent lenses of clastic sandstone now metamorphosed to quartzite, it is the writer's interpretation that the majority of the large reefs are vein quartz that was intruded into, and replaced, the enclosing rocks, and that they are similar in origin to the numerous stout lenses and stringers of vein quartz which form as much as 50 percent of some parts of the Blue Springs formation.

Metamorphism of the Precambrian Rocks

The regional metamorphism of the Precambrian metasediments has been, in general, of low to moderate intensity. The schists composed dominantly of hornblende, plagioclase, quartz, and epidote are assigned to the amphibolite facies (Turner, 1948, p 76). Basham (1951, pp 81-82) suggests the attainment of equilibrium from two directions, owing to progressive and retrogressive metamorphism. In the former, epidote of the hybrid rock between the Sevillita metarhyolite and the basic sills was converted to hornblende and labradorite. In the latter, pyroxene and, possibly, olivine of the basic sills retrogressed to hornblende. Accompanying the formation of the amphibolite facies in the South Manzano Mountains, the country rock appears to have been folded, and an axial-plane schistosity was developed. The Monte Largo stock probably was intruded early during the deformation and was involved in the folding.

The intrusion of the Priest granite into already partially metamorphosed metaclastics formed a thermal aureole, which is best developed in the Blue Springs schist. New minerals were formed in the Sais and Blue Springs rocks by the addition of material to the border zones, recrystallization of original constituents, and reaction with hydro-thermal solutions from the granite batholith. Muscovite is not found outside the thermal aureole but is abundant near the granite in both the quartzite and schist. Secondary quartz, forming rims around the grains of poikilitic muscovite, is common.

Mineral zoning is recognized more easily in the Blue Springs schist than in the coarser grained metaclastics. At its contact with the Priest granite, large muscovite porphyroblasts with poikilitic texture are the most prominent feature. The muscovite appears about 400 ft from the granite and increases to a maximum of 50 percent at the schist-granite contact. The muscovite zone is cut by many muscovite-rich pegmatite dikes and apophyses from the granite.

Sericite increases in the schist as the granite is approached, averaging 2 percent in quartzose siltstone at 1,800 ft from the granite, and increasing to 58 percent at 15 ft from the contact. Immediately at the contact, it is recrystallized to muscovite. Sericite occurs throughout the Blue Springs schist. It is a product of earlier metamorphism.

Quartz decreases from 82 percent in siltstone at 1,800 ft to 1 percent 15 ft from the granite. There is a corresponding increase in average grain size from .05 to 0.2 mm.

Biotite increases from 5 percent at 1,800 ft to 8 percent at the granite contact. Chlorite shows an increase as the granite is approached. Both biotite and chlorite are widespread throughout the Blue Springs schist.

Feldspar attains a maximum of 15 percent in the Blue Springs aureole at the granite contact. It is mostly oligoclase-andesine, although orthoclase also may be present. Except in the highly altered inclusions, it does not form distinct porphyroblasts as commonly as in the Sais quartzite. Altered centers of the feldspar grains are surrounded by clear borders.

Garnet occurs in megascopic grains only within the immediate aureole, where the mineral encloses quartz. As these garnet crystals do not disturb the schistosity and show no signs of rotation, they appear definitely related in origin to the granite intrusion.

Epidote in small rounded grains occurs in siltstones 1,800 ft from the granite and disappears in some outcrops as the contact is approached.

Tourmaline-bearing dikes are present in Marker Canyon. Tourmaline occurs in blades and lath-shaped poikiloblasts at several places in the Blue Springs schist. Although not restricted to the immediate aureole, it is related probably to the granite intrusion.

Sillimanite occurs in two localities, 160 ft from the granite contact near Abo Pass, and immediately adjacent to the contact in Marker Canyon.

At many places within the 400-ft aureole, there are muscovite pseudo-morphs ranging from microscopic size to 5 x 5 x 25 mm, suggestive in their columnar outlines of alterations from andalusite or sillimanite. They are similar in appearance to pseudosillimanite crystals in mica schist near Mt. Monadnock, New Hampshire, described by Fowler-Billings (1949, pl 4). The muscovite areas are surrounded by chlorite and quartz. Magnesium, aluminum, and iron impurities apparently were expelled from the original porphyroblasts, forming the bordering chlorite laths. Excess silica to form quartz was probably a byproduct of the alteration of the sillimanite to muscovite. Turner (1948, p 154) states that aggregates of white mica, pseudomorphs after andalusite, show that thermal preceded hydrothermal metamorphism. It is probable that the pseudosillimanite in the Blue Springs schist is of this origin.

From a study of a section of Abo Pass, Staatz and Norton (1942, p 44) concluded that the overall contact metamorphism was more dependent on original composition of the sediments than on nearness to the granite, but they mapped a zoning effect as follows: (1) a zone of epidote farthest away from the intrusion; (2) a zone of no distinctive mineral; (3) a sillimanite zone; and (4) a zone of muscovite porphyroblasts nearest the intrusion. General agreement with this is shown by the data presented above, with the addition of pseudosillimanite (?) and garnet in the muscovite zone nearest the granite.

In Marker Canyon, the zoning differs slightly from that near Abo Pass, epidote and sillimanite being much closer to the granite contact. The pseudosillimanite (?) crystals, which are prominent at Abo Pass, are inconspicuous or absent from the schists in Marker Canyon. Garnets, abundant in the aureole at Abo Pass, were not found in Marker Canyon. These variations might be explained by differences in original composition of the schists, or by differences in emanations from the intrusion.

However, similar siltstones are present in both localities, and the development of muscovite porphyroblasts appears to be identical in each area. The differences in metamorphic intensity may be due to higher temperatures in the Abo Pass area.

General field relations lend some support to the above interpretation. In Marker Canyon, there are numerous large aplite dikes and fine-grained granite bodies both within the granite and in the adjacent Blue Springs schist. This aplitic material may have served to separate the metaclastics from the main igneous mass. Folding is more complex at Abo Pass, and the contorted metaclastics near the granite are cut by pegmatites. These structures are well developed in the reentrant of Blue Springs schist in the granite just north of Abo Pass.

Metamorphism of the Sevillita metarhyolite by the Priest granite developed abundant porphyroblasts of garnet and chloritoid in rhyolite previously metamorphosed to sericite schist. Muscovite-chloritoid-almandine-quartz is listed by Turner (1948, p 89) as a typical mineral assemblage of the epidote-amphibolite facies, and this subfacies is believed applicable to the Sevillita rhyolite. This would be a higher grade metamorphism than the green-schist facies characteristic of the Blue Springs formation, and a lower grade than the amphibolitic facies of the black schists.

Evidence of intense shearing is conspicuous in all the Precambrian metasediments. Some of this shearing undoubtedly was associated with the development of the large central syncline.

Quartzite adjacent to the Montosa thrust averages 10 percent sericite, forming in certain zones as much as 20 percent of the rock. Similar zones of sericite-quartz schist are developed in the White Ridge quartzite along the Paloma thrust and in the Sais quartzite along the Bartola thrust. Granulation, flaser, mortar, and augen textures are prominent in the shear zones.

Structure

GENERAL STATEMENT

The major events in the structural history of the South Manzano Mountains were: (1) folding, which produced the central syncline or synclinorium; (2) thrust faulting in post-Pennsylvanian time, which brought the Precambrian against Paleozoic sediments; (3) block faulting of the Basin and Range type, which resulted in the present straight and precipitous western front of the Los Pinos and Manzano Mountains.

The most recent disturbance in the region, probably Quaternary, has resulted in small gravity faults in the western pediment, exposing Permian and Triassic sedimentary beds (pl 1). Small remnants of an olivine basalt flow, just south of the small scarps in the pediment, are presumably of the same age as Quaternary basalt and andesite flows west and south of the Los Pinos Mountains.

FOLDING

The large syncline forming the central part of the area is asymmetric with its steeper eastern limb overturned in the northern 5 miles of its exposure. The axial plane strikes N. 30° E., the beds showing progressively steeper dips from north to south: 60° SE. at Capillo Peak, 70° SE. in Colorado Canyon, and 85° SE. on Manzano Peak. Thus, a lessening of the overturning to the south is indicated. The syncline has an average plunge of not more than 5 or 6 degrees to the southwest. Local steepening and reversals of the plunge are evident in many outcrops.

Drag folds are present in all the formations and are especially well developed in the steep, overturned eastern limb of the syncline. In the Blue Springs schist and in the sericitic schists of the rhyolite flows, the drag folds are small, rarely more than 1-2 in. across and commonly in repeated smaller and smaller crinklings. In the Sais and White Ridge quartzites, the drag folds range from 2 to 10 ft in width. In one vertical exposure in Estadio Canyon (pl 8-B), the drag folds are isoclinal, averaging 10 ft across and 40 ft high. These folds plunge 20° SW., and their axial planes dip 60° SE. The plunge of these folds is much steeper than the average plunge of the major syncline. Locally, a series of small faults has sheared the anticlinal drag folds over one another with such intensity that the synclines between them are almost obliterated.

Structural adjustment following the formation of the central syncline is indicated in many outcrops. The regional schistosity strikes N. 30° E., generally paralleling the axial plane of the central syncline; there are, however, many local divergences from this direction. In Comanche, Jaramillo, and Trigo Canyons, the regional schistosity in the Blue Springs schist has been folded and faulted. In Comanche Can-yon, a normal fault, downthrown on the north, trends N. 40° E., for almost the entire length of the schist outcrop. The schistosity on both sides of the fault has been folded by this faulting. Similar distortions of the schistosity occur in Jaramillo and Trigo Canyons to the south.

The Sais quartzite and Blue Springs schist, immediately north of the Atchison, Topeka and Santa Fe Railway and west of the Montosa thrust fault, contain folds that cross the regional trend of the central syncline. An anticline, syncline, and anticline occur in an outcrop less than a mile wide. The folds trend northwest and plunge in the same direction. Axial plane cleavage is developed on the major folds, but small drag folds commonly show folding of the schistosity.

Reiche (1949, p 1197) reports Precambrian faulting and folding and infers three successive orogenies:

> (1) Compression directed from the south-southeast and southeast caused slaty cleavage and thrust faults. (2) Cleavage was plicated, with an asymmetry which seems to imply settling or relaxation of the rock mass toward the former direction of thrusting . . (3) Later, east-west or southwest-northeast compression caused broad folds whose steep southeasterly pitch was inherited from previous disturbances.

No such clear sequence of directional compressions was recognized in the South manzano area, but it is clear that there were several periods of deformation.

The early development of the central syncline, the intrusion of a granite stock with associated dikes and vein quartz, and a later period of intensive folding, shearing, and fracturing would, in general, agree with Reiche's three periods of Precambrian orogenies, although the directions of compressive disturbance are not so sharply defined.

FAULTING

GENERAL STATEMENT

Two thrust faults in the Los Pinos Mountains strike longitudinally along the range and conform generally in dip to the westerly dip of the metasediments and rhyolite flows (Stark and Dapples, 1949, pp 1159-1161). These thrusts, the Montosa on the east and Paloma on the west, continue northward without interruption into the South Manzano Mountains and are recognized in repeated outcrops of silicified fault breccia, displacement of formations, slickensided shear surfaces, and the upturning and reversals of dip of the Paleozoic sediments against which the Precambrian formations were thrust. Approximately 3½ miles south of Capillo Peak, the two faults merge, and a single fault continues north-ward as the Montosa thrust.

The Padilla thrust mapped by Reiche (1949, pl 5) along the eastern front of the North Manzano Mountains, if projected southward from Capillo Peak, would intersect the Montosa thrust. The observed length of the eastern fault zone in the South Manzano and Los Pinos Mountains is 42 miles. Covered by flows of late Tertiary or Quaternary basalt, this fault can be traced several miles farther, south of the Los Pinos Mountains.

A third zone of thrusting, comparable with the Montosa and Paloma thrusts, is exposed in two outcrops about 6 miles apart, near the mouths of Comanche, and West Bartola and Monte Largo Canyons respectively. The great width of the silicified fault breccia, the direction of thrusting on slickensided faces, and the southwestward trend, which takes this third zone of thrusting under the pediment gravels, are all suggestive of a third, more western, zone parallel to, rather than branching from, the Paloma thrust.

Associated with the major thrust zones are many small cross faults with horizontal offsets ranging from a few feet to half a mile. Small gravity faults of Quaternary or Recent age form a line of scarps in the alluvial fans of the western pediment.

MONTOSA THRUST FAULT

The easternmost fault, the Montosa thrust fault, is traceable in almost continuous outcrop, from Abo Pass northward, along the entire eastern front of the South Manzano Mountains. The general trend is N. 18° E., and the westerly dip more or less parallels the dip of the Precambrian metaclastics. The dip steepens near the surface at the contact with the Paleozoic sediments. Except in the vicinity of Kayser Can-yon, where it is covered by alluvial gravels, the silicified fault breccia is recognizable in nearly every valley of the eastern slope of the range.

The thrusting brings Precambrian quartzite, schist, metarhyolite, and granite against Pennsylvanian limestones, which, as a result of the faulting, stand vertical or are overturned. In Sand Canyon, 2 miles north of Abo Pass, the upturned Paleozoic rocks form spectacular vertical cliffs, which rise 400 and 500 ft above the valley floor and extend several miles up the canyon. Vertical and overturned Paleozoic beds mark the eastern limit of the fault zone in every large valley between Sand Canyon and Capillo Peak. South of the railroad, just east of Abo Pass and a short distance east of the vertical beds just described, a small syncline has formed in the Pennsylvanian beds.

In all but two localities, the Montosa fault lies between Precambrian and Paleozoic formations. In Sand Canyon, where the Priest granite is thrust against Pennsylvanian limestone, the fault passes into the sediments for a short distance, leaving a mile-long slice of limestone and sandstone on the upthrust western side. Here, the basal Pennsylvanian sandstone rests on the granite, in depositional contact. The contact is in a gradational zone of deeply weathered granite and conglomeratic sandstone. Again, in the vicinity of Capillo Peak, the fault passes into the limestone for a distance of nearly 3 ½ miles across the head of Comanche Canyon, where it appears continuous with the Padilla thrust zone of the North Manzano area.

In the northern part of the Los Pinos Mountains, north of Parker ranch, the throw of the Montosa thrust is approximately 1,200 ft, equal to the thickness of the Derry, Des Moines, and Missouri strata of the Pennsylvanian (Stark and Dapples, 1946, p 1161). The throw increases northward; near Pine Shadow Springs, in Priest Canyon, almost the entire thickness of the Pennsylvanian is cut out. Reiche (1949, p 1201) reports a throw of 2,000 ft on the Padilla thrust, the northern continuation of the Montosa fault.

PALOMA THRUST FAULT

The Paloma thrust zone represents on a larger scale some features of the Montosa thrust: silicified fault breccias, vertical and overturned beds, and broad zones of slickensided surfaces showing directional movement from west and southwest upward and eastward. The average trend of the Paloma thrust (N. 30° E.) swings eastward from Abo Pass across the range to Colorado Canyon, 34°38' N. latitude, where it joins the Montosa thrust. The dip of the fault zone is steeply westward to overturned in surface outcrops, but is thought to flatten with depth, approximating the dips of the metaclastics and rhyolite flows. The highly sheared sericitic and chloritic siltstones of the Blue Springs schist very likely offered less resistance to overthrusting and formed favorable lubrication for the eastward movement. Southward, the zone is continuous with the Paloma thrust of the Los Pinos area.

In crossing the range, the Paloma thrust brings successively from south to north: White Ridge quartzite over Blue Springs schist, south of the railroad at Abo Pass; White Ridge quartzite against White Ridge quartzite, between the railroad and Muir reservoir; White Ridge quartzite against Sais quartzite, in canyons north of Muir reservoir; White Ridge quartzite over Blue Springs schist, in Marker Canyon. At the last locality, the zone of thrusting widens, and slickensided shearing surfaces extend southeast for nearly half a mile, crossing the intrusive contact of the Priest granite with White Ridge quartzite and Blue Springs schist. A half mile northeast of Manzano Peak, the fault zone again cuts out entirely the Blue Springs formation and brings White Ridge quartzite against Sais quartzite. Two and one-half miles farther to the northeast, the Paloma joins the Montosa thrust.

The throw of the Paloma fault, as a minimum, is equal to the thickness of the Blue Springs schist. This formation is completely cut out in two localities, bringing the younger White Ridge quartzite over the older Sais quartzite. Where the Blue Springs schist is closely folded, with dips averaging 75 degrees, the thickness across the western limb of the central syncline approximates 11,500 ft. Unquestionably, this represents many repetitions by folding. In Marker Canyon, where the Blue Springs schist appears least folded, the thickness across a half-mile width of outcrop, with dips averaging 50 degrees, is 2,420 ft. This figure should approximate the true thickness of the Blue Springs schist and represent the probable minimum throw of the Paloma thrust.

BARTOLA THRUST FAULT

A fault breccia, thoroughly slickensided, with broad shear planes that indicate an eastward updip movement of the Sais quartzite, is exposed in a zone 250 ft wide and 1 mile long at the mouth of West Bartola Canyon, latitude 34°38' N. The fault is named from this type locality. It trends N. 35° E., disappearing southward beneath the pediment gravels. A similar zone of fault breccia, approximately one-fourth mile square, with slickensided shear surfaces striking N. 20° E., crops out in the Sais quartzite immediately north of the mouth of Comanche Canyon, latitude 34°43' N. Between the two outcrops, the pediment gravels encroach upon the mountain slopes, but the general trends and similarity of the zones suggest that the thrust is continuous under the gravels. This break possibly may represent a branch of the Paloma thrust; more likely, it is a third, more westerly, thrust fault of major proportions, roughly paralleling the Paloma and Montosa thrusts.

In the southern outcrops, the Sais quartzite is thrust against Blue Springs schist and the Monte Largo granite. In the northern outcrops, the fault zone is confined to the Sais quartzite. In each place, a massive quartz reef is immediately east of the brecciated zone, and vein quartz is prominent in the breccia. Because of the similarity in all respects to the brecciated zones of the Paloma and Montosa thrust faults, which are believed to represent Laramide orogeny, the Bartola thrust is thought to be a part of the same disturbance. Many hundreds of slickensided faces leave no doubt as to the eastward direction of thrusting.

NORMAL FAULTING

There are undoubtedly many small faults, associated with the in-tense Precambrian orogenies and Laramide thrusting, that are concealed in the complex structures exposed today. Reiche (1949, p 1197) recognized several Precambrian thrusts and later normal faults in the North Manzano Mountains. In the South Manzano area, shear zones other than those immediately in the brecciated zones of the major thrusts occur in all the Precambrian formations and were crossed repeatedly in every traverse across the range. They were not considered as zones of major displacement, however, and were not mapped. Normal faults are mapped in many outcrops.

There is a normal fault just north of the mouth of Comanche Canyon, where Sais quartzite rests unconformably on the older metaclastic series (Reiche, 1949, pl 5). The downthrow is on the west. The strike of this normal fault is parallel to the trend of the broad silicified zone of the Bartola thrust.

A similar sequence of normal faults is associated with thrust movement of the Bartola thrust at the mouth of West Bartola Canyon. Here the Sais quartzite is conformably overlain by the Blue Springs schist. A normal fault repeats the two formations on the downthrown side west of the broad brecciated zone of the Bartola thrust. The trend of the normal fault here, as at the Comanche Canyon exposure, lies in, and parallels, the breccia of the thrust.

The repetition of stratigraphic evidence for normal faulting and the similarity of the shear surfaces, silicified fault breccias, and directional movements indicated by the slickensides, add support to the interpretation that the two outcrops are continuous under the pediment gravels that separate them at the surface. In the Los Pinos Mountains, the normal faulting is believed to be due to relaxation following the compression that produced the thrusting. That such reversal of movement following Laramide thrusting is not exceptional is indicated in several large thrusts of Laramide age in the Sawatch Range of central Colorado, where stratigraphic displacement and crosscutting slickensides on earlier slickensided faces show clearly that at this locality normal faulting occurred in the original thrust zones (Stark, 1934, pp 1012-1015).

Three small faults, apparently closely associated with the Bartola thrust, occur in sec. 22, T. 5 N., R. 4 E. Two north trending faults, west of the broad zone of silicified breccia, show downthrow to the west, causing offsets in the Sais quartzite, Blue Springs schist, and Monte Largo granite. They probably represent postthrust normal faulting.

Near the mouth of West Bartola Canyon, a small strike-slip fault trends east and offsets Sais quartzite, a massive quartz reef, Blue Springs schist, and the Monte Largo granite approximately 1,000 ft.

A normal fault in the Blue Springs schist follows the northeast trend of Comanche Canyon for 2 miles. Folding of the schistosity along the entire length of the fault indicates that the downthrow is on the south-east side. In Trigo Canyon, sec. 17, T. 5 N., R. 5 E., a broad brecciated zone in a massive quartz reef trends northwest with the valley. Slickensides indicate that the southwest side was downthrown. At the head of Jaramillo Canyon, sec. 9, T. 5 N., R. 5 E., a normal fault in the Blue Springs schist trends northeast, exposing on the northwest the down-dropped block of Pennsylvanian sandstone and limestone. This fault appears continuous with the normal fault just south of Capillo Peak.

A small normal fault in the SE ¼ sec. 8, T. 4 N., R. 5 E., strikes northwest and dips steeply northeast. The fault is recognized by a well-developed fault breccia and slickensiding.

The normal fault of greatest displacement occurs along the western front of the mountains. It is now buried beneath pediment gravel. This fault is believed to be responsible for the elevation of the Manzano and Los Pinos Mountains. Denny (1940, pp 96-99) cites as evidence for the fault the distribution of Tertiary Santa Fe beds in the Rio Grande Valley and on the western escarpment of the mountains. The approximate throw may be estimated, as the Permian and Triassic beds crop out in the pediment 4 miles west of the Precambrian exposures of Comanche Canyon. The total thickness of the Pennsylvanian in this area is 1,400 ft, and the thickness of the Permian is 2,800 ft (Reiche, 1949, pp 1198-1199).

The elevation difference between the top of the Permian beds in the pediment and the unconformity between the Pennsylvanian and the Precambrian is 3,200 ft. A total throw of approximately 7,400 ft is possible.

All faults shown on Plate 1 are drawn on the basis of clear field data, fault breccias, extensive slickensided surfaces, drag, and offset of formations. Where the evidence seems conclusive, lines are dashed. Projected trends are shown by dotted lines. In several places, faulting is suggested by the areal distribution of outcrops, but without the support of additional data, the faulting has not been shown on the map.

Such an area is represented by the roughly rectangular reentrant into the western slope, beginning 2 miles north of Abo Pass. The open west side of the reentrant is continuous with the pediment gravels. On three sides, the floor is surrounded by slopes of Priest granite. The Paloma thrust fault is projected across the mouth of the reentrant. At the south end, the thrust cuts White Ridge quartzite and is marked by prominent silicified breccia and slickensides. On the north side of the reentrant, equally prominent breccia marks the fault: here, White Ridge quartzite is thrust onto Sais quartzite, cutting out entirely the Blue Springs schist. The straight north and south walls of the reentrant suggest the possibility of cross faulting. Such an interpretation would help explain the apparent offsets in the metasediments north and south of the reentrant.

The pediment gravels are offset in a north-south scarp 25-100 ft high, 3-5 miles west of the mountain front, from latitude 34°38' northward. This scarp connects with the Pliocene Ojuelos fault of Reiche (1949, p 1203). Permian and Triassic sediments and Quaternary basalt are exposed on the pediment surface in the eastern upthrown block of the scarp, and Tertiary and Quaternary beds in the western downthrown block.

The Grober no. 1 well (latitude 34°39', longitude 106°40'), 6 miles west of the pediment scarp, penetrated to a depth of 6,300 ft and bottomed in the Triassic Chinle formation. The well log is on file at the office of the New Mexico Bureau of Mines and Mineral Resources, in Socorro. If the beds continue horizontally eastward from the well to the Ojuelos fault, the pediment scarp represents only a small fraction of the displacement of a much larger fault that throws Tertiary against Permian strata.

FOLDING ASSOCIATED WITH FAULTING

Along the eastern side of the Montosa thrust fault, Pennsylvanian sediments are steeply tilted, overturned, and commonly folded into small synclines and anticlines in front of the eastward thrust Precambrian formations. There are excellent exposures of these structures in Abo Pass and for several miles along the east wall of Sand Canyon. Less accessible exposures of similar structures occur at the following localities: tributary of Priest Canyon, sec. 31, T. 4 N., R. 5 E.; near north end of Priest Canyon, sec. 30, T. 4 N., R. 5 E.; Canyon de la Mina, sec. 16, T. 4 N., R. 5 E.; Colorado Canyon, sec. 28, T. 5 N., R. 5 E.; Water Can-yon, sec. 22, T. 5 N., R. 5 E.; New Canyon, sec. 10, T. 5 N., R. 5 E.; Capillo Peak, sec. 34, T. 6 N., R. 5 E.; and in numerous outcrops between these valleys.

AGE OF FAULTING AND FOLDING

The Pennsylvanian sediments were folded by the Laramide thrusting. Much of the intense folding in the Precambrian occurred before the intrusion of the Priest granite, because apophyses, dikes, and quartz veins from the granite cut the central syncline and the many small drag folds which accompanied the synclinal folding. Large cross folds in the Sais and White Ridge quartzites, together with innumerable small drags in both the Blue Springs schist and the schistose Sevillita metarhyolite and intercalated basic schist, involve many of the pegmatite and aplite dikes associated with the granite.

A few folds in the Precambrian, with axes parallel to the major thrust faults, are not dated so easily, raising the question as to whether they may not be due to drag in the overthrust Precambrian formations. An example of such folding is a small anticline in the Sais quartzite, latitude 34°30' N., longitude 106°30' W., trending N. 30° E., with its axial plane dipping steeply to the northwest. The strike parallels the contact of quartzite and Priest granite, which may have acted as a buttress against which the quartzite was folded during Laramide thrusting. On the other hand, the fold parallels the regional schistosity and may be interpreted equally well as Precambrian in age.

The position, attitude, direction of dip, and extent all show striking similarity to Laramide thrusting in the southern Rocky Mountains. It is, therefore, assumed that the major thrusting in the South Manzano Mountains is Laramide in age.

Summary of Geologic History

The geologic history of the general region begins with the green-stone and pre-Sais lower metaclastic series of the North Manzano Mountains. In the South Manzano Mountains, the recorded sequence of events is interpreted as given below, beginning with the lowest member of the upper metaclastic series:

1. Deposition, in a marine environment, of approximately 7,000 ft of Sais sands (now quartzite), Blue Springs shales and siltstones (now schists), and White Ridge sands (now quartzite), and the tectonic setting of an unstable shelf. Structural disturbance in Middle White Ridge time, with the deposition of lower quartzite beds, followed by the deposition of the upper arkosic sand and conglomerate beds.
2. Emergence and tilting of the rocks to the east, with removal of the White Ridge arkosic member from the western area.
3. Extrusion of the Sevillita rhyolite flows upon the eroded surface of the White Ridge quartzite, with a few sill-like intrusions of rhyolite into the upper part of the quartzite. Total thickness of the rhyolite approximately 5,000 ft.
4. Intrusion on a large scale of basic igneous rock as sills in the Blue Springs, White Ridge, and Sevillita rhyolite. Predominance of the sills, probably andesitic or basaltic, in the rhyolite; possible combined thickness of more than a mile. Soaking and contact metamorphism of the rhyolite by the basic rock, with many contact zones showing a complete mixing of the two formations.
5. Folding of the formations into a north-northeast trending syncline, with the eastern limb overturned and the axial plane dipping steeply south-east. Large drag folds in the quartzite and intense crumpling into small drags in both the Blue Springs schist and sericitized metarhyolite and basic sills accompanying the major folding. Development of regional schistosity paralleling the axial plane of the syncline. Intense shearing in the thinner sills and along border zones of the sills and flows.
6. Intrusion of the Monte Largo stock, probably early during the folding.
7. Invasion of vein quartz. Several periods of probable quartz deposition. Parallelism with regional schistosity and subsequent folding and shearing, suggestive of its presence before completion of the folding.
8. Invasion of quartz reefs. Formation of massive quartz reefs, in part at least, later than the small stringers and lenses in the schists, as indicated by crosscutting relations. Increase in size of quartz veins to reeflike masses, in places; apparent contemporaneity with the smaller lenses.
9. Cross folding, faulting, and regional schistosity, subordinate fracture cleavage and schistosity accompanying the cross folding.
10. Intrusion of the Priest granite; formation of an irregular contact aureole in the metaclastics, and garnet and chloritoid porphyroblasts in the Sevillita metarhyolite. Pegmatite and aplite dikes and apophyses cutting across earlier structures.
11. Possible Precambrian normal faulting.
12. Erosion of Precambrian rocks.

13. Submergence and deposition of Pennsylvanian sandstones and limestones.
14. Deposition of Permian red beds, sandstones, and limestones followed by deposition of the Mesozoic marine and nonmarine sequence.
15. Emergence and erosion followed by eastward thrusting of Laramide orogeny. Silicification of the fault breccia; later movements, forming extensive slickensided surfaces in the thoroughly cemented zones.
16. Relaxation of compressive forces, with accompanying normal faulting; in some places, reverse movement along zones of earlier thrusting.
17. Tertiary block faulting and deposition of nonmarine Santa Fe beds.
18. Pedimentation of several different stages.
19. Offset of pediment by Ojuelos fault.

Mineral Resources

Mineralization of economic importance is unknown in the South Manzano Mountains. In view of the large amount of vein and reef quartz, the numerous silicified fault breccias, and intrusions of granite, the barrenness of these mountains is striking. A few prospect pits have been dug into the quartz reefs and along shear zones at the mouth of East Bartola Canyon, in the Blue Springs schist in Salas Canyon, and in contacts of Blue Springs schist and Sais quartzite along the crest trail south of Capillo Peak. Examination of the dumps of the prospect pits shows only very slight traces of pyrite, hematite, manganese, and, in one place, chalcopyrite.

At Abo Pass, just south of the Atchison, Topeka and Santa Fe Rail-way, an extensive quarry is operated by the Sharp and Fellows Construction Company. The excavation cuts into the brecciated fault zones of the Sais quartzite. In 1950, the operations were yielding 1,000 cu yd, or approximately 20 rail carloads, per day. The rock is crushed at the quarry for use as coarse railroad ballast, some finer material being used in addition for station platforms.

Appendix

STRATIGRAPHIC SECTIONS ACROSS PRECAMBRIAN ROCKS ON WEST SLOPE OF SOUTH MANZANO MOUNTAINS

FROM SAIS QUARTZITE TO PRIEST GRANITE, SMALL VALLEY, LATITUDE 34°28'30"

White Ridge quartzite

172'	quartzite
13'	black schist
161'	black schist, banded
26'	black schist
209'	quartzite, blue and massive
89'	covered
84'	quartzite, dark-gray
125'	quartzite
47'	granite dike

Blue Springs schist

195'	black schist; sillimanite and tourmaline porphyroblasts
39'	black schist cut by aplite

granite

FROM SAIS QUARTZITE TO PRIEST GRANITE, LATITUDE 34°28'45"

White Ridge quartzite

219'	covered
108'	quartzite, gray and massive
148'	black schist, knotty
132'	quartzite
29'	schist-quartzite
32'	quartzite
78'	granite dike
24'	quartzite
5'	black schist
5’	quartzite

Blue Springs schist

120'	black schist
6’	quartzite
78'	granite dike
626'	black muscovite schist

granite

FROM SAIS QUARTZITE TO PRIEST GRANITE, LATITUDE 34°28'50"

White Ridge quartzite

132'	covered
26'	quartzite, gray and thin-bedded

87'	covered
50'	quartzite, gray-pink
67'	covered
16'	quartzite, gray
147'	quartzite, fine to black schist
24'	quartzite, white
156'	covered
33’	quartzite
304'	quartzite, gray with schist bands
3'	granite sill, several aplites
185'	quartzite cut by aplites

Blue Springs schist

86'	black schist
149'	covered

granite

FROM SEVILLITA METARHYOLITE TO PRIEST GRANITE, SMALL VALLEY, LATITUDE 34°30'45°

Sevillita metarhyolite

111'	black schist
78'	sericite schist
30'	black schist
29'	metarhyolite
13'	black schist
24'	metarhyolite
24'	black schist
3'	metarhyolite
34’	black schist
24'	metarhyolite
36'	black schist
116'	sericite to quartz schist
64'	black schist
18'	schist
3'	quartz dike
351'	black schist
21'	quartzite
10'	black schist
45'	quartzite, gray
113'	quartzite-schist, black bands

White Ridge quartzite

72'	quartzite, gray
200'	quartzite, thin-bedded with schist bands
378'	quartzite, schistose to massive
213'	quartzite, massive white (closely folded anticline)

Sais quartzite

239'	quartzite, massive white (anticlinal nose)
71'	quartzite, massive white
517'	quartzite, white-bluish
214'	quartzite, massive white
232'	quartzite, white-bluish

granite (Priest)

FROM SEVILLITA METARHYOLITE TO WHITE RIDGE QUARTZITE, FIRST VALLEY OF MARKER CANYON, LATITUDE 34°31'45"

Sevillita metarhyolite

536'	metarhyolite
24'	black schist
8'	metarhyolite
39'	black schist
93'	metarhyolite
779'	black schist, diorite ovoid inclusions
330'	metarhyolite, sheared at center
64'	black schist
104'	garnet-sericite schist
162'	black schist
138'	metarhyolite
23'	black schist
57'	metarhyolite
8'	black schist
69'	metarhyolite
19'	black schist
100'	metarhyolite
56'	black schist
128'	metarhyolite
29'	black schist
17'	metarhyolite
13'	black schist
22'	metarhyolite
5'	black schist
8'	metarhyolite
5’	black schist
8'	metarhyolite
3'	black schist

FROM BASIC SCHISTS TO PRIEST GRANITE, MARKER CANYON, LATITUDE 34°32'15"

Sevillita metarhyolite

235'	black schist
32'	schist
43'	black schist
6’	metarhyolite
58'	black schist
5’	metarhyolite
8'	covered
134'	metarhyolite
85'	muscovite-garnet schist
21'	black schist
115'	schist
173'	black schist
78'	schist, sericitic
38'	schist, gray, garnetiferous
215'	garnetiferous schist
60'	covered
10'	black schist
5’	schist

33'	black schist
311'	covered
121'	metarhyolite
159'	schist, anticline crest
438'	black schist
196'	black schist, light spots to 2 in. long
206'	metarhyolite
220'	sericite schist
185'	metarhyolite, black schist lenses
20'	black schist
157'	metarhyolite, massive
470'	metarhyolite

White Ridge quartzite

142'	quartzite and schist
69'	quartzite, white
273'	quartzite, red, thin-bedded
73'	quartzite, shear zones
128'	quartzite schist
31'	quartzite
120'	quartzite, massive

Blue Springs schist

137'	schist, gray, sericitic
117'	schist, knotty
130'	schist, gray to dark gray
10'	schist, gray
115'	schist, gray-black
30'	schist, siltstone
59'	sillimanite schist
271'	siltstone, pink pegmatite
258'	siltstone, pink-gray
61'	covered

granite

SEVILLITA METARHYOLITE, FIRST VALLEY NORTH OF MARKER CANYON, LATITUDE 34°32'45"

Sevillita metarhyolite

92'	metarhyolite
35'	black schist
27'	garnet schist
57'	metarhyolite
753'	black schist
13'	diorite
23'	metarhyolite
259'	black schist
3'	metarhyolite
32'	metarhyolite stringers
251'	black schist
8'	metarhyolite
49'	black schist ovoids, diorite inclusions
25'	black schist, "basic"
47'	black schist
8'	metarhyolite, black schist

94'	black schist
40'	metarhyolite
132'	black schist, fine-grained
46'	garnet-sericite schist
101'	schist
23'	black schist
140'	metarhyolite
220'	black schist
85'	metarhyolite
51'	metarhyolite
11'	garnet-sericite schist
37'	black schist
5'	sericite schist
129'	metarhyolite, garnet-sericite schist
112'	garnet-sericite schist
11'	black schist
60'	metarhyolite, sheared
205'	black schist
38'	garnet schist
237'	black schist, "basic"
11'	metarhyolite
44'	black schist
95'	metarhyolite, sericitic and sandy
117'	black schist
83'	metarhyolite
397'	black schist
94'	sericite schist

metarhyolite to head of valley

ACROSS BASIC SCHISTS AND SEVILLITA METARHYOLITE, FIRST VALLEY SOUTH OF ABAJO CANYON, LATITUDE 34°34'15"

Sevillita metarhyolite

48'	black schist
89'	metarhyolite, massive
32'	garnet-sericite schist
50'	black schist
42'	metarhyolite
1262'	black schist
473'	metarhyolite
8'	black schist
8'	metarhyolite
11'	black schist
16'	metarhyolite
222'	black schist, lenses of coarser schist
296'	black schist, alternating coarse and fine bands, feldspar lenses
218'	metarhyolite
130'	black schist
16'	metarhyolite
126'	black schist
100'	metarhyolite
906'	black schist
5'	metarhyolite
183'	black schist
11'	garnet-sericite schist

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Numbers in boldface indicate main references.