Precambrian Geology of the Needle Mountains, Southwestern Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 644-A

Precambrian Geology of the Needle Mountains, Southwestern Colorado

By FRED BARKER

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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A restudy of the Precambrian metamorphic and igneous rocks of the Needle Mountains uplift

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PRECAMBRIAN GEOLOGY OF THE NEEDLE MOUNTAINS, SOUTHWESTERN COLORADO

By Fred Barker

ABSTRACT

The Needle Mountains of southwestern Colorado are an uplifted mass of Precambrian rocks. Paleozoic and Mesozoic sedimentary rocks flank the uplift on the southeast, south and west; and Tertiary volcanic rocks flank it on the north and northeast. The Needle Mountains uplift extends from Weminuche Creek on the east to Electra Lake and U.S. Highway 550 on the west, and from Vallecito Reservoir on the south to Silverton on the north.

The Precambrian rocks of the Needle Mountains have been restudied, and the results have led to a revision of the geologic history presented by Whitman Cross and associates in 1905–10. Field relations, petrographic descriptions, and isotopic age determinations indicate that these rocks were formed in two cycles of deposition, folding, metamorphism, and injection of plutonic rocks. The first cycle was approximately 1,800 to 1,700 m.y. (million years) ago, and the second, about 1,650 to 1,450 m.y. ago.

The older cycle consisted of:

1. Deposition of the Vallecito Conglomerate, a quartzose rock whose matrix is quartz sericite, and hematite and whose clasts are quartzite, quartz, red and black jasper, chert, and minor argillite and volcanic rocks. The conglomerate is at least 2,400 feet thick and perhaps 5,000 feet thick, and its base and the underlying rocks are not exposed.
2. Volcanism, probably in a eugeosynclinal environment, during which great but unknown thicknesses of olivine basalt, tholeiitic basalt, and rocks of intermediate to acidic compositions accumulated. These rocks and interlayered graywacke, quartzite, impure sandstone, siltstone, and clay make up the Irving Formation.
3. Formation of the now foliated, partly lineated, and metamorphosed Twilight Gneiss either as a complex of sills of porphyry in layered basalt and more acidic lavas and tuffs or as an extrusive accumulation of lavas and tuffs of both silicic and basaltic compositions.
4. Intense folding, in part isoclinal; folds trend generally north to northeast.
5. Accompanying metamorphism of all the rocks to the amphibolite facies.
6. Intrusion of the postkinematic Tenmile Granite, which is mostly biotite quartz monzonite, and of the Bakers Bridge Granite, which is alkali hornblende granite, about 1,720 m.y. ago.
7. Profound erosion.

The younger cycle consisted of:

8. Deposition of the Uncompahgre Formation as quartz sands, aluminous muds that partly were carbonaceous and sulfurous, and minor silt and conglomerate. The upper layers are not preserved and the overlying rocks are unknown, but a postmetamorphism thickness of about 8,000 feet is now present.
9. The Uncompahgran disturbance, predominantly isoclinal folding along easterly to southeasterly trends. The quartzite layers show parallel folds, and the pelitic layers show similar folds.
10. Metamorphism to slate and phyllite grade in the west. Metamorphism of thermal type possibly caused by underlying Eolus Granite is superimposed in the east, with nondirectional fabrics and such minerals as chiastolite, garnet, and staurolite.
11. Intrusion of the postkinematic Eolus Granite as two large composite masses, each more than 100 square miles in area, and each mostly biotite-hornblende quartz diorite; and intrusion of the Electra Lake Gabbro; both about 1,460 m.y. ago.
12. Intrusion of the Trimble Granite into the Eolus Granite and of minor dikes and stocks of various basic and acidic rocks into the Irving Formation, Vallecito Conglomerate, Bakers Bridge Granite, and Uncompahgre Formation.
13. Deep erosion and deposition of Cambrian and younger sediments.

Chemical analyses show that the Twilight Gneiss is sodic rather than potassic; that the Tenmile, Bakers Bridge, and Trimble Granites lie in or close to the granite minimum melting trough; and that the Eolus Granite and the associated quartz diorite of Pine River show a trend from a relatively calcic composition to the granite minimum.

INTRODUCTION

The rugged Needle Mountains of Colorado lie in the southwestern part of the much larger San Juan Mountains and form the only extensive exposure, about 425 square miles, of Precambrian rocks in this part of Colorado. Tertiary volcanic rocks bound the Precambrian on the north and east, and Paleozoic and Mesozoic rocks bound it on the south and west. The U.S. Geological Survey is investigating the geology of the 1° by 2° Durango quadrangle, which includes the Needle Mountains, and I have studied the geology of the Precambrian rocks as a part of this larger effort.

Whitman Cross and his associates (see p. A3) mapped the geology of the western two-thirds of the Needle Mountains at a scale of 1:62,500, and of the eastern one-third at 1:250,000. One feature of these maps is controversial—Cross inferred that many of the Precambrian formations lie in fault contact with each other. I have restudied the area mapped by Cross, with emphasis on the interrelations of the various Precambrian formations, and have remapped the geology of the eastern one-third of this area, covered previously by reconnaissance only.

LOCATION AND ACCESS

The Needle Mountains lie from 20 miles north to 40 miles northeast of Durango, Colo., and 10 miles southwest to 25 miles southeast of Silverton, Colo. (figs. 1, 4) or roughly between lat 37°25′ and 37°45′ N. and long 107°25′ and 107°50′ W.

The western part of the Needle Mountains is accessible in the summer by the Denver and Rio Grande Western narrow-gage railroad, which passes through the Animas Canyon; by State Highway 550 to the west; and by the gravel roads along the southern and eastern flanks of the range. Most of the Needle Mountains lies in the San Juan Primitive Area and, therefore, is accessible only by trail, with travel limited to nonmotorized means. The now abandoned mining town of Beartown, on the northeast side of the range near the head of Bear Creek, is accessible to four-wheel-drive vehicles via a side road from the old Silverton–Stony Pass–Rio Grande wagon road.

PHYSICAL FEATURES

The Needle Mountains are some of the most rugged mountains in Colorado; and many sharp peaks 13,000 to 14,000 feet high are cut by precipitous canyons. The mountains are of two main types: those of quartzite, as in the north to northeast, which are mostly in rows parallel to the east to southeast strikes of the more resistant layers; and those of granite, amphibolite, and other rocks, which are randomly arranged and have an irregular drainage pattern. The predominant drainage of the Needle Mountains is southward (fig. 4), through deep canyons cut by the Pine River, Vallecito Creek, the Animas River, and Lime Creek.

PREVIOUS WORK

The Precambrian rocks of the Needle Mountains were examined by geologists prior to 1890. (See, for example, Endlich, 1876; Comstock, 1883; Lakes, 1889.) A significant conclusion by Emmons (1890, p. 257) was that over 10,000 feet of closely folded quartzites, conglomerates, and slates of Precambrian age (Algonkian) occur near Ouray. Emmons further concluded that these rocks of the Grenadier Range, then called the Quartzite Peaks, probably are of the same series. Van Hise (1892, p. 319–323) observed the rocks of the Animas Canyon between Silverton and Needleton, and tentatively concluded that the clastic Uncompahgre Formation is younger than the crystalline Irving Formation and Tenmile Granite. He noted the marked discordance in structural attitudes of the Uncompahgre Formation and of the Irving Formation and Tenmile Granite.

Intensive geologic investigations in the Needle Mountains were made by Whitman Cross and his associates. The results of their investigations include the Silverton folio (Cross, Howe, and Ransome, 1905), the Needle Mountains folio (Cross, Howe, Irving, and Emmons, 1905), and the Engineer Mountain folio (Cross and Hole, 1910). This work also led to the summary publications of Cross and Larsen (1935) and of Larsen and Cross (1956). A review paper by Hinds (1936) discusses the younger Precambrian rocks of the San Juan Mountains. Cross, Howe, and Irving (1907), Kelley (1946), Luedke and Burbank (1962), and Burbank and Luedke (1964) described the Uncompahgre Formation of the type locality. Varnes (1963, p. A7–A8) described the Precambrian rocks of the South Silverton mining area. Figure 1 shows the areas covered in the pertinent field investigations.

ACKNOWLEDGMENTS

I am pleased to acknowledge the close cooperation and informative discussions of Professors M. E. Bickford, George Wetherill, and L. T. Silver, whose radiometric age determinations constitute a valuable contribution. R. E. Zartman of the Geological Survey determined potassium-argon ages of two minerals. W. J. Hail, P. W. Lipman, R. G. Luedke, and T. A. Steven, all members of the Geological Survey who are studying the geology of the Durango quadrangle, have helped me in many ways. T. K. Hinderman, geologic field assistant, worked capably during the wet summer of 1965.

GEOLOGIC SEQUENCE

The Precambrian rocks of the Needle Mountains have a complex history, including two major Precambrian tectonic events, which consisted of:

1. Deposition of the Vallecito Conglomerate, a quartzose conglomerate at least 2,400 feet thick and perhaps 5,000 feet thick. The base and the underlying rocks are not exposed.
2. Deposition of the Irving Formation, now metamorphosed volcanic and sedimentary rocks of great

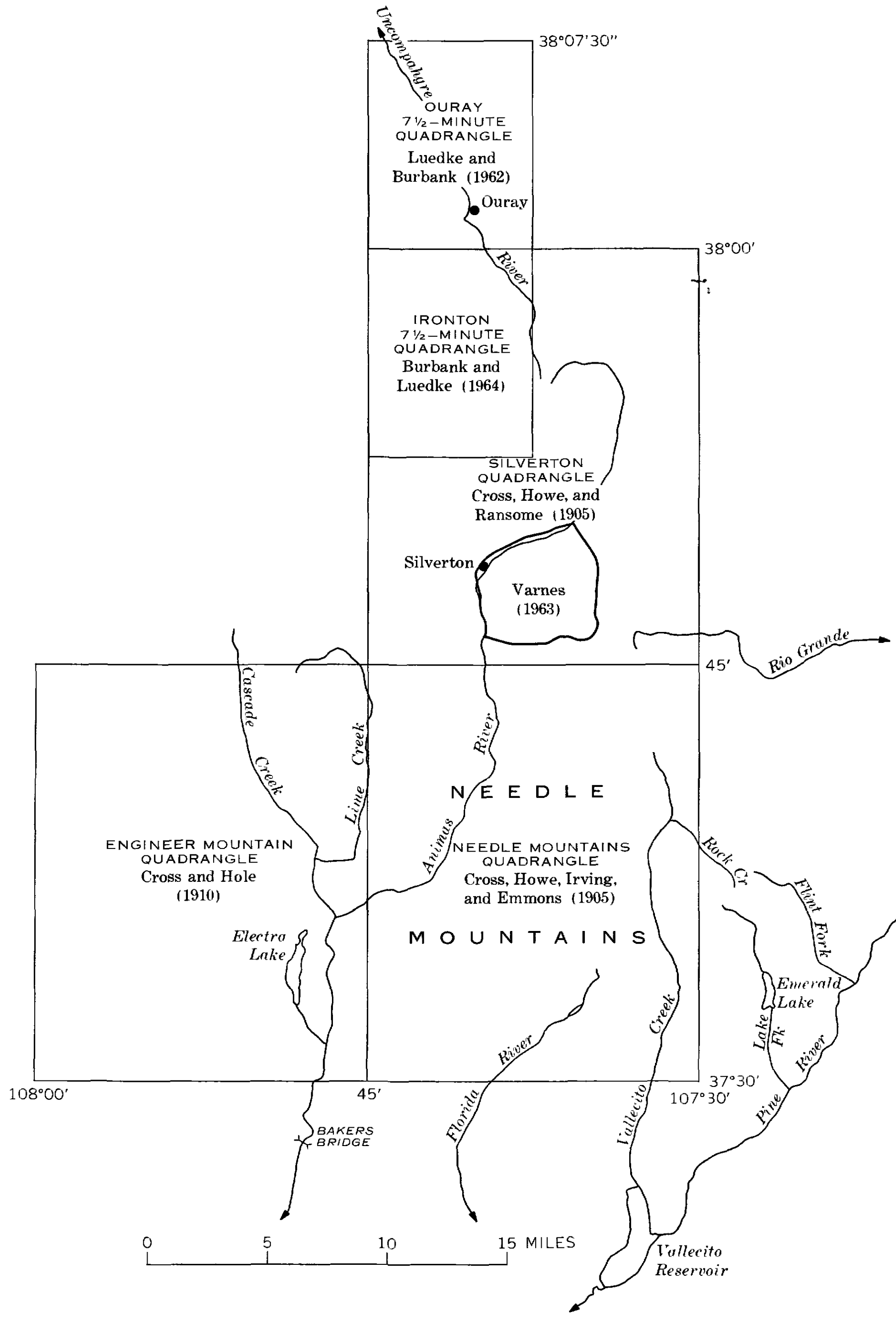


FIGURE 1.—Map showing areas of previous, detailed geologic investigations of Precambrian rocks in the western San Juan Mountains. Geologic maps by Cross and Larsen (1935) and Larsen and Cross (1956) show the entire San Juan Mountains.

but unknown thickness. Twilight Gneiss formed as flows or sills of dacite to quartz latite.

3. Folding along general north to northeast trends, metamorphism to high rank, and posttectonic intrusion of the 1,720 million-year-old Bakers Bridge Granite, which is massive alkali hornblende granite, and Tenmile Granite, which is largely massive biotite quartz monzonite.
4. Deep erosion.
5. Deposition of the Uncompahgre Formation, now quartzite, slate and schist, siltstone, and conglomerate. The aggregate thickness is at least 8,000 feet, and the upper layers are not preserved.
6. The Uncompahgran disturbance, involving isoclinal folding along east to southeast trends, metamorphism to low to medium rank, and development of

a phyllonite along part of the unconformity below the Uncompahgre Formation.

7. Intrusion of the Eolus Granite batholith (biotite-hornblende and biotite quartz monzonite with minor biotite-hornblende-augite quartz diorite) and of the Electra Lake Gabbro and Trimble Granite stocks.
8. Deep erosion followed by deposition of Cambrian and younger sediments.

Though rocks below the Vallecito Conglomerate are not exposed, clasts in the conglomerate indicate that the source terrane included much massive quartz—either quartzite or veins or both—red and black jasper, chert, argillite, iron-formation, and epidote-rich greenschist.

The rocks of the Needle Mountains Precambrian are shown on the geologic sketch map in figure 2, and their relations are given in a schematic cross section in figure 3. The geographic place names and topographic features cited in this report are shown in figure 4.

LAYERED ROCK FORMATIONS

VALLECITO CONGLOMERATE

The Vallecito Conglomerate was named by Cross, Howe, Irving, and Emmons (1905, p. 3) for the type locality in the gorge of Vallecito Creek in the southeastern part of the Needle Mountains 15-minute quadrangle and in the northeastern part of the Vallecito Reservoir 7½-minute quadrangle. The formation is found only in the southeastern part of the Needle Mountains (fig. 2), where, for the most part, it is superbly exposed in steep canyon walls and cliffs, particularly along the Pine River (Larson and Cross, 1956, figs. 3, 4).

The Vallecito Conglomerate is metaconglomerate and pebbly quartzite. Its clasts are subangular to rounded fragments of milky quartz, red and black jasper, chert, gray argillite, ferruginous quartzite, iron-formation, intermediate volcanic rocks, epidote-rich greenschist, and muscovite schist. This formation contains randomly distributed beds of coarse-grained quartzite 1 to 18 inches thick, and a few much thicker beds. The clasts range in maximum dimension from less than 1 mm to about 1 foot, but ones larger than 4 inches are rare. Those 1 to 4 inches in size are most common. The matrix is a very poorly sorted aggregate of quartz and sericite, with minor hematite, leucoxene, garnet, albite, biotite, and epidote. The matrix is mostly gray but is locally pink to purple, and the grains are largely ⅛ to 1 mm in size. The original sediment was wholly recrystallized during metamorphism as shown by the following: (1) Quartz in the matrix and in the various types of clasts in which it occurs has grown into polygranular mosaic fabrics; (2) the sericite is mostly well alined and gives a schistose aspect to the matrix; (3) the few garnets all lie enclosed in sericite and may be metamorphic rather than detrital; and (4) epidote grains only rarely show rounded outlines, a feature which suggests detrital origin and later recrystallization. Many of the quartz clasts contain 1- to 2-mm grains that are dispersed amongst ⅛- to 1-mm grains. These larger grains constitute 10–20 percent of these clasts. This fabric suggests that these clasts were derived from quartzite or from fine-grained conglomerate that contained larger detrital grains set in a finer matrix. Bands of hematite 1–3 mm thick are abundant in much of the formation. Ovoid aggregates 1 to 3 mm in diameter of sericite, sericite plus quartz plus albite and of sericite plus epidote plus biotite plus quartz are also present. These aggregates are interpreted as metamorphosed grains of feldspar or of relatively fine grained quartzo-feldspathic rocks. These rocks were probably volcanic rocks of intermediate to rhyolitic compositions in which original potassic feldspar has been hydrolyzed to sericite and original plagioclase has been converted to albite and epidote.

In outcrop the Vallecito Conglomerate is mostly gray but is locally pink or purple. It is thin to very thickly bedded and shows well-developed cross-stratification (fig. 5) of the trough type of McKee and Weir (1953, p. 387) or the pi-type of Allen (1963, p. 109), except that the cross-strata are lithologically heterogeneous—hematite laminae are interlayered with pebble conglomerate. Joints in the rock cut clasts and matrix alike. A few folds having amplitudes of one hundred to several hundred feet were found, but smaller folds having amplitudes of a few inches to several feet are extremely rare.

The southernmost exposure of the Vallecito Conglomerate on the west side of the Vallecito Creek valley consists of impure, sparsely pebbly quartzite. This quartzite layer (1) has an apparent thickness of about 1,500 feet, (2) shows rare west-facing cross-stratification, (3) is gray to blue gray, massive, fine to coarse grained, and (4) contains 10–15 percent muscovite, microcline, biotite, andalusite, and magnetite. Andalusite occurs as cores in grains of muscovite and may have formed in the regional metamorphism 1,720 to 1,780 m.y. ago. This quartzite unit has a gradational contact with the conglomerate to the east which it apparently overlies. It underlies the Irving Formation to the north and is overlain by Paleozoic rocks on the west and by alluvial gravel to the south.

The exposed thickness of the Vallecito Conglomerate remains uncertain. At Granite Peaks Ranch in the Pine River valley, where there is good top-and-bottom control by cross-stratified beds, the formation is more than

2,400 feet thick. Larsen and Cross (1956, p. 24) reported "an estimated exposed thickness of more than 3,000 feet west of Pine River." The Vallecito Conglomerate, however, may well be more than 5,000 feet thick, and an unknown additional thickness to the south is covered by younger rocks.

The origin of such a thick mass of conglomerate and pebbly quartzite that is relatively homogeneous as to types of clasts and matrix is problematical. The source terrane included quartzose and ferruginous sedimentary rocks, intermediate to basic volcanic or metavolcanic rocks, and argillite and schist. Poorly sorted cross-strata, commonly containing pebbles as large as 2 inches in diameter, imply fluvial deposition. The Vallecito Conglomerate may be deltaic, deposited perhaps in a tectonically controlled basin.

The Vallecito Conglomerate underlies the Irving Formation, as indicated by cross-stratification in the conglomerate near the contact, which is mostly steep to vertical, both along Vallecito Creek and to the northeast on the broad ridge west of Emerald Lake. West of Vallecito Creek bedding surfaces in the conglomerate lie at angles of 10°–30° to the Vallecito-Irving contact, which is not well exposed; whether this discordance is due to local tilting and erosion of the Vallecito before deposition of the Irving or is due to folding along the contact could not be determined. However, there is no evidence that the discordance is due to faulting. West of Emerald Lake the Vallecito-Irving contact is clearly exposed, and the two formations are conformable.

IRVING FORMATION

NAME AND CORRELATION

The name Irving Greenstone was applied by Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, p. 2) to the amphibolite, biotite schist, metagraywacke and biotite-bearing metavolcanics, metamorphosed plutonic rocks, micaceous metasiltstone, quartzite, and iron-formation of the southeastern Needle Mountains, underlying Irving Peak, and extending eastward to Lake Fork of the Pine River and southward along Vallecito Creek. Because it has so little true greenstone this formation is here renamed the Irving Formation. The areas in the western and northern parts of the Needle Mountains that are designated Irving Formation in figure 2 were called Archean schist and gneiss by Cross and Howe (Cross, Howe, and Ransome, 1905, p. 2–3; Cross, Howe, Irving, and Emmons, 1905, p. 1–2; Cross and Hole, 1910, p. 2–3); the rocks are largely amphibolite, plagioclase-quartz-biotite gneiss, and metagraywacke or intermediate metavolcanic rocks. From their lithologic similarity to the type Irving rocks, their common but not ubiquitous retrograde metamorphism, their structural trends, and their position under the major unconformity, I have grouped all these rocks under the name Irving Formation. The accuracy of this correlation, however, awaits testing by radiometric dating.

SOUTHEASTERN NEEDLE MOUNTAINS

The Irving Formation in the southeastern Needle Mountains contains:

1. Much amphibolite, which is composed of green or blue-green hornblende, andesine or calcic oligoclase, epidote or biotite, and ilmenite or magnetite, and presumably is metabasalt and meta-andesite.
2. Biotite-bearing and epidote-bearing schists and gneisses that contain such assemblages as epidote-quartz-actinolite-magnetite-plagioclase, quartz-biotite-albite-epidote, hornblende-biotite-albite-magnetite, albite-hornblende-biotite, and sericite-quartz-chlorite-oligoclase; some of these rocks probably were derived from volcanic rocks of intermediate compositions and some probably from graywackes.
3. Metamorphosed feldspathic plutonic rocks, of which andesine quartz-hornblende-biotite gneiss and albite-hornblende-epidote-chlorite-biotite rocks are typical.
4. Meta-andesite that exhibits relict outlines of phenocrysts of plagioclase and a mafic mineral (probably clinopyroxene or hornblende); these original feldspar phenocrysts are now sericite and epidote, the mafic mineral phenocrysts are ragged blue-green hornblende, and the matrix is hornblende, oligoclase, epidote, sericite, ilmenite, and chlorite.
5. Quartzite and feldspathic quartzite.
6. Metasiltstone that is composed of quartz, muscovite, and biotite.
7. Banded iron-formation that consists of the assemblage quartz-magnetite-biotite-garnet and of various hornblende-mica-epidote-quartz-magnetite assemblages, according to J. E. Gair and Harry Klemic (unpub. data).
8. Muscovite-quartz-biotite schist.

Most foliation and compositional layering in this area trend north and dip steeply.

Much of the Irving Formation here shows mild retrograde metamorphism in which plagioclase is partially altered to sericite and epidote; hornblende to epidote, chlorite, calcite, and perhaps albite; and biotite to chlorite. A pelitic schist on the northwest side of Irving Peak collected just south of the Irving-Uncompahgre unconformity consists of pseudomorphs of sericite and chloritoid after andalusite(?). These pseudomorphs are

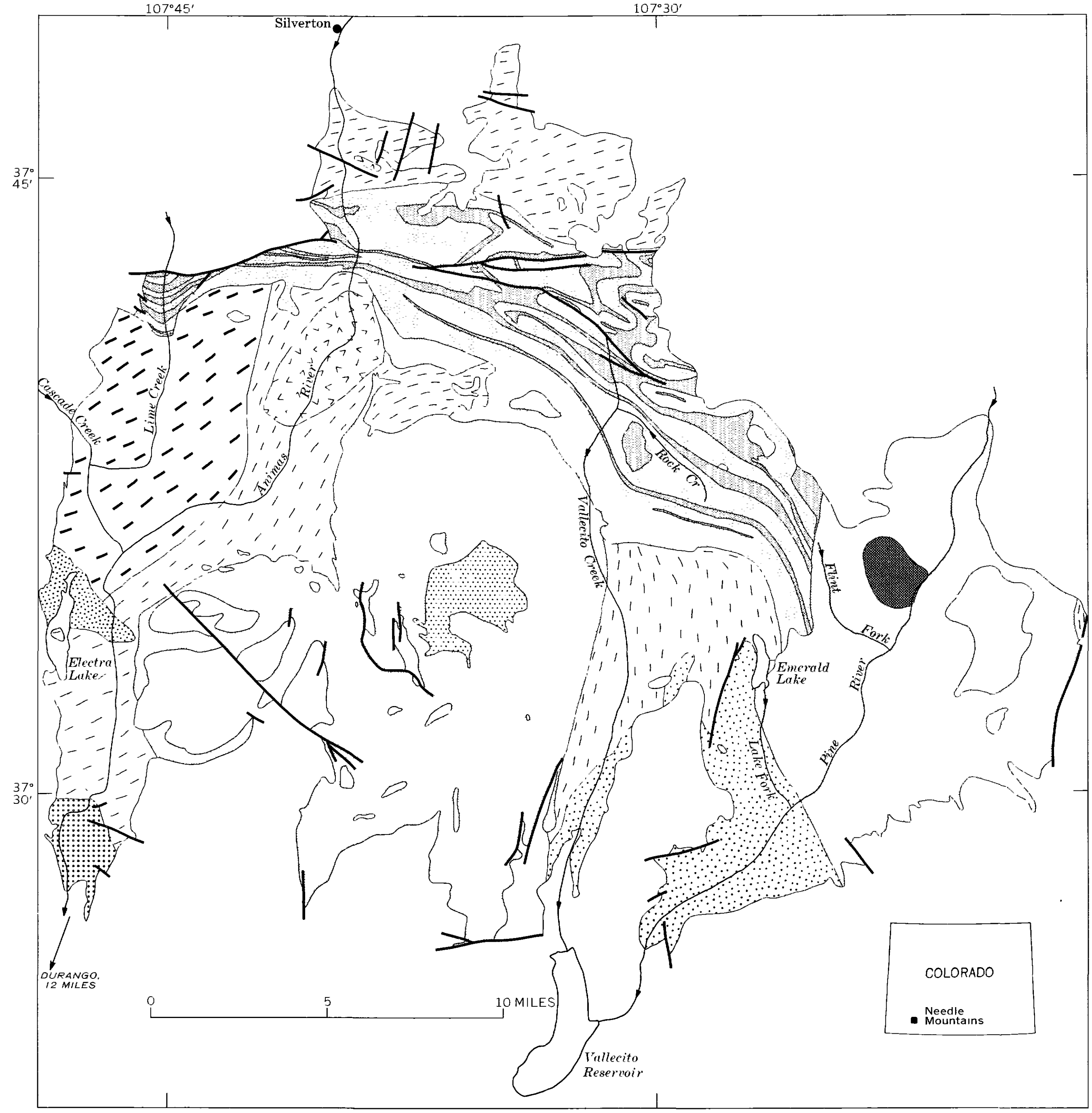
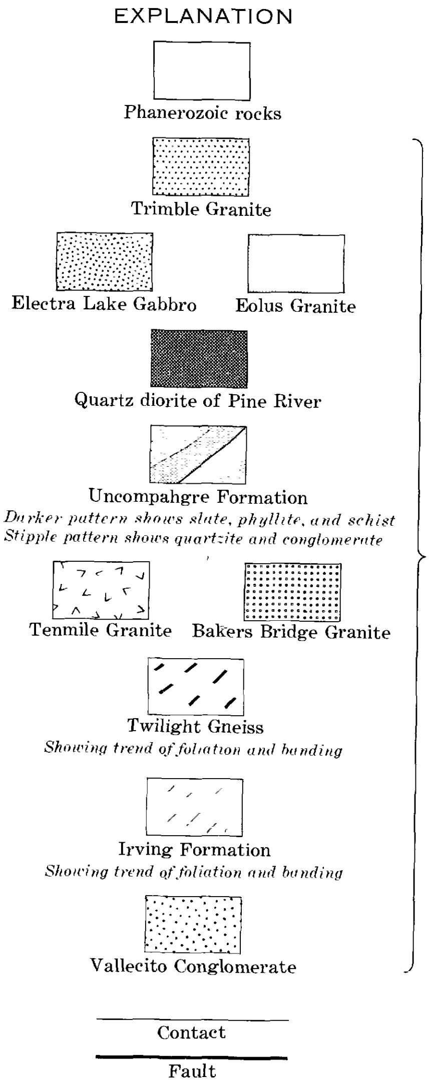


FIGURE 2.—Geologic sketch map of Precambrian rocks of the Needle Mountains, southwestern Colorado.

set in a matrix of quartz, chlorite, chloritoid, garnet, and ilmenite.

A distinctive, 40- to 50-foot-thick gray conglomerate lies several hundred feet above the base of the Irving Formation at Vallecito Creek. This rock contains subangular to subrounded granules to cobbles of both polygranular quartz and metavolcanic rock of the assemblage hornblende-plagioclase-magnetite-quartz, in which the plagioclase is untwinned oligoclase or andesine. The matrix is comprised of quartz, plagioclase, hornblende, and magnetite. About 1.1 miles south-southwest this layer lies directly on the Vallecito Conglomerate, and farther southwestward it is absent. This relationship suggests that in this locality the Irving is a wedge-shaped deposit overlying the Vallecito Conglomerate.



The Irving Formation in the southeastern Needle Mountains is cut by scattered thin dikes, mostly 1–20 feet thick, of fine-grained leucocratic quartz monzonite or granite. Microcline, quartz, and albite or oligoclase are the principal mineral constituents. These dikes are homogeneous and massive in texture and are posttectonic. They are described below on page A28.

WESTERN NEEDLE MOUNTAINS

The Irving Formation in the western Needle Mountains is well exposed for about 16 miles along the canyon of the Animas River, from near Rockwood northward and northeastward to Snowdon Peak and Balsam Lake. (See Cross, Howe, Irving, and Emmons, 1905; Cross and Hole, 1910.) The formation consists largely of dark-gray well-foliated amphibolites consisting of green hornblende and andesine and partly of biotite, garnet, or epidote. In the south half of this terrane and near the Twilight Gneiss the amphibolites are interlayered with medium-grained gray to pinkish-gray commonly banded plagioclase-quartz-biotite gneiss. The gneiss forms from a few percent to the bulk of individual outcrops. Augen are conspicuous in parts of this gneiss. Layers of this gneiss range in thickness from 6 mm to several tens of feet. A widespread lineation of clustered biotite grains in the gneiss invariably is parallel to the lineation in adjacent amphibolites that is given by parallel prisms of hornblende. Contacts between amphibolite and gneiss typically are parallel to the foliations but crosscutting relations are common in which thin dikes extend out from conformable layers of gneiss and cut the amphibolite at high angles to the foliation. The type of occurrence in which dikes crosscut the gneiss grades into a breccia with a matrix of plagioclase-quartz-biotite gneiss enclosing broken slabs of amphibolite; in some places marked rotation and bending of the fragments of amphibolite has occurred. Other rock types in this area of Irving Formation are hornblende-plagioclase-quartz-biotite gneiss and plagioclase-quartz-biotite-garnet gneiss. Retrograde effects here are mild and present only locally; they include partial sericitization of plagioclase and alteration of garnet to biotite along fractures and margins of grains.

Amphibolite lies north of the main mass of Tenmile Granite but is cut by dikes and sills of that granite. This rock is fresh, banded in outcrop, and dark grayish green. It shows a pronounced lineation of acicular hornblende grains that are 1/8–1 mm in size. This amphibolite is about 70 percent green hornblende, 25 percent zoned, rarely twinned, calcic oligoclase to sodic andesine, and 5 percent colorless clinopyroxene that shows a reaction texture with hornblende and plagioclase. The clinopyroxene and plagioclase occur in the rock as disseminated lenses about 1 mm thick and 5–10 mm long, and their long axes are parallel to the hornblende lineation. This clinopyroxene may be of regional metamorphic origin or it may be a contact product of the Tenmile Granite. The linear disposition of the clinopyroxene-plagioclase lenses suggests the former. Analyses by C. L. Parker of this amphibolite, collected near the railroad tracks 200 yards north of the Tenmile Granite, gave:

Chemical analysis	
SiO_2	51.66
Al_2O_3	12.77
Fe_2O_3	2.04
FeO	8.01
MgO	8.44
CaO	11.41
Na_2O	3.31
K_2O	.26
H_2O+	1.26
H_2O-	.00
TiO_2	.35
P_2O_5	.09
MnO	.17
CO_2	.06
Cl	.01
F	.03
Subtotal	99.87
Less O	.01
Total	99.86

CIPW norm	
Orthoclase	1.536
Albite	27.934
Anorthite	19.258
Halite	.016
Wollastonite	15.111
Enstatite	14.018
Ferrosilite	8.511
Forsterite	4.906
Fayalite	3.283
Magnetite	2.958
Ilmenite	.665
Apatite	.213
Fluorite	.053
Calcite	.136
Total	98.600
Salic	48.745
Femic	49.855

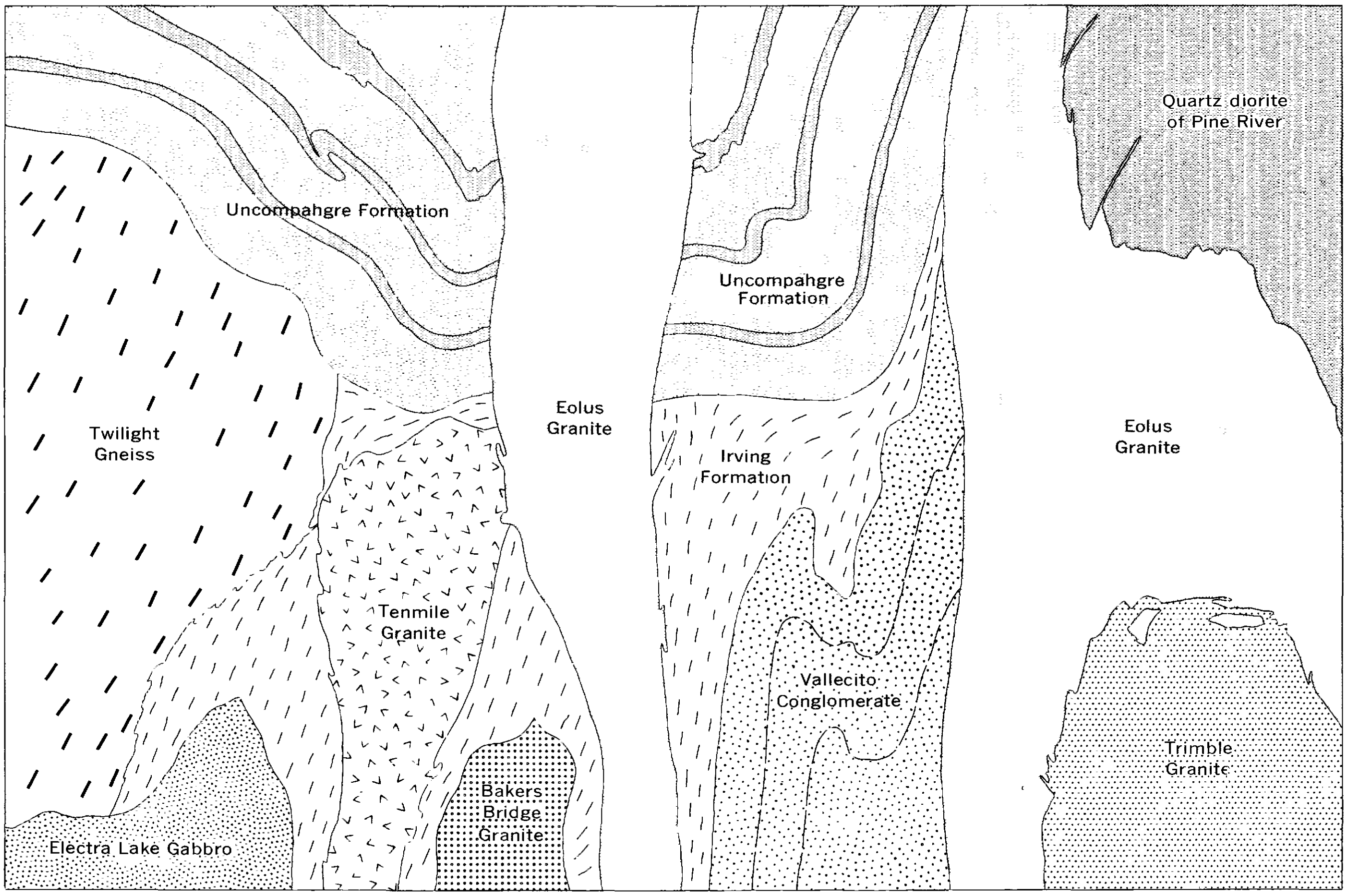


FIGURE 3.—Schematic cross section of Precambrian rocks of the Needle Mountains. Map patterns are the same as in figure 2.

This amphibolite, containing more than 8 percent normative olivine, probably is a metamorphosed olivine tholeiite.

Trends of foliation and compositional layering of the Irving Formation in the western Needle Mountains are mostly north-northeast to east-northeast, with steep dips to the southeast or northwest; a few east and north-northwesterly trends were found. Most lineations are at angles less than 30°, and they plunge northeast or southwest.

NORTHERN NEEDLE MOUNTAINS

The Irving Formation in the northern Needle Mountains is superbly exposed in the canyon of the Animas River south of Silverton, well exposed eastward in the vicinity of Highland Mary Lakes and at the headwaters of Deep and and Quartzite Creeks, and poorly exposed near Beartown.

This formation in the Animas Canyon consists of interlayered fine-grained dark-gray to grayish-green banded amphibolite and various fine-grained gray to green plagioclase-quartz-biotite-bearing gneisses and minor sericite-biotite-chlorite schists. Amphibolite is the more abundant rock type; typically it consists of blue-green hornblende, untwinned calcic oligoclase or andesine, and epidote, but varieties with biotite, chlorite, or quartz are not uncommon. Lenses of quartz and epidote and feldspar-rich bands are scattered through much of the amphibolite. Most of the plagioclase-quartz-biotite gneiss also contains one to several of the following minerals: Chlorite, epidote, microcline, garnet, calcite, magnetite, and pyrite. One specimen contains scattered ½- to 2 mm aggregates of quartz, plagioclase, and epidote with chlorite, and the individual grains are $\frac{1}{10}$–¼ mm in size. These aggregates may be recrystallized phenocrysts. Much of the disseminated chlorite, epidote, and calcite was formed during retrograde metamorphism; at least some of the biotite was also formed then, because it forms partial pseudomorphs after garnet.

Eastward, around Highland Mary Lakes and the southern headwaters of Deep Creek and along Bear Creek, the proportion of amphibolite in this formation decreases, and fine- to medium-grained gray well-foliated partly banded plagioclase-quartz-biotite gneiss is

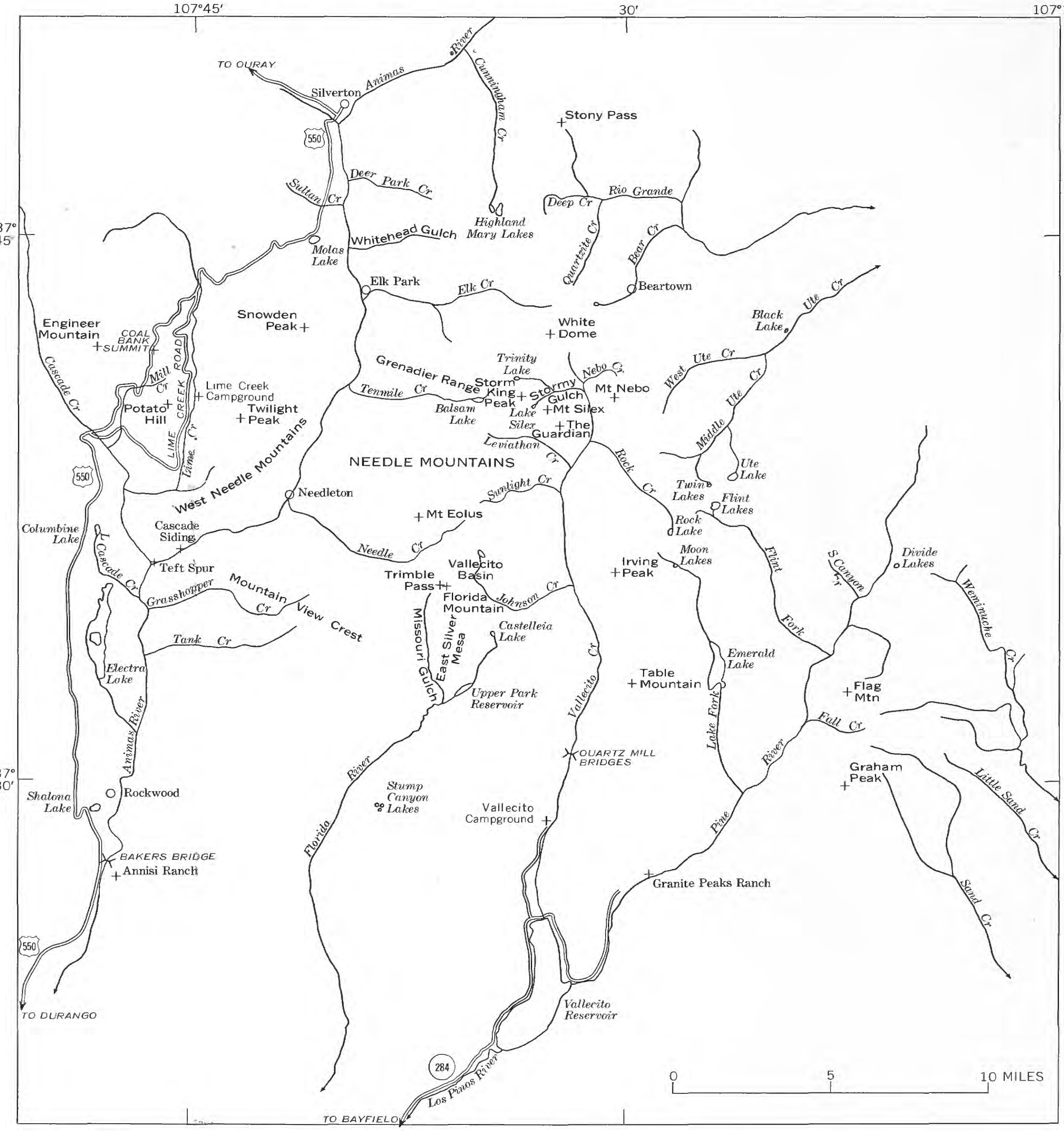


FIGURE 4.—Map of the Needle Mountains area, showing geographic place names and topographic features.

the preponderant rock type. The gneiss contains both feldspathic and biotitic layers, which are 1–20 mm thick and intensely contorted. This gneiss is of quartz dioritic or granodioritic composition, and most probably is metamorphosed igneous rock. An origin from volcanic, hypabyssal, or plutonic parent rock could not be determined in this study, but the interlayered amphibolite is at least partly metavolcanic, as shown by pillow structure near Highland Mary Lakes (fig. 6). Contacts between the plagioclase-quartz-biotite gneiss and the amphibolite are mostly conformable but are locally crosscutting, as at Bear Creek. Biotite schist and muscovite schist also are interlayered in some places with the gneiss and amphibolite. Retrograde metamorphism here

FIGURE 5.—Cross-stratification in the Vallecito Conglomerate, Vallecito Creek Trail about 0.5 mile north of Vallecito Campground.

FIGURE 6.—Metamorphosed pillow lava, Irving Formation, Highland Mary Lakes.

is similar to that along the Animas River, as sericite, chlorite, epidote, and calcite have formed.

The attitude of foliation and the compositional banding are parallel in this northern area of the Irving Formation; the formation strikes mostly east-northeast and dips very steeply, although flat dips were noted along the Animas River near its junction with Sultan Creek. Lineations of fold axes and of parallelism of elongate grains, observed at several places in this terrane, lie at both low and very steep angles.

STRATIGRAPHIC THICKNESS

The stratigraphic thickness of the Irving Formation could not be determined, mostly because of the lack of prominent marker horizons, but the Irving probably is at least several thousand feet thick in each of its three areas of exposure.

ROCKS OF WEMINUCHE CREEK

A small exposure of Precambrian interlayered quartzite and mica schist with associated sheared granite and massive pyroxenite lies in the eastern part of the area near the head of Weminuche Creek, at the northeastern corner of the eastern mass of Eolus Granite (fig. 2). These rocks are mapped in figure 2 with the Irving Formation. These rocks are intruded by the Eolus Granite, are unconformably overlain by Tertiary volcanic rocks on the north, and are in fault contact with Mesozoic rocks to the east. The quartzite is vitreous, gray, blue, and red. Bedding at about N. 15° E. with steep dips is visible in only a few outcrops. This rock is massive and so thoroughly recrystallized that no traces remain of original grain outlines. The grains are 1–6 mm in size and consist mainly of quartz but include 1–2 percent of muscovite and traces of rutile, hematite, and zircon. The schist is largely muscovite, biotite, and quartz; its original garnet has been altered to limonite and a colorless material of very low birefringence. Poor to fair exposures indicate that layers of quartzite and schist several feet to about 100 feet in thickness are interlayered and possibly isoclinally folded. Pyroxenite, sheared pink Eolus(?) Granite, and quartzite lie in roughly north-trending bands in the eastern part of this Precambrian mass. The pyroxenite is greenish brown, massive, and medium to coarse grained and consists mostly of twinned clinopyroxene and minor green hornblende and very fine grained alteration products.

The position of these rocks in the stratigraphic sequence is not known; however, the nature of the quartzite suggests affinities with the Vallecito or Irving Formation.

UNCOMPAHGRE FORMATION

The thick sequence of Precambrian interlayered quartzite and slate in the canyon of the Uncompahgre

River above Ouray was named the Uncompahgre Formation by Cross and Howe (Cross, Howe, and Ransome, 1905, p. 3). This section, whose basal and uppermost parts are not exposed, was described by Kelley (1946, p. 296–297, 306), who stated that about 8,700 feet of strata are exposed, and it later was shown on the geologic quadrangle maps of Luedke and Burbank (1962) and Burbank and Luedke (1964). The quartzite and slate of the Needle Mountains area were correlated on the basis of their lithological similarity with those of the Uncompahgre Canyon by Cross and Howe (Cross, Howe, and Ransome, 1905, p. 3; Cross and others, 1907). This correlation has not been verified by modern geochronologic methods, but I see no reason to doubt it.

The Uncompahgre Formation in the Needle Mountains area is exposed in a great arc, about 22 miles long, that extends eastward from Lime Creek (Cross and Hole, 1910) across the north end of the West Needle Mountains and the Animas Canyon, along the Grenadier Range and the peaks that lie to the north (Cross, Howe, Irving, and Emmons, 1905), and southeastward across Vallecito Creek to the upper drainages of Ute Creek and Flint Fork and to the high ridge between the Lake Fork and Flint Fork of Pine River. This formation ends at its intrusive contact with the Pine River batholith of Eolus Granite. The Uncompahgre Formation unconformably overlies older rocks and occurs in a synclinorium—here termed the "Uncompahgre synclinorium." Similarly, the episode of folding and metamorphism that affected the Uncompahgre Formation is here named the "Uncompahgran disturbance."

The Uncompahgre Formation is largely quartzite and pelitic rock (slate and schist); siltstone and conglomerate are present in very minor amounts.

BASAL CONGLOMERATE

Conglomerate of varying thickness lies at the base of this formation at several localities: in the vicinity of Snowdon Peak where it is 8 feet thick (fig. 10); at the junction of the Animas River and Whitehead Gulch where interlayered conglomerate and pebbly quartzite are about $1\frac{1}{2}$ feet thick; on the west rim of the canyon of the Animas River east-southeast of Molas Lake where $2\frac{1}{4}$–$3\frac{1}{2}$ feet of conglomerate contain about one-third pebbly quartzite; and along the north side of the valley of Tenmile Creek the conglomerate is as much as 20 feet thick. These bodies are lenticular; for example, on the west slope of the Animas Canyon, between the Snowdon Peak and Tenmile Creek localities, there is no conglomerate at the base of the Uncompahgre Formation. Many exposures of this conglomerate and of the overlying quartzite show cross-stratified layers whose tops invariably face away from the unconformity.

Lithologically the basal conglomerate is similar to the Vallecito Conglomerate, and they may have been derived from the same source rocks. The clasts rarely exceed 4 inches in maximum dimension, and most are $\frac{1}{2}$–$1\frac{1}{2}$ inches. Subrounded to rounded quartz clasts are most abundant and form 70–95 percent of the total; some show fabrics similar to those of metamorphosed quartzites, but most are so thoroughly recrystallized that their origin cannot be ascertained. Jasper clasts occur in all the conglomerate and pebbly quartzite; both red and dark-gray types are found, and the latter is more abundant. Most of the conglomerate contains gray chert fragments, which are recrystallized to mosaic fabrics of $\frac{1}{50}$- to $\frac{1}{10}$-mm grains. Subangular tabular fragments of dark-gray argillite were observed in the conglomerate west of Snowdon Peak. The matrices of these conglomerates are mostly quartzose with minor interstitial sericite, but some is sericitic with minor quartz. Minor amounts of hematite, limonite, ilmenite, leucoxene, tourmaline, and zircon are present in the matrix of most specimens. Grain size of the quartz in the matrix commonly ranges from about $\frac{1}{20}$ to $\frac{1}{2}$ mm, and that of the sericite from $\frac{1}{100}$ to $\frac{1}{20}$ mm. This basal conglomerate was sampled and analyzed for gold but gave negative results (Barker, 1969a).

QUARTZITE

The quartzite layers of the Uncompahgre Formation are indistinguishable from each other in outcrop, and they are described here as a group. The quartzite layers are very resistant to erosion and form most of the spectacular peaks of the northern Needle Mountains, of which the Grenadier Range (fig. 7) is the most prominent. These rocks are light gray to pale blue, commonly show buff-colored joint surfaces in weathered outcrops, and are thin to thick bedded. They contain laminae of hematite 1–3 mm thick and show trough-type cross-stratification in many outcrops. Rare interlayered beds of pebbly quartzite and quartz pebble conglomerate 5–10 cm thick also occur. They are 95–99 percent quartz; the remainder is hematite, which formed from detrital magnetite during metamorphism, and interstitial sericite. Individual quartz grains in much of the quartzite range from $\frac{1}{10}$ to 2 mm, but some quartzite contains original detrital grains as large as 3 cm. In thin section the quartz grains show a polygonal mosaic texture in which original grain outlines are obliterated and in which grain growth was minor. Some specimens consist of very irregularly shaped grains 3 to 15 mm in maximum dimension in which the outlines of original, smaller grains are indicated by strung-out grains of hematite and aggregates of sericite. All quartz grains are

FIGURE 7.—View of the eastern Grenadier Range, from the northeast, showing, from left to right, The Guardian, Mount Silex, and Storm King Peak.

characterized by moderate to pronounced undulatory extinction.

Layers of siltstone are found locally in the Uncompahgre Formation. They are mostly a few inches to a few feet thick and buff to red to gray, and they consist largely of quartz and sericite.

The origin of the sericite in the quartzite layers is problematical. Three possible sources are: Coatings of clay on original detrital grains; clay from the interlayered shale beds that was flushed into the original pores sometime after deposition and before diagenesis and metamorphism; and hydrolysis of detrital potassic feldspar during metamorphism. I favor the third hypothesis but cannot rule out the first and second.

SLATES, PHYLLITES, AND SCHISTS

Pelitic rocks form about 25 percent of the Uncompahgre Formation, as shown in figure 2. Argillaceous slates and schists are preponderant, but interlayers of siltstone and fine-grained sandstone are present in many of the pelite layers, especially the one that is under Rock Lake. The pelites are described in this report from west to east and southeast, which also corresponds to the direction of increasing grade of metamorphism.

The westernmost exposures of the Uncompahgre pelites in the Needle Mountain uplift are at Lime Creek. These rocks are banded gray, green, and black extremely fine grained slates. They consist of sericite-quartz assemblages with carbon and pyrite as common accessories. Pyrite forms lenses parallel to bedding and occurs also along postcleavage joints, suggesting relatively late growth of this mineral. The banding is in units 1–5 mm thick, and the grain size in individual bands changes from $\frac{1}{50}$–$\frac{1}{100}$ mm at the bottom to $\frac{1}{100}$–$\frac{1}{200}$ mm at the top. These bands may be varves. Slaty cleavage is well developed and apparently is parallel to axial planes of minor folds. Intense folding is evident from many outcrops, as the bedding is at low to high angles to the slaty cleavage. A specimen of gray siltstone about 20 mm thick from a slate layer at Lime Creek consists of $\frac{1}{40}$- to $\frac{1}{10}$-mm quartz grains and 15–20 percent of interstitial sericite; bedding is faintly visible because of slight variations of the sericite content.

The slate layers in the canyon of the Animas River mostly are of the typical gray to dark-gray commonly carbonaceous varieties. However, the northernmost layer (fig. 2) is largely purple hematitic slate and siltstone with poikiloblasts of andalusite, the westernmost occurrence found of this mineral. The next layer to the south, whose westernmost part is greatly thickened by folding, is pale-green, gray, and grayish-green slate and banded siltstone of quartz, sericite, and chlorite that locally contains biotite and plagioclase. The latter rock type suggests provenance from intermediate or basic volcanic rocks.

To the east the pelitic layers from the south side of White Dome to Trinity Lake are mostly dark-gray to black fissile banded slate of the assemblage quartz-sericite-carbon, and they commonly contain minor pyrite and(or) ilmenite. This slate has interlayers of muscovite-chloritoid-quartz-garnet phyllite, muscovite-chlorite-quartz-andalusite phyllite, muscovite-chlorite-chloritoid-quartz-ilmenite-carbon slate, quartz-sericite siltstone of $\frac{1}{20}$-mm grain size, and similar rocks. The metamorphic grade thus has increased from the westward to an area where chloritoid and garnet appear. This study, however, is not sufficiently detailed to determine the order of appearance of these two minerals.

The lower part of the layer that lies south of Storm King Peak and The Guardian is dark-gray and greenish-gray slate, in part chlorite bearing. The upper part is mostly micaceous siltstone and fine-grained sandstone, in part contains both muscovite and biotite, and is locally cross-stratified.

The pelite layers in the vicinty of Beartown and south to the head of Vallecito Creek are finely banded, gray to black slates with typical assemblages of quartz-sericite-biotite-carbon and sericite-chlorite-quartz-biotite-carbon. Pyrite, ilmenite, albite, and tourmaline are accessories. Biotite here is in randomly oriented ragged anhedrons that indiscriminately cut across bands of well-oriented sericite; this ragged biotite is believed to be of postkinematic crystallization and of thermal metamorphic origin, as further discussed on page A31–A32.

South of the latitude of Mount Nebo along Vallecito Creek the slates and phyllites contain randomly oriented metacrysts of gray chiastolite 1–2 inches long that show the usual regularly arranged carbonaceous inclusions. The metamorphic grade increases rapidly to the south, for the pelite layer that crosses under Vallecito Creek about 0.4 mile north of the junction of Vallecito and Rock Creeks contains the assemblage biotite-chiastolite-muscovite-quartz and the following sets of additional phases: chloritoid-garnet-plagioclase-staurolite, chloritoid-garnet-plagioclase, and chloritoid-plagioclase-staurolite. Compositional banding is common in these schists, as shown in figure 8. The plagioclase is calcic albite and sodic oligoclase. Colorless to gray-green to blue-green tourmaline is a common accessory. The trio graphite-ilmenite-pyrite also are accessory and are stable together. Pale-green chlorite forms ragged partial to complete pseudomorphs after biotite but is not a stable phase. Sericite, of much finer grain than stable muscovite, is the other secondary mineral. Biotite is pleochroic straw yellow to medium brown. Chiastolite is pink in hand specimen, the only occurrence of this color variation in the Needle Mountains. Chloritoid is pale

FIGURE 8.—Banded chiastolite-garnet-staurolite schist in the Uncompahgre Formation, 0.4 mile north of the junction of Rock and Vallecito Creeks.

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violet and shows no visible pleochroism. Garnet is blood red in hand specimen and pale pink in thin section. Staurolite has Z = pale yellow rather than golden yellow. The matrices of these schists, which are mostly quartz, muscovite, and plagioclase, range in grain size from $\frac{1}{40}$ to $\frac{1}{10}$ mm, whereas the metacrysts of biotite, chloritoid, garnet, and plagioclase are $\frac{1}{10}$–$\frac{3}{4}$ mm, those of staurolite 1–10 mm, and those of andalusite 5–50 mm. These rocks are banded, as is typical of the Uncompahgre pelite, but they definitely are not schistose. Even the biotite and muscovite are randomly oriented, and the rocks are granoblastic and porphyroblastic. The fabrics are those of hornfels rather than of regionally metamorphosed pelites. Chloritoid was not observed east or south of this locality.

East to southeast and south of the junction of Vallecito and Rock Creeks the layers of Uncompahgre schist mostly have similar granoblastic and porphyroblastic fabrics, but rocks retaining their well-defined schistosity and finer grain are not uncommon. Chiastolite schists sampled along the northeast slope of Rock Creek valley, 1.1 miles east-southeast of the Vallecito-Rock Creek junction, contain rare staurolite and no chloritoid. Staurolite was not observed east or south of this locality. Schists from here to the head of Rock Creek and near the divide with Flint Fork contain prominent poikiloblasts and knots of chlorite along with disseminated octahedral magnetite. These rocks contain only traces of biotite, or none at all, and biotite may have reacted late in the metamorphic process to produce this chlorite and magnetite. The biotite was not analyzed but probably is more ferruginous than the chlorite. Locally high activities of H_2O, perhaps of magmatic generation as discussed subsequently, are believed to have driven this reaction. Partial to complete alteration of chiastolite to sericite also has taken place in these rocks. Schist collected 1.4 miles south of the chiastolite-chloritoid-garnet-staurolite occurrence of Vallecito Creek, from near the 13,250-foot summit ridge between Vallecito and Rock Creeks, is especially notable because it contains much secondary sericite and chlorite.

The pelitic schists at the head of Rock Creek and north across the Continental Divide to the head of Middle Ute Creek are gray to black banded fine-grained rocks with the following assemblages: muscovite-quartz, biotite-chlorite-garnet-muscovite-quartz, biotite-chiastolite-garnet-magnetite-muscovite-quartz, and biotite-chiastolite-muscovite-quartz. Each assemblage contains graphite, tourmaline, and pyrite as accessory minerals. The chlorite in the second assemblage is in ragged tablets, similar in habit to the biotite in this rock, and apparently is in equilibrium. The chiastolite metacrysts are 1–2 inches long (fig. 9) and gray, and

FIGURE 9.—Chiastolite schist in the Uncompahgre Formation, 0.35 mile south of Twin Lakes, Middle Ute Creek drainage.

most show some secondary very fine grained sericite, quartz, and chlorite. Quartz-biotite-muscovite schist, which apparently was deposited as silt or very fine sand, is interlayered with the chiastolite schists.

The Uncompahgre schists in the headwaters of the Flint Fork of Pine River contain andalusite and chlorite as stable phases, with typical assemblages: andalusite (poikiloblastic, not carbonaceous)-biotite-chlorite-garnet-muscovite-quartz, and andalusite-biotite-chlorite-muscovite-plagioclase (albite-oligoclase)-quartz. Graphite is a common accessory.

Within about ½–1 mile of the Pine River batholith of Eolus Granite the Uncompahgre schists show contact metamorphic effects. Sillimanite occurs in place of andalusite, plagioclase is slightly more calcic, pinite occurs as pseudomorphs after cordierite(?), and microcline is present but chlorite absent within a few hundred feet of the contact. Typical assemblages are biotite-muscovite-pinite-quartz-sillimanite, biotite-muscovite-plagioclase-quartz-sillimanite, and biotite-garnet-microcline-plagioclase.

Lenses of quartz are scattered throughout the Uncompahgre pelite. Most are but a fraction of an inch thick, and many are contorted by folding. Most are parallel to bedding, but oblique ones are not uncommon. These lenses may be metamorphosed chert nodules or lenses or quartz veins.

The pyritic pelites of the Uncompahgre Formation were analyzed for 30 metals (Barker, 1969a), including gold, and were found to contain generally less metal than the average shale.

A study of carbon isotopes in the slates and schists of this formation by Barker and Friedman (1969) shows that the carbon is isotopically light, with delta C^{13} values ranging from about −23 to −31 per mil. The carbon most probably is of photosynthetic origin.

The ground water that issues from the pyrite-bearing pelite of the Uncompahgre Formation commonly leaves a gelatinous coating of ferric hydroxide on stream boulders. Pyrite is unstable in aerated ground waters and oxidizes (Hem, 1960, p. 71) to give a ferrous sulfate water. The ferrous iron is further oxidized at the surface and precipitates largely as ferric hydroxide. Springs of iron sulfate-bearing water issue from the great slab of schist that underlies the north-facing mountain slope southeast of the junction of Rock and Vallecito Creeks and from the underlying quartzite. The waters have killed trees, stained cliffs of quartzite and boulders in Rock Creek below, and caused fish to leave the lower part of Rock Creek. A 2-quart sample of water issuing from one of the springs on this slope was collected and analyzed by G. F. Scarbro and M. R. Midgett, with the following results:

	Parts per million	*Equivalent per million*
SiO_2	14	--------
Al	18	2.00
Fe	12	.64
Mn	12	.44
Ca	77	3.84
Mg	114	9.38
Sr	.40	.01
Na	3.2	.14
K	.8	.02
Li	.12	.02
Cu	.13	.00
Zn	1.5	.04
Acidity (as H_2SO_4)	11	10.91
Total cations		27.44
Sulfate (SO_4)	1,270	26.44
Chloride (Cl)	1.8	.05
Fluoride (F)	1.7	.09
Nitrate (NO_3)	.1	.00
Phosphate (PO_4)	.00	.00
Total anions		26.58
Dissolved solids	1,530	--------
Hardness as $CaCO_3$		
Total	661	--------
Noncarbonate	661	--------
Specific conductance (μmhos at 25° C)	2,440	
pH	2.6	

The sample was not analyzed for bicarbonate (HCO_3) or for carbonate (CO_3).

THICKNESS

The thickness of the Uncompahgre Formation cannot be measured precisely because the quartzite layers locally show minor folding and the pelitic layers almost everywhere show complex minor folding. A rough estimate can be made from the relatively simple section that is exposed from Balsam Lake to the 12,985-foot summit about 1.4 miles northeast of the junction of Vallecito and Rock Creeks. Here, as elsewhere, the uppermost part of the formation is not preserved. This section is perhaps 8,000 feet thick and consists of the following units:

4th slate layer, 50–100 ft (estimated thickness);
4th quartzite layer, 1,000 ft;
3d slate layer, 200–300 ft;
Quartzite of Stormy Gulch, 800 ft;
Slate of Trinity Lake, 200–400 ft;
Quartzite of Storm King Peak, 2,000 ft;
Slate and siltstone of Lake Silex, 400–500 ft;
Quartzite at Balsam Lake, 3,000 ft;
Unconformity.

The position of the measured section of the Uncompahgre River south of Ouray relative to this one is not known, for no individual unit can be recognized as common to both areas.

ORIGIN

The following facts bear upon the origin of the Uncompahgre Formation: (1) Compositions of the original sediments of this formation are essentially bimodal—highly quartzose sands alternate with aluminous clays and form 80–90 percent of the formation; (2) clasts in the basal conglomerate are mostly quartz, jasper, and argillite; the granitic and metavolcanic rock types that lie below the Uncompahgre unconformity elsewhere are not found; and (3) the formation is more than 8,000 feet thick. The bimodal nature of the sediments is most easily explained if one postulates a source area of quartzite, argillite, jasper, and iron-formation or jaspilite. This postulate appears reasonable when one considers that similar clasts occur in both the basal Uncompahgre conglomerate and the older Vallecito Conglomerate. Thus, I suggest that the Vallecito Conglomerate and the Uncompahgre Formation had the same source rocks and that some of the Vallecito or other first-cycle sediments exposed in the area may have been recycled into the Uncompahgran trough. The thickness and known extent of the Uncompahgre Formation necessitate a relatively extensive source area.

THE SUB-UNCOMPAHGRE UNCONFORMITY AND PHYLLONITE

A phyllonite lies along a part of the unconformity between the Uncompahgre Formation and the Irving Formation and Twilight Gneiss. This unconformity, of course, was deformed during the younger Uncompahgran disturbance and everywhere is now steeply dipping, except south and west of Snowdon Peak (fig. 10) and south of Balsam Lake. (See Cross, Howe, Irving, and Emmons, 1905, geol. map; fig. 4, this report.) The angles between the banding or foliation of the Irving Formation and of the Twilight Gneiss and the bedding of the Uncompahgre Formation range from a few degrees to almost 90°; greater and more abrupt differences occur along the south margin of the Uncompahgre Formation than along the north margin.

An unusual rock, which apparently is a phyllonite and can be classified as quartz sericite schist, lies in gradational to abrupt contact with the Irving Formation and Twilight Gneiss at and west of the Animas River at both the north and south margins of the Un-

FIGURE 10.—Basal contact of the Uncompahgre Formation, about 0.4 mile southwest of Snowdon Peak. Man (center) stands in front of the 8-foot-thick basal conglomerate, which is overlain by quartzite and underlain by phyllonite. Broken Twilight Gneiss and amphibolite, both sheared and altered, lie at the left.

compahgre Formation. This rock unit ranges from 4 to about 40 feet thick and consists of about 10 to 50 percent of ¼- to 4-mm subrounded to rounded single grains and polygranular aggregates of quartz set in a schistose matrix of sericite with minor hematite, limonite, and leucoxene. The schistosity in all outcrops observed is parallel to the bedding of the adjacent Uncompahgre Formation. The phyllonite probably was derived from rocks of granitic composition, in which the original quartz grains were not comminuted but were first severely strained and then recrystallized and in which much of the original ferrous iron was oxidized. A granite dike in the Irving Formation 75 feet north of the unconformity and immediately east of the Animas River contains similarly strained and recrystallized quartz. Similar quartz-sericite schist which also probably is phyllonite and 50 to 75 feet thick lies along the unconformity west of Moon Lakes; this is the only outcrop of this type of rock found east of the canyon of the Animas River.

The unconformity also was observed northwest of Irving Peak and at Beartown (See Cross, Howe, Irving, and Emmons, 1905, geol. map); in both places the phyllonite is absent and the Uncompahgre quartzite lies directly on the Irving Formation. Northwest of Irving Peak, sheared and recrystallized quartzite of the Uncompahgre Formation lies on a quartz-sericite schist containing chloritoid, garnet, chlorite, and ilmenite and having schistosity almost perpendicular to the bedding of the quartzite. At the Beartown locality massive quartzite of the Uncompahgre Formation lies on sheared and closely fractured fine-grained feldspar-quartz-biotite gneiss that has been largely altered to sericite, clay minerals, calcite, and limonite.

Both types of occurrence, in which phyllonite or sheared quartzite or gneiss is present, indicate relative movement of unknown but considerable magnitude along the unconformity and suggest that the massive basal quartzite and conglomerate of the Uncompahgre Formation greatly exceeded in competence the Irving Formation and the Twilight Gneiss. Thus, in a sense, at least part of this unconformity is a thrust fault. Mineral transformations in the Irving and Twilight rocks that produced sericite and other retrograde minerals apparently were a major contributor to the low competence of these rocks. The phyllonite formed during the Uncompahgran disturbance and is synchronous with the folding and metamorphism of the Uncompahgre Formation.

IGNEOUS ROCKS

TYPES AND AGE RELATIONS

The various types of Precambrian intrusive rocks of the Needle Mountains, except for the Bakers Bridge Granite and the Electra Lake Gabbro, were named by Cross, Howe, Irving, and Emmons, (1905); all except the Bakers Bridge were described briefly and their general age relations given. Cross' names are used here with little or no modification, and the reader should keep in mind that most of these rocks that are termed "granite" actually are quartz diorite and other less potassic types. Pertinent information on these rocks is summarized in table 1, and more detailed descriptions are given below under individual headings. Chemical analyses and CIPW norms of most of the intrusive types are presented in table 2, and ternary plots of normative Ab-Or-An, Ab-Or-Qz, and (Ab + An)-Or-Qz are shown in figure 11. Plots of the ratios of Na_2O versus K_2O and of Na_2O versus CaO are shown in figure 12.

TWILIGHT GNEISS

Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, p. 7) named their Twilight Granite from the extensive exposures at Twilight Peak, in the West Needle Mountains. This unit underlies the central and western West Needle Mountains, the canyons of Lime and Cascade Creeks, Potato Hill and the area to the south, the area east and southeast of Columbine Lake, and the Animas Canyon in the vicinity of Cascade Siding and Teft Spur—an area of about 60 square miles. This rock is a gneiss of trondhjemitic to quartz monzonitic composition and is here renamed the Twilight Gneiss.

The Twilight Gneiss has a metamorphic fabric in that it is well foliated and commonly exhibits a lineation of strung-out clusters of biotite. It is homogeneous in outcrop except for ubiquitous and locally abundant slabby interlayers of amphibolite and for very subordinate interlayers of other rocks. Hornblende prisms in the amphibolite interlayers are lineated parallel to the biotite-cluster lineation of the granite, indicating that these rocks were crystallized together.

The Twilight Gneiss is light to medium gray, partly with pink, green, or red tones. It is fine to medium grained, and many specimens exhibit bimodal grain size; a quartzo-feldspathic matrix of mostly $\frac{1}{10}$- to ¼-mm grains encloses quartz "eyes", plagioclase anhedra, biotite tablets, and rare microcline anhedra of ½- to 3-mm size. The quartz ovoids or "eyes" give

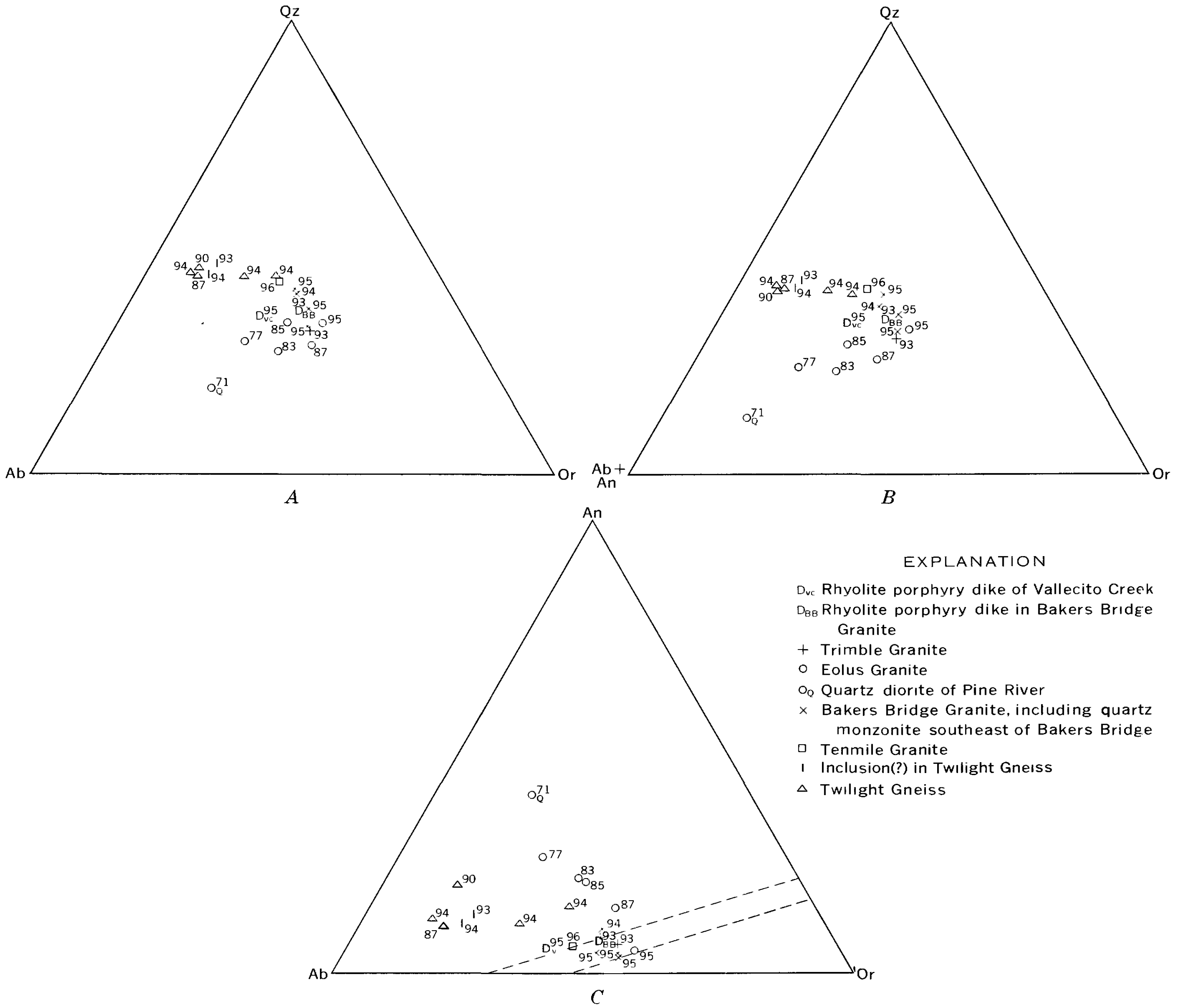

FIGURE 11.—Ternary plots of normative minerals in Precambrian granitic rocks of the Needle Mountains. Superscripts are percentages of normative salic minerals. *C* shows the minimum melting trough after Yoder, Stewart, and Smith (1957) and Kleeman (1965).

many specimens an unusual appearance; they are polygranular, and adjacent grains differ only slightly in optic orientation—suggesting origin from single grains. Some ovoids are straight-sided, blocky aggregates that may be recrystallized, dipyramidal grains. The size distribution and quartz "eyes" may well indicate genesis from a porphyry.

The Twilight Gneiss ranges in composition from quartz diorite to quartz monzonite, and much of the light-colored oligoclase-bearing rock deserves the name trondhjemite. Oligoclase or sodic andesine and quartz comprise the bulk of most specimens; microcline ranges in content from several to about 25 percent. Biotite forms 5–10 percent of all specimens, and accessory minerals include hornblende epidote, garnet, opaque oxides, and muscovite. Hornblende and muscovite were not seen in the same thin section. Microcline is fresh, but plagioclase of most specimens shows faded albite twinning and moderate to heavy alteration to sericite, clay, and epidote, and clear rims of albite are not common. The hornblende is blue green to green, but the biotite varies widely in color, from golden brown to dark green to olive brown.

TABLE 1.—*Description of the Precambrian intrusive rocks of the Needle Mountains*

Formation	Named by	Rock type	Fabric	Orogenic type [1]	Geologic relations	Radiometric age [2]
Twilight Gneiss	Cross, Howe, Irving, and Emmons (1905).	Quartz diorite, granodiorite quartz monzonite, trondhjemite.	Foliated	Prekinematic or synkinematic.	Metamorphosed to amphibolite facies; contains many slabs of amphibolite; ovoid quartz grains in most specimens may be relics from an original porphyritic fabric.	1,780 m.y. (U-Pb); 1,805 m.y. (Rb-Sr determination by Barker, Z. E. Peteman, and R. A. Hildreth, unpub. data).
Whitehead Granite (name abandoned in this report).	do	Mostly quartz monzonite, partly trondhjemite.	Mostly massive, partly foliated.	Mostly postkinematic, partly synkinematic.	Older lineated metamorphosed trondhjemite similar to Twilight Gneiss; younger massive strained quartz monzonite similar to Tenmile Granite; dike of the younger type is truncated by Uncompahgre unconformity.	1,780 m.y. (U-Pb); 1,720 m.y. (U-Pb); 1,695 m.y. (Rb-Sr).
Tenmile Granite	do	Quartz monzonite	Massive to foliated.	Postkinematic	Originally massive but strained with partial development of foliation in the Uncompahgran disturbance.	1,720 m.y. (U-Pb); 1,724 m.y. (Rb-Sr).
Bakers Bridge Granite	This report	Granite, alaskite, quartz monzonite.	Massive	do	Mafic minerals are altered, but fabric apparently has not changed since the rock was first formed.	1,720 m.y. (U-Pb); 1,692 m.y. (Rb-Sr).
Quartz diorite of Pine River	Renamed this report.	Biotite-hornblende quartz diorite.	do	do	Surrounded and crosscut by Eolus Granite; probably a forerunner of the Eolus batholith.	Not determined.
Eolus Granite, includes Pine River batholith of Larsen and Cross.	Cross, Howe, Irving and Emmons (1905).	Granodiorite, quartz monzonite granite.	do	do	Intruded Uncompahgre Formation as well as older rocks; compound batholith; original fabrics well preserved.	1,460 m.y. (U-Pb); 1,466 m.y. (Rb-Sr); 1,460 m.y. (K-Ar on hornblende).
Electra Lake Gabbro	This report	Olivine gabbro, hypersthene gabbro, diorite.	do	do	Heterogeneous intrusive; original fabrics well preserve 1; not in contact with Eolus Granite, so relative age relations unknown.	1,460 m.y. (U-Pb); 1,454 m.y. (Rb-Sr).
Trimble Granite	Cross, Howe, Irving, and Emmons(1905).	Quartz monzonite	do	do	Intruded Eolus Granite; marked alteration of original plagioclase and mafic minerals.	1,350 m.y. (?) (Rb-Sr).
Rhyolite porphyry and granitic dikes.	Not named	Rhyolite porphyry, alaskite.	do	do	Most intrude the Bakers Bridge Granite; some intrude the Irving Formation in Vallecito Creek.	1,460 m.y. (U-Pb: one sample from Vallecito Creek determined); 1,314 m.y. (Rb-Sr) determined for both localities.

[1] Refers to cycle during which body was emplaced.
[2] U-Pb ages determined on zircons, Silver and Barker (1968); Rb-Sr whole-rock ages from Bickford, Barker, Wetherill, and Lee-Hu (1968); K-Ar age by R. E. Zartman (written commun., 1966).

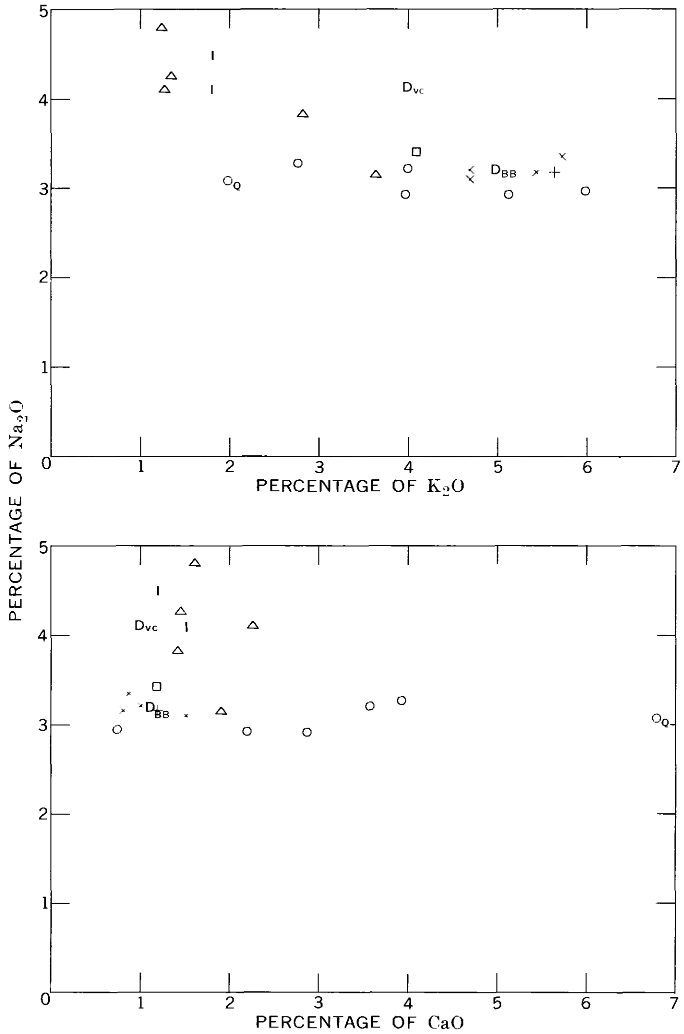

FIGURE 12.—Plots of Na_2O versus K_2O and of Na_2O versus CaO, in weight percent, for Precambrian granitic rocks of the Needle Mountains. Symbols are the same as in figure 11.

Chemical analyses and CIPW norms of five specimens are given in table 2. Relative proportions of Na_2O and K_2O and of Na_2O and CaO are plotted in figure 12, and three ternary combinations of the normative feldspars and quartz are plotted in figure 11. These rocks are relatively sodic, having low contents of both K_2O and CaO. All show normative corundum, as do many others of the Needle Mountains granitic rocks. Three specimens, BSJ–13, BSJ–17, and LS–T2, are trondhjemitic, whereas BSJ–48 is a quartz monzonite. BSJ–113, which shows excellent "eyes" of quartz, is intermediate and is a leucogranodiorite. Thus, the five analyses, though insufficient in number for the purpose, do suggest a trend from trondhjemite to quartz monzonite and toward granite, as expressed in the terminology of plutonic rocks.

The age of the Twilight Gneiss, as determined by the uranium-lead isotopic method (Silver and Barker, 1968), is 1,780±20 m.y. A rubidium-strontium isochron of 12 samples of Twilight Gneiss and interlayers of albite gneiss and amphibolite gives an age of 1.805±35 m.y. and an initial Sr^{87}/Sr^{86} ratio of 0.7015 (Fred Barker, Z. E. Peterman, and R. A. Hildreth, unpub. data). These two determinations are thus well within limits of error.

Slabby interlayers of amphibolite are found throughout the Twilight Gneiss. Locally, as at the hairpin turn on U.S. Highway 550 one-half mile east of Mill Creek, the slabby interlayers are brecciated, and a weakly foliated to massive, variably gray-colored matrix of Twilight contains irregularly shaped fragments of amphibolite, which range in size from a fraction of an inch to 3 feet and in shape from irregular and angular to elongate and lenticular. Two samples from amphibolite interlayers, BSJ–18 from a thick layer and BSJ–114 from a 2-foot fragment, were chemically analyzed (table 2). These two compositions are equivalent to tholeiitic basalt; they show normative quartz and hypersthene and are free of normative olivine and nepheline. The similarity of the two analyses might suggest little or no change in composition during intrusion and metamorphism of the Twilight, except of course for hydration.

The northwestern part of the Twilight Gneiss contains scattered interlayers of oligoclase-quartz-muscovite-biotite-garnet gneiss. These are mostly lenticular, are several inches to several feet thick, have their foliation parallel to that of the Twilight Gneiss, and only locally are crosscut by the gneiss. These interlayers possibly are metamorphosed graywacke.

Along U.S. Highway 550 several tenths of a mile east of Mill Creek the Twilight Gneiss contains scattered slabby masses of fine-grained pinkish-gray albite-quartz-chlorite-microcline-biotite gneiss. These masses show a faint to fair banding that resembles flow banding in acidic volcanic rocks. The slabs are a few feet to about 20 feet thick, and both their contacts and their foliation are parallel to the foliation of the enclosing Twilight Gneiss. This albite gneiss shows chevron folds with axes plunging 60°–65° NE., which is roughly normal to the lineation of the Twilight Gneiss and suggests that these slabs may be inclusions. The albite gneiss contains only 7–10 percent of dark minerals, has an average grain size of about one-half mm, and is relatively homogeneous in outcrop. Chemical analyses and norms of specimens from two of these inclusions (?) are given in table 2, and these two rocks are represented in figures 11 and 12. These rocks, much alike in composi-

TABLE 2.—*Chemical analyses and CIPW norms of Precambrian*

[0, looked for but not detected; ------, not looked for. Analyst C. L. Parker: BSJ-13, Rapid rock analyses by P. L. D. Elmore, S. D. Botts, Gillison Chloe, J. Glenn, Lowell 209, 210, 214, 216–218; CO–199]

	Twilight Gneiss					Amphibolite of Twilight Gneiss		Metarhyodacite of Twilight Gneiss		Tenmile Granite	Whitehead Granite	
Field No.	BSJ-13	BSJ-17	BSJ-48	BSJ-113	LS-T2	BSJ-18	BSJ-114	BSJ-214	BSJ-216	BSJ-19	BSJ-217	BSJ-66a
												Chemical anal
SiO_2	71.29	75.11	74.38	74.67	71.21	50.31	51.55	74.1	75.2	75.91	73.7	74.5
Al_2O_3	14.07	12.98	13.22	13.15	13.91	13.26	13.53	13.3	13.0	12.94	13.3	14.0
Fe_2O_3	1.32	.77	.36	.61	.36	3.38	3.31	1.3	.62	.34	.79	.17
FeO	3.13	1.73	1.82	1.76	3.69	11.84	11.25	1.7	1.8	.61	2.1	.36
MgO	.75	.33	.39	.53	1.56	5.16	5.28	.44	.33	.20	.65	.17
CaO	2.26	1.60	1.90	1.41	1.44	8.91	8.94	1.5	1.2	1.17	.81	.31
Na_2O	4.11	4.81	3.16	3.82	4.27	2.28	2.03	4.1	4.5	3.41	3.1	3.2
K_2O	1.26	1.23	3.64	2.82	1.34	.88	.55	1.8	1.8	4.09	3.3	5.8
H_2O^+	.83	.60	.52	.56	1.12	1.52	1.79	1.2	1.2	.41	1.2	.51
H_2O^-	.08	.04	.01	.03	.06	.06	.03	.00	.00	.03	.05	.05
TiO_2	.27	.13	.13	.13	.26	1.60	1.35	.15	.13	.09	.15	.02
P_2O_5	.08	.02	.03	.03	.08	.15	.14	.00	.00	.01	.08	.02
MnO	.08	.07	.05	.06	.09	.24	.24	.23	.19	.02	.06	.03
CO_2	.01	.16	.09	.04	.18	.09	.01	.08	$<.05$	.37	.08	.05
Cl	.00	.01	.01	.01	.00	.02	.02	.004	$<.001$	.01	.004	.005
F	.05	.06	.05	.09	.07	.06	.07	.050	.030	.02	.078	.028
Subtotal	99.59	99.65	99.76	99.72	99.64	99.76	100.09	------	------	99.63	------	------
Less O	.02	.03	.02	.04	.03	.03	.03	------	------	.01	------	------
Total	99.57	99.62	99.74	99.68	99.61	99.73	100.06	100	100	99.62	99	99
												CIPW
Quartz	35.01	38.12	36.62	37.18	33.93	4.27	7.58	38.86	37.83	38.44	39.61	32.81
Corundum	2.18	1.42	1.05	1.67	3.60	.00	.00	2.20	1.55	1.72	3.73	2.13
Orthoclase	7.45	7.27	21.51	16.66	7.92	5.20	3.25	10.64	10.64	24.17	19.50	34.27
Albite	34.78	40.63	26.66	32.25	36.13	19.15	17.03	34.69	38.08	28.78	26.23	27.08
Anorthite	10.29	6.36	8.31	5.90	5.00	23.43	26.26	6.57	5.73	3.26	2.46	.88
Halite	.00	.02	.02	.02	.00	.03	.03	.00	.00	.02	.00	.00
Wollastonite	.00	.00	.00	.00	.00	7.86	6.95	.00	.00	.00	.00	.00
Enstatite	1.87	.82	.97	1.32	3.89	12.85	13.15	1.10	.82	.50	1.62	.42
Ferrosilite	4.36	2.46	2.92	2.63	6.22	16.75	16.14	2.23	2.93	.73	3.07	.54
Magnetite	1.91	1.12	.52	.88	.52	4.90	4.80	1.88	.90	.49	1.14	.25
Ilmenite	.51	.25	.25	.25	.49	3.04	2.56	.29	.25	.17	.29	.04
Apatite	.19	.05	.07	.07	.19	.36	.33	.00	.00	.02	.19	.05
Fluorite	.10	.12	.10	.18	.14	11	.13	.10	.06	.04	.15	.06
Calcite	.02	.36	.21	.09	.41	.20	.02	.18	.00	.84	.18	.11

SAMPLE LOCALITIES

BSJ-13: U.S. Highway 550, 9,920 ft alt, 0.20 mile SW. of Mill Creek.
BSJ-17: Lime Creek road, 9,200 ft alt, 0.6 mile N. of Lime Creek Campground.
BSJ-48: Purgatory trail in canyon of Cascade Creek at 8,040 ft alt, 0.35 mile from the Animas River.
BSJ-113: Lime Creek road, 9,100 ft alt, 0.05 mile N. of Lime Creek Campground.
LS-T2: U.S. Highway 550, 10,260 ft alt, 1.1 mile S. of Coal Bank Summit.
BSJ-18: Lime Creek road, 9,470 ft alt, 0.15 mile N. of La Plata-San Juan County line.
BSJ-114: Same as BSJ-113.
BSJ-214: U.S. Highway 550, 9,880 ft alt, 0.15 mile SW. of Mill Creek.
BSJ-216: U.S. Highway 550, 9,930 ft alt, 0.20 mile SW. of Mill Creek.
BSJ-19: Animas River canyon, at railroad track about 0.4 mile N. of bench mark 8756.
BSJ-217: Animas River Canyon, 0.11 mile S. of mouth of Sultan Creek, about 30 ft E. of railroad track.
BSJ-66a: East of Animas River canyon, at 12,000 ft alt, 0.51 mile N. and 0.53 mile W. of SE. corner of Silverton 7½-minute quadrangle (lat 37° 45′ N., long 107° 37′ W.).
BSJ-28: U.S. Highway 550, 7,080 ft alt, 0.6 mile S. of Shalona Lake.

tion, probably are metarhyodacites with low color indices. Their composition, incidentally, is much like that of some of the Twilight Gneiss. Uranium-lead isotopic analyses of zircon (L. T. Silver, written commun., Nov. 1967) from this gneiss plot on a concordia diagram just to the right of the well-defined chord of the Twilight, and thus the albite gneiss appears to be slightly older.

Small pegmatites and aplites of pale-orange microcline, quartz, and muscovite are irregularly dispersed in the Twilight Gneiss but are more abundant in the northwestern part than elsewhere. The pegmatite dikes range in thickness from about 1 to 30 feet, and the aplites from about 1 to 12 inches. Both types commonly are closely fractured and strained and probably formed before the Uncompahgran disturbance.

The contact with amphibolites of the Irving Formation on the southeast side of the Twilight Gneiss consists of a zone about 1,500 feet thick that includes 40–60 percent of tabular masses of amphibolite in foliated quartz diorite. This contact is especially well exposed in cliffs along the Animas River between the mouths of Little Cascade and Grasshopper Creeks. The smaller slabs of amphibolite, less than about 2 feet thick, are broken and pulled apart, and massive plagioclase-quartz aplite is in the fractures, yet the slabs show only slight rotation. (See fig. 11 of Cross, Howe, Irving, and Emmons, 1905.) The larger amphibolite layers are cut by dikes of the aplite. Because the foliated interlayers of quartz diorite grade into the massive plagioclase-quartz dikes, I infer that metamorphic conditions here *granitic rocks and their inclusions from the Needle Mountains*

17–19, 48, 113, 114; LS–T2, E1. Analyst Edythe Engleman: BSJ–92–94,133, 141, 158, 208.
Artis, H. Smith, J. Kelsey, P. Aruscavage, E. Gray, and J. Budinsky: BSJ–28, 53, 66a,

	Bakers Bridge Granite			Quartz monzonite SE of Bakers Bridge	Eolus Granite					Quartz diorite of Pine River	Trimble Granite	Rhyolite porphyry dikes		Alaskite dike
	BSJ–28	BSJ–53	BSJ–210	BSJ–209	BSJ–93	BSJ–94	BSJ–141	BSJ–158	BSJ–208	BSJ–92	BSJ–133	CO–199	BSJ–218	LS–E1
yses (in percent)														
	73.16	74.26	74.6	76.0	63.97	65.86	65.09	72.50	61.60	55.48	70.99	72.9	72.4	73.28
	13.48	12.45	12.2	11.7	14.51	15.00	14.50	14.68	14.00	16.20	14.51	12.9	14.6	14.00
	.63	1.03	.76	.53	1.46	1.52	2.79	.43	2.17	2.70	.65	.58	.90	.41
	1.40	1.44	1.4	.88	5.04	3.60	3.86	1.39	7.18	7.02	1.57	2.2	.64	.81
	.19	.15	.27	.16	1.49	1.22	1.42	.29	1.77	3.60	.66	.29	.39	.38
	.86	.80	1.5	1.0	3.56	2.18	2.86	.72	3.91	6.80	1.17	1.1	1.0	.87
	3.35	3.17	3.1	3.2	3.21	2.93	2.93	2.96	3.29	3.09	3.19	3.2	4.1	3.13
	5.73	5.46	4.7	4.7	4.00	5.11	3.97	5.99	2.75	1.98	5.60	5.0	4.0	5.83
	.47	.41	.85	1.1	.62	.81	.70	.46	1.11	.70	.67	1.2	1.2	.50
	.04	.05	.00	.00	.03	.14	.08	.08	.06	.13	.05	.00	.02	.06
	.19	.26	.20	.11	1.11	.76	1.02	.19	1.34	1.30	.27	.20	.22	.10
	.02	.02	.00	.00	.33	.23	.32	.04	.33	.48	.08	.00	.03	.03
	.05	.07	.25	.11	.11	.08	.10	.03	.16	.15	.04	.35	.26	.05
	.16	.25	.05	<.05	.07	.02	.00	.05	.06	.00	.22	.09	.11	.28
	.02	.01	.015	.007	.04	.02	.02	.00	.02	.04	.01	.005	.002	.01
	.09	.03	.15	.32	.20	.12	.17	.13	.09	.14	.12	.13	.088	.02
	99.84	99.86	------	------	99.75	99.60	99.83	99.94	99.84	99.81	99.80	------	------	99.76
	.04	.01	------	------	.09	.05	.07	.05	.04	.07	.05	------	------	.01
	99.80	99.85	100	99	99.66	99.55	99.76	99.89	99.80	99.74	99.75	100	100	99.75
Norms														
	29.66	33.19	34.83	37.54	18.71	21.54	24.02	29.75	18.04	8.66	27.44	31.30	30.93	30.80
	.89	.59	.00	.40	.00	1.28	.95	2.23	.00	.00	1.78	.80	2.27	1.74
	33.86	32.26	27.77	27.77	23.64	30.20	23.46	35.40	16.25	11.7	33.09	29.55	23.64	34.45
	28.20	26.75	26.08	27.00	27.16	24.79	24.79	25.05	27.84	26.15	26.99	27.00	34.69	26.41
	2.47	2.05	5.57	2.62	13.37	9.19	12.10	2.99	15.31	24.49	3.89	3.94	3.42	2.21
	.03	.02	.03	.02	.00	.00	.00	.00	.00	.00	.00	.02	.00	.02
	.00	.00	.19	.00	.71	.00	.00	.00	.65	2.55	.00	.00	.00	.00
	.47	.37	.67	.40	3.71	3.04	3.54	.72	4.41	8.97	1.64	.72	.97	.95
	1.83	1.49	2.08	1.20	6.42	4.25	3.28	1.94	9.48	8.79	1.97	3.88	.55	1.08
	.91	1.49	1.10	.77	2.12	2.20	4.05	.62	3.15	3.91	.94	.84	1.31	.59
	.36	.49	.38	.21	2.11	1.44	1.94	.36	2.54	2.47	.51	.38	.42	.19
	.05	.05	.00	.00	.78	.55	.76	.10	.78	1.14	.19	.00	.07	.07
	.18	.06	.31	.66	.00	.00	.00	.00	.00	.00	.00	.27	.18	.04
	.36	.57	.11	.00	.16	.04	.00	.11	.14	.00	.50	.20	.25	.64

BSJ–53: Animas River canyon, at railroad track 0.5 mile E. of Rockwood.
BSJ–210: NW¼SW¼ sec. 18, T. 37 N., R. 8 W., 200 ft E. of small unnamed pond at 7,080 ft alt.
BSJ–209: SW¼SE¼, sec. 19, T. 37 N., R. 8 W., 400 ft NW. of Annisi Ranch.
BSJ–92: South Canyon Creek, alt 10,100 ft (1⅝ mile SW. of Divide Lakes).
BSJ–93: Pine River trail, 9,200 ft alt, about 0.2 mile S. of Flint Fork.
BSJ–94: Pine River–Sand Creek divide, 0.6 mile SW. of Graham Peak, 11,910 ft alt.
BSJ–141: Pine River trail, 8,700 ft alt, 0.75 mile below Falls Creek.
BSJ–158: Slope S. of Sunlight Creek at 10,270 ft alt, 0.38 mile W. of Vallecito Creek.
BSJ–208: At road in Tank Creek, 10,300 ft alt.
LS–E1: SW¼NE¼ sec. 12, T. 38 N., R. 9 W., shore of Electra Lake.
BSJ–133: 150 ft W. of Trimble Pass.
CO–199: SE¼NE¼ sec. 13, T. 37 N., R. 9 W., 7,200 ft alt, 750 ft W. of the Animas River.
BSJ–218: Vallecito Creek trail, 150 yds S. of Quartz Mill Bridges.

were so intense that the Twilight Gneiss partly melted to plagioclase-quartz aplite, which then intruded the amphibolite layers along tensional fractures.

The origin of the Twilight Gneiss deserves comment. This rock has undergone amphibolite-facies metamorphism, and most of the original fabric has been obliterated. The quartz ovoids or "eyes" in much of it, however, may be relict phenocrysts. The rock is generally similar in appearance in all its exposures; yet it ranges in composition from quartz diorite to quartz monzonite. The tabular interlayers of metamorphosed tholeiitic basalt and other, much less abundant rocks are generally parallel to the foliation of the granite; yet crosscutting relations on a scale of a few inches are common. The proportion of these slabby interlayers ranges from about 1 percent to about 80 percent in zones 50 to 200 feet thick; and at the contact of the Twilight Gneiss with the Irving Formation the proportion of amphibolite increases irregularly southeastward through a 1,500-foot-thick zone to almost 100 percent.

In view of these facts, two leading hypotheses for the origin of the Twilight Gneiss are: (1) A complex of sills of porphyritic dacite to quartz latite intruded a flat or gently dipping pile of basalt layers, a part of the Irving Formation, and metamorphism and folding of both produced what is now called Twilight Gneiss; or (2) a closely interlayered volcanic sequence of basalt and silicic extrusives, the latter including much crystal tuff, was deposited in close association with the Irving Formation, perhaps under marine conditions, and later folded and metamorphosed. In both hypotheses I assume that magma of partly trondhjemitic type and partly more potassic type was generated in a eugeosynclinal environment, as is not uncommon. The possible slightly older age of the interlayers of albite gneiss in the Twilight Gneiss suggests that the first hypothesis is more likely, but the available data are certainly insufficient to rule out the second hypothesis. The fact that the trondhjemitic gneiss, albite gneiss, and amphibolite of the Twilight lie on the same isochron, however, tends to support the second hypothesis. Another, and less attractive hypothesis, is that the Twilight Gneiss is metamorphosed graywacke, but this possibility is not supported by the rubidium-strontium data.

TENMILE GRANITE

Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, p. 7) named the Tenmile Granite from the exposures along the lower part of Tenmile Creek. This unit is a stock of very rough oval map pattern; the major axis trends east-northeast and is about 4.2 miles long, and the minor axis trends west-southwest and is about 2.2 miles long. The granite intrudes the Irving Formation. The main mass of Tenmile Granite lies no closer than about 0.7 mile to the nearest exposure of the Uncompahgran unconformity, but dikes of it are truncated by that unconformity.

In their petrographic description Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, p. 8) stated:

> The Tenmile rock as a whole is a rather coarse light-pink or gray granite, but there is an intricate mingling of granite of other textures, shades and colors, ranging from coarse pink pegmatites to fine dark-gray gneissoid rocks rich in biotite, that resemble some mica-diorites. The association of these rocks is most intimate, but notwithstanding the diversity of their megascopic characters, their mineralogical compositions show no marked differences.

These authors further stated that intrusion of the darker varieties followed very closely after intrusions of the lighter granite and gave as evidence the very diffuse contacts between the two types at some places. They interpreted that the older, lighter rock here first crystallized to an extent that it behaved coherently and then was both brecciated and disintegrated at its margins by the younger, darker intrusive.

The Tenmile Granite typically is pink to light gray to brownish gray, medium to coarse grained, and mostly homogeneous in outcrop. It locally contains xenoliths of biotite amphibolite and in some outcrops shows a faint to moderately well defined foliation which usually—strikes east-west and dips vertically. Many granitic dikes cut the main mass of the Tenmile. In this section the Tenmile Granite is seen to be a severely strained quartz monzonite in which the fresh well-twinned microcline shows marked undulatory extinction. The sodic oligoclase has albite twinning with fractures and pink bands, shows undulatory extinction, and is patchily altered to sericite and a brownish-gray opaque substance. The original quartz grains, whose outlines are preserved, have recrystallized to aggregates of much finer ($\frac{1}{10}$-$\frac{1}{2}$ mm) grains. The original biotite has been altered to chlorite, sericite, and a clay mineral. Epidote, garnet, allanite, apatite, and zircon are accessory minerals. The deformation and alteration are judged to have occurred during the Uncompahgran disturbance.

A chemical analysis of typical Tenmile Granite is given in table 2 and is represented in figures 11 and 12.

Radiometric age determinations on the light-colored variant of Tenmile Granite are 1,720±20 m.y. by the uranium-lead method on zircons (Silver and Barker, 1968) and 1,724±55 m.y. by the rubidium-strontium whole-rock method (Bickford and others, 1968). These two results show a remarkably good agreement.

WHITEHEAD GRANITE

Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, p. 8) named the Whitehead Granite from exposures of several small stocks and a multitude of dikes in and about Whitehead Gulch, a tributary to the Animas River about 4 miles south of Silverton. They classified all the granitic dikes and small stocks in the Irving Formation north of the Uncompahgre Formation as Whitehead Granite. Their petrographic description of it, as a pink or light-red granite containing only "a little oligoclase," grossly applies to the stocks and to some, but not all, of the dikes.

In this study of Cross and Howe's Whitehead Granite two rock types were found. An earlier type, in generally concordant and lenticular bodies, is a strongly foliated or lineated, fine- to medium-grained quartz monzonite, granodiorite, and light-colored quartz diorite; the oligoclase-albite is extensively altered to sericite and a brown clay, and it contains small amounts of chlorite and epidote as well as biotite. A later type is a massive medium- to coarse-grained biotite quartz monzonite. In view of the dual nature of the formation, I abandon the name Whitehead Granite.

The earlier type of dike underwent first deformation and metamorphism with the Irving Formation and later retrograde metamorphism apparently in the Uncompahgran disturbance. The second type was intruded after metamorphism of the Irving and was later affected by the Uncompahgran disturbance. A sample of the earlier type gave a uranium-lead age on zircons of 1,780±20 m.y. (Silver and Barker, 1968), and a sample of the later type gave a uranium-lead age on zircons of 1,720±20 m.y. (Silver and Barker, 1968) and a rubidium-strontium whole-rock isochron of 1,695±65 m.y. (Bickford and others, 1968).

A gneissic quartz monozonite dike of the earlier type was chemically and spectrographically analyzed. In chemical composition (table 2) and trace-element content determined spectrographically (Barker, unpub. data), the dike is very similar to the Twilight Gneiss. Thus, this earlier type of dike, included in Whitehead Granite by Cross and Howe (Cross, Howe, Irving, and Emmons, 1905), is of the same age, petrographic and chemical type, and geologic occurrence as the Twilight Gneiss.

The younger dikes are similar to the several stocks of biotite quartz monzonite shown by Cross and Howe (Cross, Howe, and Ransome, 1905; Cross, Howe, Irving, and Emmons, 1905), and the largest dike is shown in figure 2. One of the dikes that cuts the Irving Formation and is truncated by the sub-Uncompahgre unconformity was sampled 75 feet north of that unconformity. This rock, which gave a uranium-lead age of 1,720 m.y., is greenish gray with flecks of orange microcline, medium to coarse grained, and massive. In thin section, the oligoclase-albite is seen to have bent and broken albite twinning, and the microcline has extreme undulatory extinction. Apparently original quartz grains were recrystallized (or annealed) to aggregates of many smaller, polygonal grains with sharp extinction, and original mafic minerals were completely altered to aggregates and veinlets of brown opaque material, epidote, and chlorite. Some of the plagioclase and microcline have mortar structure. This dike is a quartz monzonite, similar in bulk composition to the Tenmile Granite.

The stock shown as Tenmile Granite in figure 2 about 1.5 miles north of the Uncompahgre synclinorium consists of massive quartz monzonite. The quartz in this rock is recrystallized to aggregates of smaller grains. The original oligoclase is albitized, heavily dusted with clay, and partly replaced by 1- to 2-mm grains of muscovite; the original biotite is now a mass of fine-grained chlorite. Irregular fractures cut across the rock, and the rock along the fractures contains crushed feldspars and much secondary chlorite. At this distance from the sub-Uncompahgre unconformity and phyllonite, the bulk of the feldspars in the rock are not conspicuously strained or fractured. In a chemical analysis this rock (table 2, sample BSJ–66a) is similar to the Tenmile Granite except for its anomalously low content of CaO, 0.31 percent, and its relatively high content of K_2O, 5.8 percent. These variations are believed to result from alteration during the Uncompahgran disturbance.

These dikes and stocks of the Whitehead Granite are similar to the Tenmile Granite to the south in their geologic occurrence, radiometric age, chemistry, and petrography. These features indicate a common origin. Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, p. 8) suggested that the Whitehead and Tenmile Granites were contemporaneous and "derived from the same source."

BAKERS BRIDGE GRANITE

The stock of massive pale-red medium- to coarse-grained granite and alaskite that is exposed in the Animas River valley at Bakers Bridge, Shalona Lake, Rockwood, and vicinity is here named the Bakers Bridge Granite. Its type locality is at Bakers Bridge in the Hermosa 7½-minute quadrangle. About 3 square miles of this granite is exposed. It passes under Paleozoic rocks to the west and alluvium to the south.

Most of the Bakers Bridge Granite is seriate inequigranular, coarse grained, massive, and homogeneous. Grains 5–15 mm in size are predominant, but some varieties have fine-grained matrices and plagioclase-mantled microcline phenocrysts 15–20 mm in maximum dimension, and others have relatively even-grained fabrics with 1–5 mm grains. Swarms of inclusions of amphibolite, presumably from the Irving Formation, occur in the granite east and northeast of Rockwood. The Bakers Bridge Granite is composed mostly of perthite and quartz and contains less than 10 percent each of plagioclase and dark minerals in most of the stock. Allanite and fluorite are accessory minerals.

In thin section the rock's characteristic brick-red microcline is seen to be a perthite of both flame and blocky types containing 20–50 percent albite; the microcline shows excellent grid twinning, whereas only the blocky albite shows albite twinning. Myrmekite lies at a few of the microcline-microcline and quartz-microcline boundaries. Quartz is present both as single grains and as aggregates of several to a dozen small grains. The aggregates probably formed by recrystallization of original, larger grains; both simple grains and aggregates show pronounced undulatory extinction. The quartz ranges from light gray to pale blue to pale violet. Plagioclase is mostly anhedral, but subhedrons, both stubby and lathlike, are not uncommon. Its composition is calcic to median andesine; clear rims of sodic albite surround many grains. Grains with faded, perhaps original, twinning and grains with sharp twinning that may be secondary may be seen in the same thin section; the cores of most grains have been irregularly altered to clay and sericite, and these areas may originally have been more calcic than albite. The ferromagnesian minerals in the Bakers Bridge

Granite are iron rich, for these rocks contain only 0.15–0.27 percent MgO, as shown in table 2. The only original mafic silicate is a hornblende with X=grayish green and Z=brownish green, and only one partially preserved hornblende grain was seen. The major alteration products of this brownish-green hornblende are biotite with Z=medium to dark green, hornblende with Z=blue-green, and tabular ilmenite that in polished sections is seen to contain finely disseminated hematite. The biotite along with a little of the primary hornblende, was altered to ferristilpnomelane that is pleochroic golden yellow to various red-brown tints. The ilmenite-hematite has been altered to leucoxene and ilmenite. Ilmenite also occurs separately from these mafic silicates, in what probably are primary grains of euhedral zircon. Other alteration minerals include epidote and chlorite associated with biotite, talc and hornblende, and sphene as rims on ilmenite. The major sequence is:

brownish-green hornblende→biotite+
blue-green hornblende+ilmenite,

and:

brownish-green hornblende+biotite→stilpnomelane.

Whether any or all of this alteration was coincident with the Uncompahgran disturbance is problematical.

Most of the granite contains only 3–8 percent of dark minerals. A mafic variety—comprised of about 60 percent microcline perthite, 25 percent ferromagnesian silicates, 10 percent quartz, 5 percent magnetite-ilmenite with rims of sphene, and 1 percent albite—forms a 20-foot-thick segregation 150 feet south of the northern contact of the stock along the tracks of the Denver and Rio Grande railroad. The contacts of this mafic variety are gradational over 2–4 inches with the quartzose alaskitic granite. The mafic silicates, whether originally hornblende or clinopyroxene, are now aggregates of actinolite, epidote, anthophyllite, chlorite, and stilpnomelane.

Chemical analyses of three specimens of Bakers Bridge Granite are given in table 2. BSJ–28 and BSJ–53 are of the seriate inequigranular variety, and BSJ–210 is of the type with blocky microcline phenocrysts set in a fine-grained matrix. All three are very similar in composition except that BSJ–210 has about 0.7 to 1.0 percent less of K_2O. This granite is characterized by very low proportions of CaO, as shown in figure 12. In figure 11 the normative minerals of Bakers Bridge Granite plot closer, as a group, to the granite minimum than any other granitic rock of the Needle Mountains.

Silver and Barker (1968) reported a uranium-lead age for zircons from the Bakers Bridge Granite of 1,720±20 m.y., and Bickford, Barker, Wetherill, and Lee-Hu (1968) obtained a whole-rock rubidium-strontium isochron of 1,692±78 m.y.

The southeastern part of the area of Bakers Bridge Granite includes a crosscutting pink massive mostly medium grained seriate inequigranular quartz monzonite. Whether or not this rock is cogenetic with the Bakers Bridge Granite is problematical. This rock consists of about 40 percent microcline microperthite, 30 percent quartz, 25 percent calcic albite, 5 percent biotite that has been mostly altered to chlorite, and traces of muscovite and fluorite. A chemical analysis of it (sample BSJ–209, table 2) is almost identical with that of a sample of Bakers Bridge Granite (BSJ–210), the variety containing large phenocrysts of microcline in a fined-grained groundmass. An age determination of uranium and lead isotopes in two samples of the zircon from BSJ–209 gives an apparent age of 1,631 m.y. (L. T. Silver, written commun., Nov. 1967). There is a possibility, which will not be discussed here, that this zircon has been disturbed, perhaps by Eolus Granite lying to the east.

QUARTZ DIORITE OF PINE RIVER

A mass of quartz diorite about 4 square miles in area lies northwest of upper Pine River at and south of the latitude of Divide Lakes. Larsen and Cross (1956, p. 29–30) briefly described this body and called it "Granodiorite of the Pine River batholith." However, potassic feldspar is developed only along the margins of this body, and the genetic relationship of this body to the Eolus-Pine River batholith is probable rather than proved, so this mass is here called the quartz diorite of Pine River. The quartz diorite mass is oval in plan, and its axes are about 2.5 and 1.8 miles long. It lies entirely within the Pine River batholith of Eolus Granite, and it is older than the Eolus, as shown by crosscutting relations and xenoliths. Several bodies of similar rock lie in Eolus Granite west of Vallecito Creek, as reported by Larsen and Cross (1956, p. 29).

In hand specimen the quartz diorite of Pine River is gray to brownish gray, massive, medium to coarse grained, and homogeneous except for the marginal variety that contains scattered dents de cheval of microcline microperthite. The rock consists of approximately 55–60 percent andesine, 15–20 percent quartz, 15 percent biotite, 7–8 percent hornblende, 2–3 percent clinopyroxene, and 1–2 percent total of magnetite-ilmenite, apatite, and sphene. The plagioclase is fresh except for spotty sericitization, shows both albite and pericline twinning, and occurs as blocky, lathlike, and irregularly shaped grains. Quartz shows only mild undulatory extinction. Biotite is in fresh irregularly shaped anhedra; it is pleochroic from pale golden brown to deep red brown. Hornblende in formless anhedra is fresh, commonly is twinned, has Z=green, and forms thick rims on ragged cores of colorless clinopyroxene. The quartz diorite of Pine River is a relatively unstrained rock and clearly is younger than the Uncompahgran disturbance. A chemical analysis of it is given in table 2. On the plots of normative quartz and feldspar in figure 11 and on the Na_2O-K_2O and Na_2O-CaO diagrams in figure 12, the quartz diorite is seen to lie along the trend of the Eolus Granite, which is highly suggestive that the quartz diorite was the first major intrusive of the Eolus batholith.

EOLUS GRANITE

The Eolus Granite is the most widespread plutonic rock in the Needle Mountains and forms two composite batholiths. It was named by Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, p. 8) from 14,084-foot-high Mount Eolus (aptly named after the ancient Greek god of the winds), which is the second highest peak in the Needle Mountains uplift.

About 100 square miles of Eolus Granite is exposed in the southern Needle Mountains between Vallecito Creek and the east rim of the canyon of the Animas River; superb exposures are in the drainage basins of the Florida River and Johnson, Needle, and Sunlight Creeks. This mass extends southward under the Paleozoic sedimentary rocks for an unknown distance. Another mass of this granite, almost as large, underlies most of the drainage basin of the Pine River above the Lake Fork (fig. 13) and extends eastward from the area shown in figure 2 into the upper reaches of Sand, Little Sand, and Weminuche Creeks. This body extends southeastward under Paleozoic and Mesozoic sedimentary rocks and is exposed along the Piedra River and lower Weminuche Creek about 8 miles from the main mass (Larsen and Cross, 1956, pl. 1). The two intrusives are here called the western and eastern bodies, respectively. Larsen and Cross (p. 29–31) called both of these bodies the Pine River batholith, which practice is not followed here, and described several varieties of the granitic rocks in them. A small mass of Eolus Granite cuts massive quartzite of the Uncompahgre Formation along Leviathan Creek. Dikes of Eolus-like granite and rhyolite porphyry cut schists of the Uncompahgre Formation in the Flint Fork drainage and metavolcanic rocks of the Irving Formation along Vallecito Creek. However, apart from these occurrences, minor intrusions of Eolus type are rare. The name Eolus Granite is here used to include all variants of these intrusive masses. Several of these variants are briefly described here, but it is to be kept in mind that this study is of a reconnaissance nature.

FIGURE 13.—Southward view of lower Flint Fork, showing Popes Nose. Entire area shown is underlain by Precambrian Eolus Granite except the slope in the middle skyline, which consists of Tertiary volcanic rocks.

The bulk of both the western and the eastern bodies of Eolus Granite is fresh mostly massive gray to pink to brick-red biotite-hornblende quartz monzonite. Conspicuous ½- to 1½-inch grains of pink blocky carlsbad-twinned microcline microperthite (fig. 14) are set in a medium- to coarse-grained matrix of andesine, quartz, biotite, and hornblende. The andesine is blocky and median to sodic. The quartz is gray to pale-blue and commonly is in clusters of equant grains. The biotite is tabular to irregularly shaped and is pleochroic from pale golden or olive brown to dark brown. The hornblende is in ragged anhedral grains with pleochroism X = pale green-brown, Y = light brown, and Z = green. Accessory minerals are ilmenite rimmed with sphene, and, in minor proportions, zircon, apatite, and allanite. Typically, 12–20 percent of hornblende and biotite is present, ½–⅘ of it biotite. This rock is homogeneous except in the zones of inclusions in the eastern body, where it grades into magnetite-bearing granodiorite. The inclusions are found miles from the walls in swarms of lenticular individuals that are 1–3 inches thick and 3–8 inches in diameter. They consist of the same minerals as the enclosing granodiorite but have greater proportions of biotite, hornblende, ilmenite, magnetite, and other accessory minerals. These inclusions apparently were equilibrated with the magma; their origin, however, is unknown. Parts of the quartz monzonite and

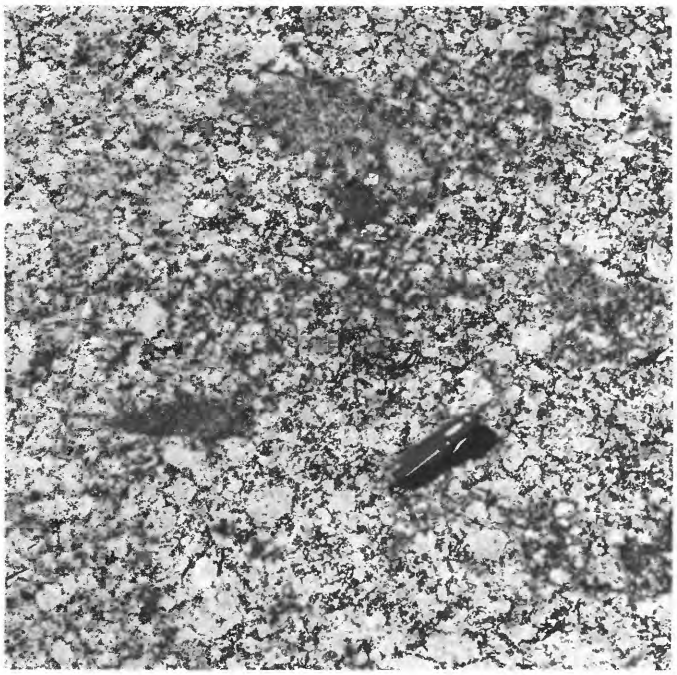

FIGURE 14.—Eolus Granite. Variety shown is coarse biotite-hornblende quartz monzonite with blocky microcline microperthite grains ½ to 1½ inches long, and with several dark inclusions of biotite-hornblende gneiss.

granodiorite show a foliation of the microcline subhedra: In the western body along parts of its margin, and in the eastern body in scattered areas in its interior, especially in the zones of inclusions, but rarely along its margin.

The biotite-hornblende quartz monzonite was intruded by biotite quartz monzonite and biotite granite, especially in the Florida River drainage. The biotite quartz monzonite is generally similar to the predominant quartz monzonite except that hornblende is absent; the microcline is tabular rather than blocky and is poikilitic with $\frac{1}{10}$- to ½-mm grains of plagioclase and quartz; little or no ilmenite and sphene are present; and the rock contains only 5–10 percent of biotite. Biotite granite crops out in the canyon of the Florida River and to the east near Stump Canyon Lakes. In the Florida River area the granite is a deep-pink homogeneous massive and fine- to medium-grained rock. In the Stump Canyon Lakes area the rock is also deep pink, homogeneous, and massive, but it consists of about 60 percent phenocrysts of tabular to blocky microcline, 5–18 mm in size, set in a medium-grained matrix of quartz, calcic oligoclase, and biotite. A brick-red microcline-rich biotite granite also intruded the eastern mass of Eolus Granite (Larsen and Cross, 1956, p. 30).

The two masses of Eolus Granite also contain dark variants. The western body at Mountain View Crest and southwestward to Tank Creek contains a granodiorite with 30–35 percent hornblende and biotite combined. The minerals in this rock are very similar to those of the predominant biotite-hornblende quartz monzonite, but the proportions are different. It is not known if this mafic granodiorite is cut by the quartz monzonite or not, but its time of crystallization as determined by isotopic methods is indistinguishable from that of the quartz monzonite, as discussed below. The eastern mass at Flag Mountain contains a dark granodiorite; this is a gray massive rock in which 10-20-mm blocky microcline phenocrysts are set in a medium-grained matrix. This dark granodiorite is cut by the biotite-hornblende quartz monzonite. An estimated mode of this grandiorite is 45–50 percent andesine, 15 percent each biotite and quartz, 10 percent hornblende, 8 percent microcline, 3 percent ilmenite, and 1 percent sphene.

Five chemical analyses and CIPW norms of three varieties of Eolus Granite are given in table 2. These varieties are the biotite-hornblende quartz monzonite, BSJ–93, –94, and –141; the dark variant of Tank Creek that contains much hornblende and biotite, BSJ–208; and the hornblende-free biotite granite, BSJ–158. These five norms, together with that of the cogenetic quartz diorite of Pine River, show in figure 11 a well-marked trend from a composition rich in normative plagioclase to one in the theoretical minimum melting trough.

The eastern contact of the western body of Eolus Granite is shown by Cross and Howe (Cross, Howe, Irving, and Emmons, 1905) as a fault. This contact was examined in detail by me west of Vallecito Creek in the vicinity of lat. 37°30′, and was found to be intrusive. Amphibolite of the Irving Formation is brecciated by the granite, and jumbled fragments of the Irving from a few inches in size to slabs 4 feet thick and 30 feet long in a matrix of hybrid granite form a marginal zone 100–200 feet thick. The Irving Formation along this contact contains many dikes of Eolus-like granite and rhyolite porphyry in a zone extending ½–1 mile east of the batholith.

The eastern body of Eolus Granite sharply crosscuts quartzite and schist of the Uncompahgre Formation as well as the Vallecito Conglomerate and Irving Formation. Furthermore, this contact of the granite with the Vallecito is linear (fig. 2), possibly owing to intrusion along a fault.

Radiometric age measurements have been made on both masses of Eolus Granite. Silver and Barker (1968) reported an age of the western body, by uranium-lead isotopic methods, of about 1,460±20 m.y. Bickford, Barker, Wetherill, and Lee-Hu (1968) obtained a rubidium-strontium whole-rock isochron from samples of both bodies of 1,466±27 m.y. and mineral isochrons of approximately 1,400 m.y. R. E. Zartman (written commun., Jan. 1966) made potassium-argon age determinations on two minerals from the eastern batholith of the Eolus: the hornblende age is 1,460±70 m.y., and the biotite age, 1,390±40 m.y. Thus one may conclude that these batholiths were emplaced about 1,460 m.y. ago and that they experienced a minor thermal disturbance 60 or 70 m.y. later.

ELECTRA LAKE GABBRO

The mass of gabbroic and related rocks that has intruded the Twilight Gneiss and Irving Formation at the northern half of Electra Lake and extends southeastward to the Animas River is here named the Electra Lake Gabbro. The type locality is on the east shore of the north half of the lake. This intrusive was first mapped and briefly described by Cross (Cross and Hole, 1910, p. 3–4). It is roughly triangular in plan, about 2½ miles along its southern, east-trending base and about 2¼ miles along its western, north-trending side. Paleozoic sedimentary rocks overlie it on the west, so its extent in that direction is unknown. The Electra Lake Gabbro sharply crosscuts its wallrocks; in some places, as along the Animas River, the contact is nearly planar and vertical; at other places many small dikes of gabbro intrude the wallrock near an irregular main contact. Dikes of pink to red alaskite and granophyre, quartzo-feldspathic pegmatite, and hornblende-bearing pegmatite cut the gabbroic rocks and apparently are genetically related to it, as first suggested by Cross (Cross and Hole, 1910, p. 4). Bickford, Barker, Wetherill, and Lee-Hu (1968) reported a rubidium-strontium whole-rock isochron for this gabbro of 1,454±50 m.y. One of these dikes, of mixed alaskite and granophyre, gives a uranium-lead age of 1,460±20 m.y. (Silver and Barker, 1968), which is essentially identical with that of the gabbro.

The Electra Lake Gabbro is markedly heterogeneous. Some individual outcrops 100 feet in maximum dimension contain gabbro, hypersthene gabbro, augite-biotite diorite, and even quartz diorite that bears a few percent microcline. The various rock types have gradational contacts with one another. The complete range of rock types extends from olivine gabbro to biotite-augite granodiorite. Gabbro with augite and median or sodic labradorite as major constituents and with minor hornblende, biotite, ilmenite, and magnetite is perhaps the most abundant single petrographic variety in the intrusive. These rocks are all massive, medium to coarse grained, of various brown to dark-gray shades, and, with one exception, relatively fresh and free from secondary sericite and other fine-grained minerals. That exception is in the easternmost area of this intrusive, in the canyon of the Animas River, where plagioclase has been extensively altered to sericite, clay, and epidote, and biotite and augite are moderately to wholly chloritized. These effects may be due to effects of the Eolus Granite, which lies about one-eighth mile east of the gabbro. Actually, the relative order of intrusion of the Electra Lake Gabbro and the Eolus Granite is not known, for the isotopic age methods do not have the necessary resolution. Plagioclase has crystallized mostly as subhedral laths, some of which enclose small grains of augite. Augite and hypersthene are stubby subhedral to anhedral prisms. Hornblende rims on augite are common, but biotite forms discrete grains of very irregular shape. Microcline shows excellent grid twinning and occurs as blocky subhedra and anhedra that have grown between plagioclase and biotite grains. Quartz is interstitial to all other minerals.

The dike of mixed fine- to medium-grained alaskite and granophyre that crops out on the west shore of Electra Lake is 10–12 feet thick, strikes about N. 10° E., and dips vertically. This rock consists of about 55 percent microcline, 30 percent quartz, 15 percent albite, and traces of muscovite, magnetite, and chlorite. A chemical analysis of this rock (sample LS–E1, table 2) also shows it to be of granophyric composition, although perhaps more potassic than average, containing 5.83 percent K_2O.

TRIMBLE GRANITE

Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, p. 8) named the Trimble Granite from its exposures at Trimble Pass. This granite underlies approximately 5 square miles of Vallecito Basin, East Silver Mesa, Missouri Gulch, and the area from Florida Mountain to Castelleia Lake. Its contacts are well defined except where many dikes extend outward into the Eolus Granite.

The Trimble Granite is a pale-pink to light-brick-red massive homogeneous fine- to medium-grained granite. It commonly is porphyritic and contains 1–5 percent blocky to tabular ⅛- to 1-inch-long microcline phenocrysts. In thin section the rock is seen to consist largely of fresh blocky anhedral microcline, ½–3 mm in size and showing superb grid twinning and rare Carlsbad twinning, and anhedral irregular quartz grains, mostly 1½–3 mm in maximum dimension. The larger microcline grains are poikilitic with randomly oriented subhedral grains of plagioclase 1/20–1/5 mm in diameter. Calcic oligoclase to sodic andesine forms 10–15 percent of the rock, is blocky subhedral to equant anhedral, shows excellent albite twinning except where altered, and commonly is slightly to intensively altered to clay and sericite. Biotite is present as thick tablets, is pleochroic golden light brown to dark olive green, forms 6–10 percent of the granite, and in some specimens is entirely altered to green chlorite, white clay, and sericite. Trace amounts of anhedral interstitial muscovite are present. Original accessory magnetite and ilmenite were altered to hematite and leucoxene, respectively. The ubiquitous nature of the alteration of the plagioclase, biotite, and opaque oxides suggests that this alteration is deuteric type. A chemical analysis of a specimen from Trimble Pass, BSJ–133, is given in table 2. As it contains 71 percent SiO_2, 5.60 percent K_2O, and 3.19 percent Na_2O, this rock is not greatly different from the BSJ–158 type of Eolus Granite (table 2).

The Trimble Granite has intruded the Eolus Granite and therefore is younger. A rubidium-strontium whole-rock age determination by Bickford, Barker, Wetherill, and Lee-Hu (1968) gives approximately 1,350±50 m.y.

MINOR INTRUSIVE ROCKS

Several types of intrusive rocks noted during this investigation occur in bodies too small to be shown in figure 2. For completeness of presentation, these varied rock types are briefly described.

METADACITE

The Vallecito Conglomerate is cut by a dike of metadacite in the southernmost area of its exposure on the west side of the Vallecito valley. The dike is fine grained, massive, and homogeneous and consists of sericitized plagioclase, quartz, biotite, pale-blue-green hornblende, epidote, and magnetite. The dike is mostly 3–7 feet thick, and it sharply crosscuts the bedding of the Vallecito at about right angles. It can be traced for about 500 feet.

RHYOLITE PORPHYRY DIKES

Dikes of rhyolite porphyry about 1–15 feet thick cut the Bakers Bridge Granite (Cross and Hole, 1910, p. 4) north of the latitude of Bakers Bridge and cut the Irving Formation along Vallecito Creek south of Quartz Mill bridges.

A 10- to 15-foot-thick dike in the Bakers Bridge Granite that was selected as typical of its kind is about two-thirds phenocrysts and one-third groundmass that is deep buff pink, massive, homogeneous, and fresh. The phenocrysts are approximately 45 percent quartz, 40 percent microcline microperthite, 10 percent oligoclase, and 5 percent pseudomorphs of chlorite after biotite (?). The quartz, which is bipyramidal, shows resorbed crystal faces and is 2–3 mm in maximum dimension. The microcline microperthite is fresh, subhedral to euhedral, and 2–8 mm in size, commonly shows carlsbad twinning, and contains 10–20 percent albite in visible streaks. The oligoclase is subhedral, 1–3 mm in maximum dimension, and faintly zoned; it shows mild to moderate sericitization and mostly albite twinning and rarely carlsbad twinning. The groundmass consists of a mosaic fabric of $\frac{1}{50}$- to $\frac{1}{10}$-mm grains of microcline and quartz, with minor, scattered sericite, chlorite, opaque minerals, zircon, and rutile. A chemical analysis of a specimen of this rock, CO–199, is given in table 2, and is notable for its relatively low content of Al_2O_3, 12.9 percent, and its high content of FeO, 2.2 percent. Both values set it apart from the rhyolite porphyry dike of Vallecito Creek. This analysis, however, is similar to that of Bakers Bridge Granite (BSJ–28, –53, and –210). The rhyolite dikes in the Bakers Bridge Granite, though, apparently are much younger than the granite, for they yield a rubidium-strontium whole-rock age of 1,314±38 m.y. (Bickford and others, 1968).

The dike of rhyolite porphyry that cuts the Irving Formation in Vallecito Creek is about 15 feet thick and is similar both in gross appearance and in thin section to the dike, specimen CO–199, in the Bakers Bridge Granite. This rhyolite porphyry in Vallecito Creek has about 60 percent phenocrysts, of which 40 percent is microcline, 35 percent is quartz, 20 percent is median albite, and 5 percent is a mixture of chlorite, muscovite, and limonite pseudomorphous after biotite. Ragged muscovite grains are disseminated through the rock, and some of these cut both phenocrysts and groundmass and, thus, may be of secondary origin. The chemical analysis of this rock, BSJ–218, is given in table 2. The analysis is similar to that of Eolus Granite (BSJ–158) except for its relatively low content of K_2O—4.0 percent. The low content, however, may be the result of loss of K_2O during the formation of the secondary muscovite. Better evidence for believing that this rhyolite porphyry is genetically related to the Eolus batholith is that uranium and lead isotopes of two samples of its zircon plot on a remarkably linear 1,460-m.y. chord (L. T. Silver, written commun., Nov. 1967) on a concordia diagram. A rubidium-strontium whole-rock determination of this dike, however, by Bickford, Barker, Wetherill, and Lee-Hu (1968) lies on the same 1,314-m.y. isochron as the rhyolite porphyry dikes in the Bakers Bridge Granite. The problem of discordance of these rubidium-strontium ages is not yet resolved.

APLITE AND PEGMATITE

Dikes of aplite and pegmatite are scattered throughout the various granitic rocks and the Irving Formation. They are rare to nonexistent, however, in large tracts of the Vallecito Conglomerate and Uncompahgre Formation, perhaps because these formations are much stiffer and were resistant to igneous intrusion. These dikes were intruded at various times: some are of Twilight age, others are of Tenmile and Eolus ages, and still others are apparently only about 1,314 m.y. old (M. E. Bickford, G. W. Wetherill, Fred Barker, and Chin-Nan Lee-Hu, unpub. data), the same age that Bickford, Barker, Wetherill and Lee-Hu (1968) obtained for the two rhyolite porphyry dikes. They were not studied in detail but are mentioned separately because of their areally wide range.

MAFIC QUARTZ SYENITE OF UTE CREEK

Biotite-hornblende quartz melasyenite is exposed in the valley of Ute Creek at and around Black Lake, as mentioned by Larsen and Cross (1956, p. 29). This syenite is northeast of the Needle Mountains and so is mentioned here only briefly. The syenite body is about 1 to 2 miles in size and is bounded on three sides by Tertiary volcanic rocks, which unconformably overlie it. On the fourth, northeast, side it appears to have an intrusive contact into massive gray quartzite. This quartzite is lithologically similar to extensive outcrops of quartzite of the Uncompahgre Formation that lie 4 to 5 miles to the south and west. The melasyenite is a dark-greenish-gray massive medium- to coarse-grained rock and consists of 40–50 percent biotite, hornblende, and augite and 50–60 percent microcline, microperthite, plagioclase, and quartz. Isotopic age determinations indicate that this intrusive is of Eolus or immediate post-Eolus age (R. F. Marvin, written commun., Feb. 1968).

BIOTITE QUARTZ MONZONITE NEAR LAKE SILEX

Biotite quartz monzonite has intruded slate and quartzite of the Uncompahgre Formation at the 12,800-foot saddle that lies 0.4 mile west of Lake Silex. Exposures are poor to good; the eastern parts of the dike are covered with talus. This body is lenticular, has contacts mostly parallel to the slaty cleavage of the enclosing slate, and is several hundred feet long and about 60 feet thick. Randomly oriented inclusions of both slate and quartzite are common in this intrusive, and the quartzite inclusions have rims of biotite 1–2 mm thick. The quartz monzonite has an unusual fabric in which 2- to 4-mm grains of blocky andesine and aggregates of ragged ½-mm biotite grains contain finer interstitial microcline, quartz, micropegmatite, biotite, and epidote. The plagioclase is heavily sericitized. Both the fabric and the association of andesine with micropegmatite in such a salic rock are unusual. The andesine-micropegmatite association, in particular, may be the result of assimilation of slate. The absolute age of this intrusive is not known; all that is known is that it postdates folding and metamorphism of the Uncompahgre Formation.

LAMPROPHYRE DIKES

Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, p. 8) stated:

> Dikes of mica-syenite or minette are found in considerable abundance in the northern third of the [Needle Mountains] quadrangle, cutting the schists, granites, and quartzites, the greater number being found in the Uncompahgre formation. A few occur as far south as Emerson Mountain and the Quartz Mill. They are commonly found intruding the softer shales and slates of the Uncompahgre, and in their field occurrence are mainly remarkable for their variability in thickness, which in few cases exceeds 10 feet, and for their lack of continuity. The occurrences in the region of the Continental Divide and in the neighborhood of Elk Park are the most noteworthy.

These dikes are not known to cut Upper Cambrian or younger rocks, and they thus may be of Middle or Early Cambrian age, or of Precambrian age. A thin section from one of these dikes consists of almost equal amounts of microcline, green biotite, and clear amphibole that shows lamellar twinning and secondary calcite, serpentine, and chlorite.

DIABASE DIKES

Dikes of diabase, mostly a few feet to about 15 feet thick, occur in Precambrian rocks of the Needle Mountains, as described by Cross and Howe (Cross, Howe, and Ransome, 1905; Cross, Howe, Irving, and Emmons, 1905). The most noteworthy occurrence is in the Irving Formation from the Animas Canyon near Deer Park Creek and Whitehead Gulch eastward to the headwaters of Deep Creek. These dikes were not studied in detail by me. They may be of Cambrian age, for Hansen and Peterman (1968, p. C87) found that the diabase dikes in Precambrian rocks of the Black Canyon of the Gunnison River are about 510 m.y. old.

STRUCTURAL GEOLOGY

In this reconnaissance investigation observations of geologic structures were neither detailed nor systematic. However, some major aspects of the structure are discussed here.

FOLDS OF VALLECITO CONGLOMERATE AND IRVING FORMATION

The sharp lithologic contrast between the Vallecito Conglomerate and the Irving Formation and the cross-stratification in the conglomerate that indicates tops and bottoms enable the noses of two folds to be delineated. One of these folds is immediately west of Emerald Lake, and the other is about 2.2 miles west of that lake and just northeast of Table Mountain. These folds originally were anticlines but the western one, at least, probably now is an inverted anticline. The Vallecito-Irving contact is not sufficiently well exposed around the nose of this fold for determination of the attitude of its axis but axes of minor folds in the conglomerate core of this fold plunge about 45° at S. 10° W. Thus, if the axes of the minor folds parallel the axis of the major fold, this structure is an inverted anticline. The eastern fold has a post-Mississippian fault along its western flank, and the small part of the nose lying between this fault and the lake to the east was not examined. These folds were formed during amphibolite-facies metamorphism of the Irving Formation and were later rotated during the Uncompahgran disturbance. The eastern fold was rotated perhaps as much as 90°, and the western one by an unknown amount, for the unconformity between the Irving and Uncompahgre Formations east of Emerald Lake was rotated about 90°. The Irving Formation adjacent to these two folds shows only its prominent north-south foliation.

TRENDS IN THE IRVING FORMATION

Trends of foliation and compositional banding in the Irving Formation are shown in figure 2. In the southeastern area of exposure these trends are from north to about N. 20° E., except northwest of Emerald Lake, where they are roughly east and dips are variable. This eastern trend apparently was formed during the Uncompahgran disturbance and is superimposed on the older, north trends.

The southwestern mass of the Irving Formation has northeast trends, which were not displaced by intrusion of the Eolus batholith. North of the Tenmile Granite body these trends swing parallel to the Uncompahgre unconformity. The northern area of Irving rocks has east to N. 70° E. trends, and much or all of this change in trend may have formed in the Uncompahgran disturbance.

Determining the amount of rotation of the Irving rocks, and of the Twilight Gneiss and Tenmile Granite as well, during the Uncompahgran disturbance remains a problem. One would expect the rocks immediately under the unconformity to have been rotated as much as the unconformity itself, but this may not be true because of shearing and attendant strain. The amount of rotation in the Irving and the two granites at distances of 1 mile or more from the unconformity is even more problematical, especially from Lime Creek to Vallecito Creek, where the contact between the Irving and Uncompahgre Formations has variable dips. Exposures of the southern unconformity in the canyon of the Animas River show it to be approximately vertical; yet to the east and west it is smoothly folded, and its dip decreases upward and southward to about zero. In spite of this variation in rotation of the unconformity, from 0° to 90°, the attitudes of foliation and compositional banding in the underlying rocks are uniform. This problem deserves detailed study.

THE UNCOMPAHGRAN DISTURBANCE

The intense folding, with attendant low- to high-rank metamorphism, that affected the Uncompahgre Formation is named the Uncompahgran disturbance, as mentioned on page A11. The Uncompahgre Formation was deposited on a surface that truncates 1,720-m.y.-old granite, was then folded and metamorphosed, and later was intruded by the posttectonic, 1,460-m.y.-old Eolus batholith. Those two dates thus bracket deposition of the Uncompahgre Formation as well as the Uncompahgran disturbance. To my knowledge no metamorphic rocks or minerals of the Uncompahgre Formation have been dated by radioactive methods.

FOLDS OF THE UNCOMPAHGRE FORMATION

The Uncompahgre Formation is intensely folded, in isoclinal fashion, as shown by Cross and Howe (Cross, Howe, Irving, and Emmons, 1905, map of areal geology) and in figure 2. The quartzites and interlayered slates, phyllites, and schists responded very differently to the tectonic environment; the folds of individual quartzite layers are of parallel type, approaching the pure flexure folds of Ramsay (1962, p. 316), whereas those in the interlayered pelites are of similar type. The folds probably are cylindroidal, but further work is needed here. Axial surfaces of the folds are not planar but gently curved; these generally are steep but locally are gently dipping. In most outcrops of the pelites bedding is not parallel to cleavage or schistosity, but parallelism of the two is not uncommon. Minor folds of irregular cross section and of many sizes occur in most of the pelite; the fold axes, for the most part, plunge less than 30° in easterly and westerly directions west of Vallecito Creek and in southeasterly and northwesterly directions east of Vallecito Creek. The axes of these folds may well parallel those of the major folds but this has not been demonstrated. However, a few minor folds with very steep to vertically plunging axes were seen. Gently warped axes of minor folds were noted in the Animas Canyon; this may be a consequence of local flattening of parallel folds (Ramsay, 1962, p. 313). Minor folds are common in the quartzite layers in the Elk Creek drainage and westward but are rare to the east. Slip cleavage and crinkles with amplitude as large as one-half inch are prominent in much of the pelite, especially along Vallecito Creek and the several forks of Ute Creek.

FAULTS

No major faults were found in this investigation, and these rocks are not known to contain any notable shear zones similar to those found in Precambrian rocks of Arizona, New Mexico, and other parts of Colorado. Figure 2 shows some of the faults discovered by Cross and his associates (Larsen and Cross, 1956, p. 1) : some minor ones along the southern margin of the Precambrian uplift; several in the Uncompahgre Formation; and two that cut the Irving Formation, Vallecito Conglomerate, and Paleozoic rocks west of Emerald Lake. Several of the faults portrayed by Cross and others (1905, 1905, 1907) in the geologic folios and by Larsen and Cross, however, were found not to exist; these include the intrusive contact between the Pine River batholith of Eolus Granite and the Uncompahgre Formation to the west, the intrusive contact between Eolus Granite and the Irving Formation, most of the depositional contact between the Vallecito Conglomerate and the Irving Formation, and the unconformable depositional contact between the Uncompahgre Formation and older rocks. The latter contact, which apparently has phyllonite developed along a part of it, is a zone of shearing and relative movement of unknown magnitude and certainly is a fault if my interpretation of the phyllonite is correct. Some doubt remains, nonetheless, and so this feature is not classed as a fault in figure 2. The relative straightness of the contact between the Eolus Granite and the Vallecito Conglomerate southeast of Emerald Lake may be due to intrusion along a fault.

METAMORPHISM

Metamorphism of the Irving Formation was to the amphibolite facies, and later retrograde metamorphism affected much of it. These rocks were not studied in enough detail, however, to warrant separate discussion here. Metamorphism of the pelitic rocks of the Uncompahgre Formation was studied more intensively in regard to the assemblages formed, even though individual mineral phases were not analyzed, and metamorphism of those rocks is treated separately.

METAMORPHISM OF THE UNCOMPAHGRE PELITES

The pelitic rocks of the Uncompahgre Formation were regionally metamorphosed to slate and phyllite. Later, a higher temperature thermal type of metamorphism was superimposed on these rocks from Vallecito Creek east and southeast to their contact with the eastern batholith of Eolus Granite.

REGIONAL METAMORPHISM

The Uncompahgre pelitic rocks from their westward exposure at Lime Creek eastward to the western and northern headwaters of Vallecito Creek are slates, typically of the assemblage quartz-sericite-chlorite. They commonly contain carbon or graphite and ilmenite and pyrite. Poikiloblastic andalusite with hematite was found in this assemblage in one layer in the canyon of the Animas River, and biotite and oligoclase also were observed with the quartz-sericite-chlorite assemblage in a pelitic layer near the Animas River. These relatively simple assemblages do not violate the phase rule and probably are equilibrium assemblages. They consist of the components Al_2O_3, C, FeO, H_2O, K_2O, MgO, S, SiO_2, and TiO_2.

THERMAL METAMORPHISM

The Uncompahgre pelites east and south of upper Vallecito Creek, east of Trinity Lake, and south of Vallecito Lake and Nebo Creek have progressively developed biotite, chloritoid and garnet, chiastolite, and in a small area, staurolite. These rocks, here loosely termed "schists," of which the muscovite-biotite-chiastolite type is most abundant, occur in an area of about 25 square miles. Sillimanite- and microcline-bearing schists, of granoblastic fabric, occur to the east within ½–1 mile of the Eolus Granite (p. A14). These latter schists have a direct spatial relationship to the Eolus Granite and thus are of contact metamorphic origin. The muscovite-biotite-chiastolite and other types of schist in the upper Vallecito area also probably are of thermal metamorphic type, presumably caused by heat from the underlying Eolus Granite. Reasons for suggesting this are:

1. Transitions from sericite-quartz-chlorite slates to the biotite-chiastolite-garnet-muscovite-staurolite schist and associated schists are relatively abrupt. The rocks change within 0.5 mile southward from the sericite-quartz-chlorite slates containing randomly oriented postkinematic biotite of Nebo Creek to sericite-quartiz-biotite-chiastolite phyllite, and within 1.2 miles west-southwestward to the chiastolite-garnet-staurolite locality. Similarly, from the quartz-sericite-graphite slate just northwest of Trinity Lake it is only 0.8 mile southeastward to quartz-muscovite-chlorite phyllite with chiastolite and chloritoid, 0.5 mile southeastward to muscovite-quartz-chloritoid-garnet phyllite, and 1.9 miles farther southeastward to the chiastolite-garnet-staurolite locality. Thus within 2 to 3 miles there is a transition from sericite-chlorite slates to chiastolite-garnet-staurolite schist.
2. The fabric changes from slates with well-developed slaty cleavage and microfolds and phyllites with clearly apparent schistosity cut by randomly oriented biotite to granoblastic porphyroblastic

fabrics in which neither muscovite nor biotite shows preferred orientation.

3. The chiastolite-bearing phyllites and schists and the associated rocks are similar to those of other contact metamorphic aureoles. (See, for example, Pitcher and Read, 1963; Compton, 1960.)
4. An offshoot of the Eolus batholith lies in quartzite 1.9 miles west-southwest of the chiastolite-garnet-staurolite locality; thus, this abrupt metamorphic gradient lies close to exposed granitic rocks. This granite is postkinematic and would be expected to cause the formation of hornfels with granoblastic fabrics, as are found in the sillimanite-bearing hornfels of Flint Fork.

The alternate possibility—that the metamorphism here is of Buchan type (Read, 1952)—cannot, though, be ruled out.

Assemblages of the chiastolite-bearing schists that lie 0.4 mile north of the junction of Rock and Vallecito Creeks contain more phases, in apparent textural equilibrium, than can be plotted in a Thompson diagram (Thompson, 1957). Whether this is due to ferric iron in chloritoid, to lime in the garnet, to H_2O as a determining inert component, or to other reasons was not determined.

Chlorite grains similar in size and habit to biotite grains in schists of Rock Creek, Flint Fork, and Ute Creek apparently are stable with chiastolite, staurolite, and garnet and very nearly are stable to the sillimanite zone. Chlorite, furthermore, locally has formed with magnetite and in place of biotite. I infer that activity of H_2O was relatively high and locally variable, as would be expected from nearby bodies of granite.

Cordierite, with the possible exception of a pinite-bearing rock east of Ute Lake, is not present in any of the chiastolite- or sillimanite-bearing rocks of the Uncompahgre Formation. Cordierite, of course, is a common constituent of pelitic hornfels and schists of Buchan type metamorphism. Its absence in the Needle Mountains must be due to the relatively ferrous nature of these pelites, which have regularly developed garnet, chloritoid, and staurolite. Cordierite probably would have formed had any of the pelites been more magnesian.

OXIDATION OF DETRITAL MAGNETITE TO HEMATITE

The dark laminae in the clastic rocks of the Uncompahgre Formation and the Vallecito Conglomerate are of special interest. These laminae are largely hematite, commonly with accessory ilmenite and rutile. The hematite not uncommonly shows octahedral forms, which indicate derivation from magnetite by oxidation. The cause of such a widespread oxidation, in which the interlayered pelites and metabasalts were not affected, apparently lies in the dissociation of interstitial water. Fugacities of oxygen in pure H_2O were calculated from 227°C to 927°C and at 1 bar and 1,200 bars water pressure, using fugacities of water. Two important conclusions reached in this investigation (Barker, 1969b) are: (1) The oxygen fugacities obtained for temperatures of low- to medium-rank metamorphism are 8 to 10 orders of magnitude greater than those of the magnetite-hematite univariant curve, meaning that pure water will oxidize stoichiometric magnetite (Fe_2O_3) under these conditions; and (2) the oxygen fugacities for 1 bar and for 1,200 bars converge with decreasing temperature, at about 150°C, so that this effect is almost independent of pressure below 400°C. Thus, a relatively pure interstitial water in these clastic rocks would be expected to oxidize detrital magnetite during metamorphism. The hydrogen generated in the oxidation of magnetite may be responsible for the hydrolysis of detrital feldspar to sericite in these rocks.

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