THE PETROLOGY OF THE PHELPS RIDGE-RED MOUNTAIN AREA
CHELAN COUNTY, WASHINGTON

By

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CHELAN COUNTY, WASHINGTON

INTRODUCTION

LOCATION OF AREA

The Phelps Ridge-Red Mountain area is situated in the northern part of the Cascade Mountains of Washington, approximately five miles east of Glacier Peak and six miles southwest of Holden, Chelan County, Washington. It includes all of Phelps Ridge and all but the northern slope of Red Mountain. It is bounded on the west by the Chiwawa River and on the east and south by Phelps Creek. This area occupies the central portion of the Holden quadrangle as mapped by the Topographic Branch of the U. S. Geological Survey (see Index Map, Plate 1).

The area may be reached by leaving U. S. Highway 10 at Leavenworth, Washington, and proceeding on Highway 150 to a point approximately two miles north of Plain, where the road to the Red Mountain Mine is taken. This road ends at the southern end of the area, with well maintained Forest Service trails making the major portion of the area easily accessible.

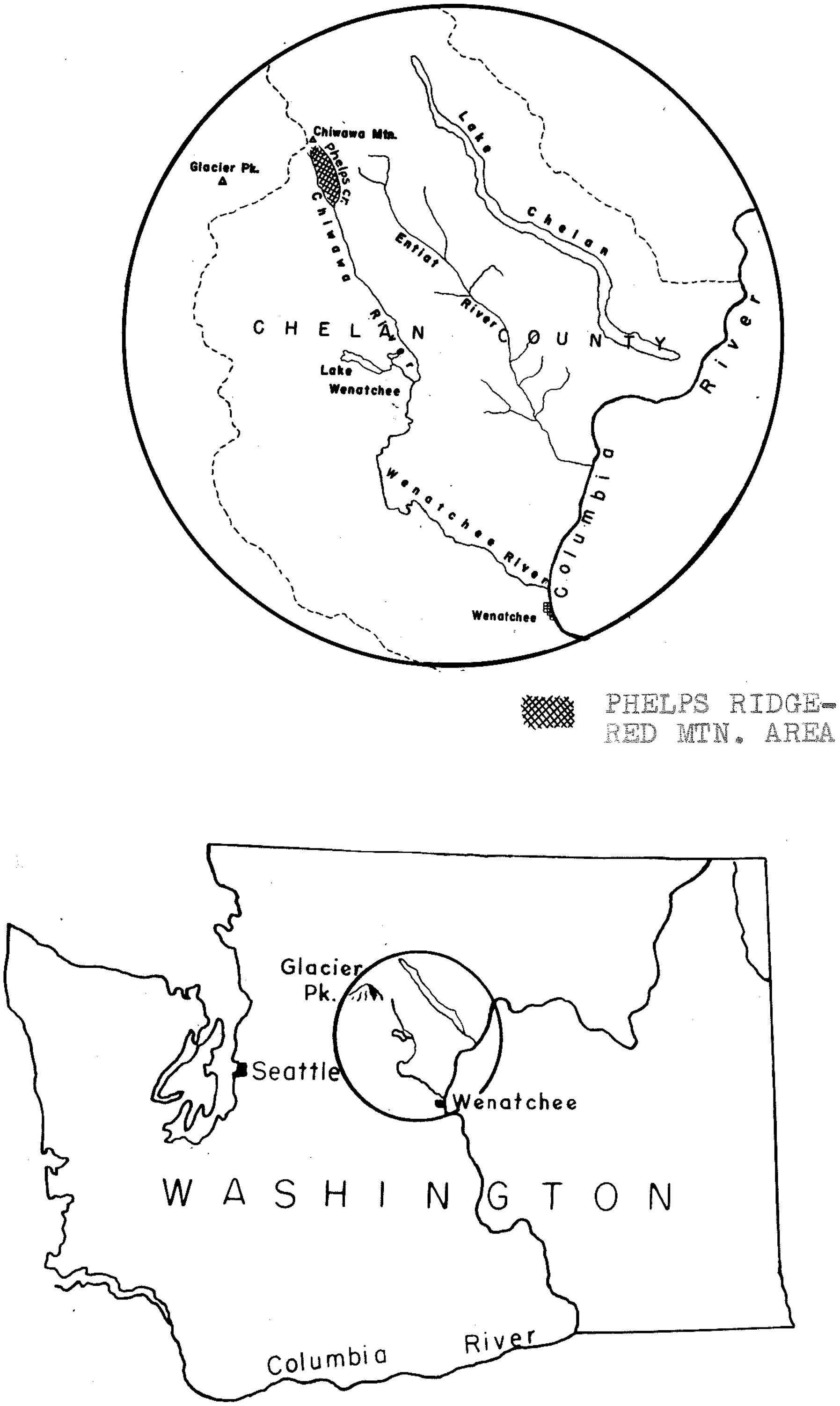

Plate 1. Index Map, showing location of thesis area.

TOPOGRAPHY

The general area, being located four miles east of the Cascade crest, is one of rugged mountains and high relief. Phelps Ridge and Red Mountain form a continuous ridge approximately six miles long. Parts of the eastern slope are extremely steep and inaccessible. Red Mountain presents a striking appearance because of its red color which results from the weathering of disseminated pyrite. Its high red slopes may be seen for many miles. It has a maximum elevation of more than 8,000 feet and a relief of 3,200 feet. Phelps Ridge rises to 7,300 feet, with a relief of about 3,000 feet. The major portion of the area has excellent exposures except for the southwestern corner which is heavily forested.

PREVIOUS GEOLOGIC WORK

Previous work consists of a broad study of a reconnaissance nature by I. C. Russell (1900). H. E. Culver reported on "General Features of Washington Geology" in 1936, and G. W. Stose compiled a preliminary geologic map of Washington in 1936. The Trinity Tunnel and immediately adjacent area have been reported on briefly by Stephen Richarz (1933), who published an article in the Journal of Geology on "Peculiar Gneisses and Ore Formations in the Eastern Cascades, Washington." Brief mention of the Trinity Tunnel was also made by H. E.

Culver and W. A. Broughton (1945) and by M. T. Huntting (1943). In September, 1926, the Engineering and Mining Journal carried a short article by R. G. MacPhee on mining operations at the Red Mountain Mine. No detailed work had been done in the area up to the time of this investigation.

In nearby areas, mapping has been done by A. C. Waters (1932) in the Entiat Mountains to the east and southeast; by C. L. Willis (1950) in the Chiwaukum quadrangle to the south; by F. K. Oles (1951) in the Stevens Pass region to the southwest; and by R. L. DuBois (1954) in the Holden area to the northeast.

METHOD OF INVESTIGATION

A total of about two months was spent in the field during the fall of 1951 and 1952. A base map was obtained by enlarging the central portion of the Holden quadrangle of the U. S. Geological Survey map six times. Being a modern 15-minute quadrangle, this supplied a reasonably accurate base map and gave ample opportunity for fairly detailed mapping. The mapping was done with the aid of a Brunton compass and an altimeter.

Well over 300 hand specimens were taken. More than 180 thin sections were made and studied during the winter of 1952-1953.

ACKNOWLEDGMENTS

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A debt of gratitude is owed Messrs. Lloyd and Boyd Keefer and Mr. Jesse Smith, claim owners in the area, for their many courtesies and kind cooperation, and to Mr. C. P. Purdy, State geologist, for many helpful suggestions both during and after his visit to the area.

Special thanks are due James L. Gualteri for his assistance during a week of reconnaissance in the field, and to Donald A. Kellum for invaluable aid in the underground mapping of the Trinity Tunnel.

Others to whom the author is indebted include his wife, Lee, for typing the final manuscript, and Mr. Bill Wallace for making his living quarters at the Red Mountain Mine available during the progress of the work there.

GEOLOGY AND PETROLOGY OF THE AREA

GENERAL STATEMENT ON BEDROCK GEOLOGY

Because of its heavy Pleistocene glaciation and its considerable relief, the Phelps Ridge-Red Mountain area has an abundance of outcrops. The most common rock type in the area is a series of gneisses and granulites. These rocks generally strike parallel to the Ridge and dip to the southwest. Lowest in the metamorphic sequence, and probably the oldest rock in the area, is a belt of amphibolite and migmatitic hornblende gneiss which occurs in the eastern part of the area near Phelps Creek. These hornblende gneisses and amphibolites strike parallel with the biotite gneisses and granulites occurring to the west and are in complete conformity with them. As will be shown later, the gneisses and granulites are believed to be of sedimentary origin. Therefore, the conformity mentioned above would simply mean that a sequence of amphibolitic rocks derived from bedded basic tuffs and possibly flows is in normal sequence, succeeded by metamorphosed argillaceous sandstones and argillites, with the transitional beds probably corresponding to tuffaceous sediments.

The biotite content of the biotite gneisses and granulites varies greatly from place to place. Some of the rocks consist mainly of quartz and feldspar, with only scarce biotite. Such rocks will be referred to as aplitic granulites.

Within the large area of biotite gneiss and granulite, it was possible to map areas in which garnet becomes an important accessory mineral. These areas are indicated on the geologic map (Plate 2). Another mineral which occurs more abundantly in some areas than in others is muscovite. It has also been shown on the geologic map.

The metamorphic rocks are part of the Paleozoic-Mesozoic Cordilleran eugeosyncline. They are on a general strike with the Swakane gneiss to the southeast, described by Waters (1932) and Willis (1950), and are very similar to those rocks in both composition and texture. DuBois (1954) has described amphibolites and biotite gneisses and granulites occurring in the region of the Holden Mine, five miles to the northeast, which resemble the rocks described here except that these rocks do not contain the diopside reported to occur in small amounts in the Holden area.

Younger than all these rocks and their regional metamorphism is a leucocratic quartz labradorite porphyry which has intruded the gneisses and granulites in the form of small stocks. The largest stock occurs in the northern part of the area on Red Mountain. There are several other small stocks in the central portion of the area. These rocks usually have clearly igneous textures and very sharp, definite intrusive contacts. Of particular interest is an occurrence of quartz labradorite porphyry exposed in the Trinity Tunnel which has the same composition but which locally displays porphyroblastic textures. The peculiar composition of this igneous rock will be discussed below.

The next younger rock in the area is a tectonic breccia which occurs in scattered outcrops on the crest and western upper slope of Red Mountain. This breccia is made up of fragments of the quartz labradorite porphyry and biotite gneiss and granulite. It stands up above the surrounding rock as resistant knobs and ridges. Upon superficial examination in the field, this rock might be mistaken for an igneous injection breccia, but closer examination and microscopic study reveal that the fragments occur in a matrix of mylonitised material which has undergone a moderate hydrothermal recrystallization. The breccia is probably the remnant of a thrust plate (cf. Tectonic Breccias).

In contrast to this resistant breccia, a very weak breccia occurs at the southern end of the area in the region of the St. Francis Mine. The matrix of this breccia consists predominantly of chlorite. In this breccia occur the mineralized zones of the Red Mountain and St. Francis Mines. Its surface exposures are very poor, but it is well exposed in the eastern end of the Trinity Tunnel, which is approximately 800 feet below the portal of the St. Francis Mine. This breccia represents a vertical crush zone.

The youngest rocks in the area are andesitic dikes, probably Tertiary in age. They are of minor importance. They vary from a few inches to 70 feet in width.

Considerable prospecting for copper has been done in the area over a period of many years. The St. Francis Mine, Red Mountain Mine, and Leprechaun Mine were the major developments in the area. The copper production has been small. Reportedly the Red Mountain Mine produced about 15,000 tons of ore during its total period of operation.

Many small prospects exist in the area but none shows any promise, except possibly the Midnight Queen which has an interesting occurrence of scheelite. This occurrence appears to be too restricted to be of great economic importance.

METAMORPHIC ROCKS

Amphibolites and Migmatitic Hornblende Gneisses

Occurrence, Field and Structural Relations

These hornblende-rich rocks are entirely restricted to the easternmost part of the area near Phelps Creek, except for a few scattered and isolated lenses of amphibolite within the biotite gneiss and granulite on the west side of Phelps Ridge. These rocks form a continuous belt along the lower eastern slope of Phelps Ridge and are entirely conformable with the overlying biotite gneisses and granulites to the west. In fact, the hornblendic rocks grade imperceptibly into these gneisses and granulites. The transitional contact relations mean that the boundary shown on the map is somewhat arbitrary; it was drawn along a line west of which biotite is the predominant mafic mineral, with hornblende either absent or occurring only in minor amounts.

Since these hornblende-rich rocks are the lowest exposed unit in a southwestward dipping conformable sequence, and since the overlying biotite gneisses and granulites do not display a higher degree of metamorphism than the hornblendic rocks, it may be assumed that the latter are the oldest exposed rocks in the area. There are no sedimentary textures preserved in this metamorphic sequence which would definitely confirm that it is right side up.

In the belt of hornblendic rocks, more uniform amphibolites predominate to the south, whereas along the strike to the north, many of these amphibolites have been converted into migmatitic hornblende gneisses. Near the southern border of the hornblendic area, the amphibolites grade along the strike into less highly hornblendic rocks, including biotite gneisses resembling those which overlie the hornblendic rocks on the west.

Intense glaciation at the headwaters of Phelps Creek, in the vicinity of Spider Glacier, has provided excellent exposures of the migmatitic hornblende gneiss. This rock presents an appearance of strong foliation and banding along with intense folding and rock flowage. White bands of quartz and feldspar are intimately interwoven with hornblende-rich bands, the entire mass presenting a striking example of intense deformation and metamorphic differentiation (see Fig. 1).

Locally actinolitic hornblende has been segregated into almost pure masses, often surrounded by a white layer of feldspar. These mafic segregations are small, reaching a maximum diameter of three feet (see Fig. 2). In these masses the actinolitic hornblende usually forms coarsely crystalline aggregates with crystals measuring up to three inches in length. Conversely, segregations of feldspar occur, often surrounded by hornblendic layers (see Fig. 3).

As stated above, this migmatitic hornblende gneiss occurs at the northern end of the area. Further south, the pronounced banding and metamorphic differentiation, with the associated contortions, are much less developed. Here the hornblende is more evenly distributed although small, coarsely recrystallized hornblendic lenses still occur.

For greater clarity the petrography of the hornblendic rocks will be discussed under the following headings: 1) amphibolites, 2) migmatitic hornblende gneiss, and 3) transitional biotite-hornblende rocks.

Fig. 1. Intense deformation and plastic flowage in the migmatitic hornblende gneiss.

Fig. 2. Segregations of actinolitic hornblende occur in the migmatitic hornblende gneiss, here with an inch wide border of feldspar surrounding it. Note the lens-like segregations of plagioclase in the foreground.

Petrography

Amphibolites

The amphibolites have a dark to light green color, depending on the relative proportions of hornblende to plagioclase. They are fine to medium grained and usually display well developed foliation. For the most part the hornblende is quite evenly distributed throughout the rocks, giving a speckled white and green rock (see Fig. 4). However, quite often bands relatively rich in hornblende alternate with bands richer in feldspar, although the banding is not nearly so pronounced as it is in the migmatized areas. Lenses of actinolitic hornblende with a diameter of two or three inches are not infrequent. These lenses have been produced by metamorphic differentiation and recrystallization under late synkinematic or static conditions, and their crystals may or may not be well aligned.

The hornblende ranges from 0.5 mm to 3 mm in length, with an average length of about 2 mm, and exhibits a moderately pronounced crystallization foliation. The amount of hornblende usually varies from 40 to 65 per cent and averages about 50 per cent. As stated above, the hornblende is for the most part relatively evenly distributed, but it may also occur in distinct bands which alternate with feldspathic bands. The alignment of the hornblende crystals is good but not perfect. The hornblende has started to crystallize under synkinematic

Fig. 3. Segregation of plagioclase in the migmatitic hornblende gneiss.

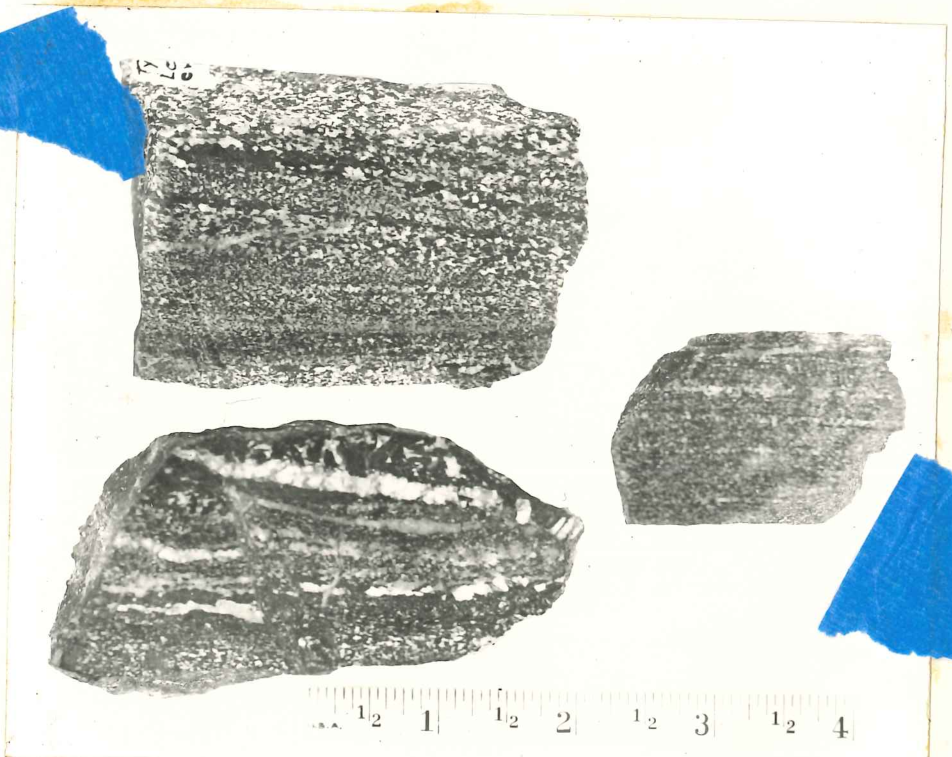

Fig. 4. Typical examples of amphibolite showing relatively evenly distributed hornblende in the upper two specimens and segregated bands of plagioclase in the lower specimen.

conditions, producing sharp alignment; but continued crystallisation after the end of deformation, that is, under static conditions, has produced non-aligned hornblende crystals and thereby reduced the degree of schistosity. This post-kinematic hornblende has crystallized at various angles (usually not over 30 degrees) to the earlier schistosity. The hornblende is the usual green variety with a pleochroism as follows: X - light yellow-green, Y - light green, Z - dark olive green. Alteration of this hornblende to faintly pleochroic actinolitic hornblende has occurred to some extent. During this alteration release of some iron has occurred, as is shown by the segregation of secondary magnetite in and near the newly formed actinolitic hornblende, which thus must have a lower iron content than the green hornblende. A late phase of weak shearing has aided in this alteration. The shearing is partly parallel and partly at an angle to the foliation. Actinolitic hornblende has almost always formed along these late shearing planes wherever they cut a hornblende crystal (see Fig. 5). There has been some solutional transfer of actinolitic hornblende along these fractures into feldspar-rich areas.

The segregation lenses of actinolitic hornblende contain up to 90 per cent actinolitic hornblende, quartz making up the remaining 10 per cent, with little or no plagioclase present.

Occasionally some of the green hornblende has been biotitised, partly with segregation of clinozoisite and epidote. Thus incipient K-introduction during a late stage of crystallization seems to be indicated. Occasionally plagioclase has replaced hornblende along its cleavage planes. In such cases, the hornblende adjacent to the plagioclase has a "leached" and "moth-eaten" appearance.

The hornblende often encloses rounded or irregular grains of sphene. Only seldom does the sphene have any semblance of crystal form. It is scattered through the rock and is also enclosed in plagioclase. It is found in amounts up to 3 per cent in some cases.

The plagioclase is anhedral to subhedral. Its composition averages about $Ab_{60}An_{40}$. It occurs in amounts from 40 to 55 per cent, averaging about 45 per cent. The grain size ranges from 0.5 mm to 3.0 mm in length, with an average length of about 2.5 mm. Its texture is crystalloblastic, often with small inclusions of quartz and hornblende. Some oscillatory zoning was noted. As mentioned above, the plagioclase sometimes replaces hornblende.

The most common alteration product of plagioclase is sericite, although some secondary clinozoisite has formed. Sericitization usually has occurred to a moderate degree, although occasionally the plagioclase is decomposed beyond identification.

Quartz occurs only in very minor amounts in the main mass of the amphibolite body and usually has irregular shapes with highly crenulated borders and a wavy extinction produced by late weak shearing.

Secondary magnetite is often an important accessory mineral. It has formed during the alteration of hornblende to actinolitic hornblende as a result of the release of iron. The magnetite occurs as irregular grains which are scattered in and about the actinolitic hornblende. Garnet also occurs as an accessory mineral occasionally.

Migmatitic Hornblende Gneiss

As stated above, the northern end of the amphibolitic belt contains a considerable amount of migmatitic hornblende gneiss. This rock is strongly banded. The bands range from an inch to a foot or more in width and are often highly contorted (see Fig. 1). Grain size in this rock is usually slightly larger than that of the amphibolites. The composing minerals and their textures are the same as in the more homogeneous amphibolites described above. There seems to be no difference in the bulk composition of this banded migmatite and of the more homogeneous amphibolite; the difference is merely in the distribution of the two main minerals. In the banded, migmatized rocks the hornblende and the feldspar have been segregated into bands and elongate lenticles (see Fig. 6). It must therefore be concluded that the migmatitic banding is the result of metamorphic differentiation.

rograph showing actinolitic hornblende forming along a fracture from green hornblende. Plane light.

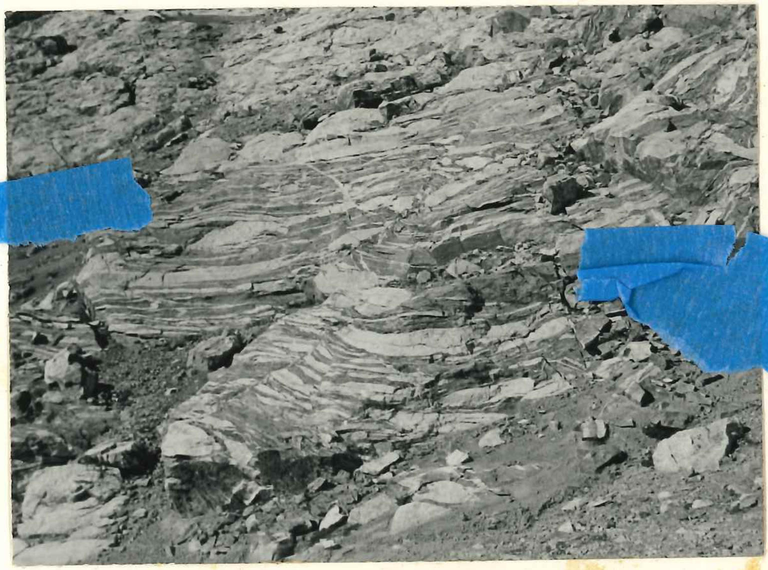

Fig. 6. Segregation of plagioclase and hornblende into elongate bands and lenticles in the migmatitic hornblende gneiss.

Lenses of hornblende and actinolitic hornblende also occur in the migmatite, the same as in the amphibolite, but here they are of a larger size. As mentioned above, the maximum diameter of such lenses is about three feet. The actinolitic hornblende of these lenses is usually much more coarsely crystalline in the banded migmatized rocks than in the more homogeneous amphibolites (see Fig. 7).

The plagioclase of the banded migmatite has the same composition as that of the homogeneous amphibolite. Occasionally it has undergone slightly more cataclasis, with some crystals being bent and some mortar being produced. There is no K-feldspar, and quartz occurs in only very minor amounts. Some hornblende has been altered to actinolitic hornblende, especially along fractures, the same as in the amphibolites (cf. above).

The textures are very similar to those of the amphibolite. They are medium grained and crystalloblastic. Late weak shearing has produced local granulation of the minerals, with little or no recrystallization.

Transitional Biotite-Hornblende Rocks

As has been previously stated, the hornblendic rocks grade into the overlying biotite gneisses and granulites to the west, and they also grade into similar rocks to the south along the strike of the amphibolitic belt. In this transition zone,

Fig. 7. Coarsely crystalline actinolitic hornblende and actinolite occurring in segregation pods in the migmatitic hornblende gneiss.

the color of the rocks changes from the dark green of hornblende-rich rocks to the light green of rocks poorer in hornblende, and finally to the brown of biotitic rocks or the grayish white of leucocratic, "aplitic" gneisses and granulites.

The rocks of this transitional unit are texturally very similar to the biotite gneisses and granulites. Their mafics include both hornblende and biotite. Since these rocks have a lower content of mafics, they are less sharply foliated than the amphibolite. They are fine to medium grained and xenoblastic.

Quartz, which occurs in only very minor amounts in the hornblendic rocks, gradually increases in amount across the transitional zone until in the biotite gneisses and granulites it averages about 45 per cent, locally reaching 65 per cent. As the quartz content increases, there is a corresponding decrease in the hornblende content.

The quartz has crenulated borders and wavy extinction such as are typical of the biotite gneisses and granulites discussed below.

The plagioclase has a composition similar to that of both the hornblendic and biotitic rocks. Its composition is commonly $Ab_{63}An_{37}$, or close to this value. The textures of the plagioclase are the same as in the biotite gneisses and granulites. It is anhedral to subhedral, with typical crystalloblastic features.

The hornblende content ranges from 15 to 0 per cent. Biotite occurs in amounts from 0 to 5 or 10 per cent, increasing in content as the hornblende content decreases. Some of the biotite has formed from hornblende. The biotite often is somewhat chloritized. Apatite, sphene, and magnetite are common accessories.

Genetic Interpretation of the Hornblendic Rocks

An amphibolite can form from the following original materials: 1) intermediate or basic intrusions or volcanic flows; 2) tuff, or mixtures of shale or greywacke with tuff; 3) dolomitic shale. In the present case, an origin from tuff seems to be most probable for the following reasons: The borders of the belt of hornblendic rocks are very transitional (cf. above), whereas sharp boundaries should be expected if the material was originally a flow or a series of flows, or an intrusion. This transitional and interfingering relationship to the quartz-rich biotitic rocks suggests an increasing admixture of ordinary sedimentary material such as might be expected at the borders of a water-laid tuffaceous unit, with a gradual facies change from purer tuff to tuffaceous sandstones or quartz-rich tuffaceous shales. This interpretation is further substantiated when the percentage of the plagioclase is considered. Plagioclase occurs in amounts up to 50 per cent. Had the original material been a dolomitic shale, the original sodium content would have been much too low to give so much plagioclase, and it would have to be assumed that considerable sodium metasomatism has occurred. Although there may have been a small amount of sodium metasomatism, there is no evidence of large-scale sodium introduction such as would be necessary to produce the amount of existing plagioclase. Field and laboratory evidence taken together presents a reasonably strong case for a tuffaceous origin. It is, of course, entirely possible that such a tuff unit may have contained some flows of a similar composition.

The combination of hornblende and a moderately calcic andesine establishes a warmer mesozonal temperature for this rock. The alignment of the early hornblende with later hornblende crystallizing in varied orientations indicates crystallization during a period of synkinematic metamorphism with continued crystallization during a later post-kinematic phase. This event was followed by late shearing, with production of some mortar structure. Associated with this was the alteration of hornblende to actinolitic hornblende and magnetite. Still later occurred the retrogressive sericitization of some of the plagioclase.

The original material of the hornblendic belt was deposited in the Cordilleran eugeosyncline. The age of the original rocks is probably Paleozoic, although it could conceivably be earlier Mesozoic. The metamorphism probably occurred in late Paleozoic or Mesozoic time.

Biotite Bearing Gneisses and Granulites
of Phelps Ridge-Red Mountain

<u>General Description</u>: Rock Types, Field Occurrence, Structural Relations

In the field it is possible to subdivide the biotite bearing rocks into three units. They are 1) biotite gneiss and biotite-poor to almost biotite-free quartz plagioclase granulite, 2) garnetiferous biotite gneiss and granulite, and 3) muscovite-biotite gneiss and granulite. These three divisions will be described separately below.

The different varieties of biotite bearing gneisses and granulites all exhibit conformable and gradational relationships to each other. Together, they form the predominant rock types in the mapped area. Among them the ordinary biotite gneiss and granulite, without either garnet or muscovite, is the most common type.

For the most part, the gneisses have a fairly well developed parallel structure produced by alignment of biotite. These rocks can properly be called gneisses in that they have a high feldspar and quartz content and a parallel structure. There is no pronounced banding. There is some compositional banding which, however, is on a very small scale only. It is shown by concentration of biotite in very thin bands which alternate with somewhat thicker quartz-feldspar bands with a much lower biotite content. There is no large-scale banding such as is commonly seen in a typically banded gneiss (see Fig. 8).

The varieties rich in biotite have a medium brown color. Locally biotite is extremely scarce or entirely lacking; some rocks essentially consist of plagioclase and quartz only. These highly leucocratic rocks are relatively equigranular and more or less directionless. Their color is light gray. They will be referred to as aplitic granulites. In these granulites the gneissose parallel structure is subdued because of their low biotite content, but some banding produced by parallel quartz lenses and bands is frequently seen (see Fig. 8, C). Patches of aplitic granulite occur throughout the gneissic area and are gradational with the gneisses. Whether or not a particular rock is to be called a gneiss or granulite is sometimes purely arbitrary.

Oxidation of disseminated pyrite has caused extensive staining of these rocks, particularly on Red Mountain. Small bands and lenses of segregated quartz up to 1 cm in width are frequently seen in both the gneisses and the granulites.

Garnet bearing areas have been indicated on the geologic map (Plate 2). The garnet bearing rocks usually have a higher than average biotite content, giving them a better than average development of schistosity. Kyanite, which occurs locally in small amounts, is entirely restricted to these garnet bearing

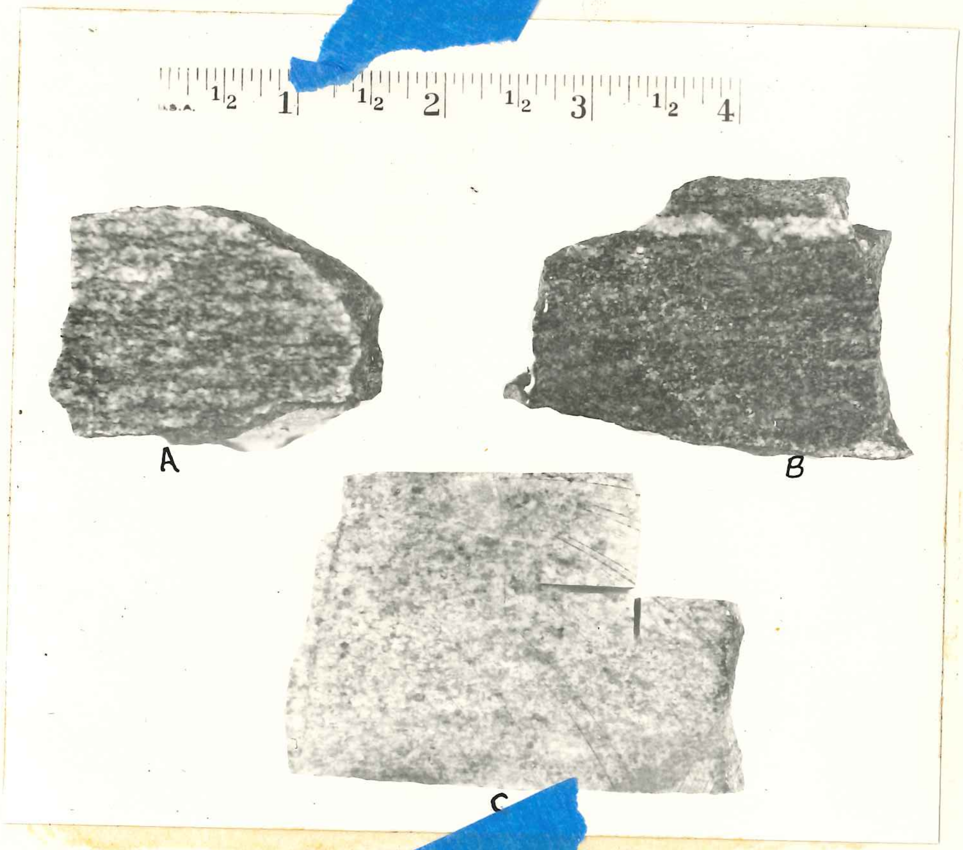

Fig. 8. A. Typical biotite gneiss; B. biotite-rich gneiss; C. Biotite-poor aplitic granulite with a slight directional element produced mainly by aligned quartz-rich layers or aggregates.

areas. Muscovite is lacking in a large part of the area but does occur locally. Muscovite bearing areas are also indicated on the map. The muscovite bearing rocks usually have a light gray color.

The foliation of the gneisses generally trends N25W and parallels Phelps Ridge. Dips range from 25 degrees to vertical, with an average dip of about 50 degrees to the southwest. The vertical dips occur in the southern end of the area, near the breccia zone of the St. Francis Mine, and probably are the result of drag during movement along this zone. Isoclinal and open minor folds (maximum size observed about 300 feet across), occurring mostly on the west side of the ridge, have axial planes which dip from 50 to 60 degrees to the west. Near the breccia zone, however, the axial planes are vertical. The fact that the axial planes have relatively steep dips, and that quite a number of the folds are open, seems to support the assumption that there has been no general eastward overturning of the section which would require a huge recumbent fold. As mentioned above, the biotite gneisses and granulites occur to the west of and above the amphibolites and migmatitic hornblende gneisses and are considered to represent a stratigraphically higher part of the section in this area.

Petrography

Biotite Gneiss and Granulite

The major constituents of the biotite gneiss in order of abundance are: quartz, varying from 25 to 65 per cent and averaging 45 per cent; plagioclase, which varies from 15 to 65 per cent and averages about 42 per cent; biotite, varying from 4 to 24 per cent and averaging approximately 6 per cent. Chlorite and sericite, forming from biotite and plagioclase, respectively, occur in varying amounts depending on the intensity of alteration of the original minerals. Minor constituents include muscovite, apatite, epidote, clinozoisite, and magnetite.

In the aplitic granulites the amount of biotite is considerably smaller, varying from a few per cent to traces. With the decrease in biotite content, there is a corresponding increase in quartz and/or plagioclase. The average proportion between quartz and plagioclase is the same as in the gneisses. Tourmaline and orthoclase locally occur, usually in very small amounts. The tourmaline has a late hydrothermal origin; it occurs more extensively in the igneous rocks of this area. It will be treated in greater detail in that section (cf. below). Orthoclase was noted in only a very few thin sections out of a large number studied. The scarcity of orthoclase will be discussed in the genetic interpretation.

The biotite gneisses and granulites are fine to medium grained. The aplitic granulites usually have uneven granular, xenoblastic, granoblastic textures. The more biotitic gneisses have similar textures except for the presence of larger amounts of xenoblastic biotite in roughly parallel alignment.

The quartz of these rocks is fine to coarse grained. It may have pavement textures, but more commonly it occurs as fine- to coarse-grained aggregates with highly crenulated borders and wavy extinction. In the biotite gneiss it may be fairly evenly scattered throughout the rock, but very often it has been segregated into relatively pure bands or lenticular to irregular aggregates (see Fig. 9). These aggregates may in some cases have been formed from sheared-out quartz pebbles of the original sediment, in that they often occur as rounded or oval shaped mosaic areas with sharp boundaries. However, there is no conclusive evidence that this interpretation is correct. Nevertheless, the most common mode of formation of these aggregates has been by segregation and recrystallization during synkinematic metamorphism which has resulted in formation of distinct bands or lenses of pure quartz.

In the aplitic granulites, the quartz commonly occurs in lenses or bands in which deformation is indicated by a pronounced wavy extinction. In some cases, the quartz of such segregations has recrystallized into a clear, unstrained mosaic. The bands of quartz constitute a directional element in these otherwise directionless biotite-poor rocks (see Fig. 10).

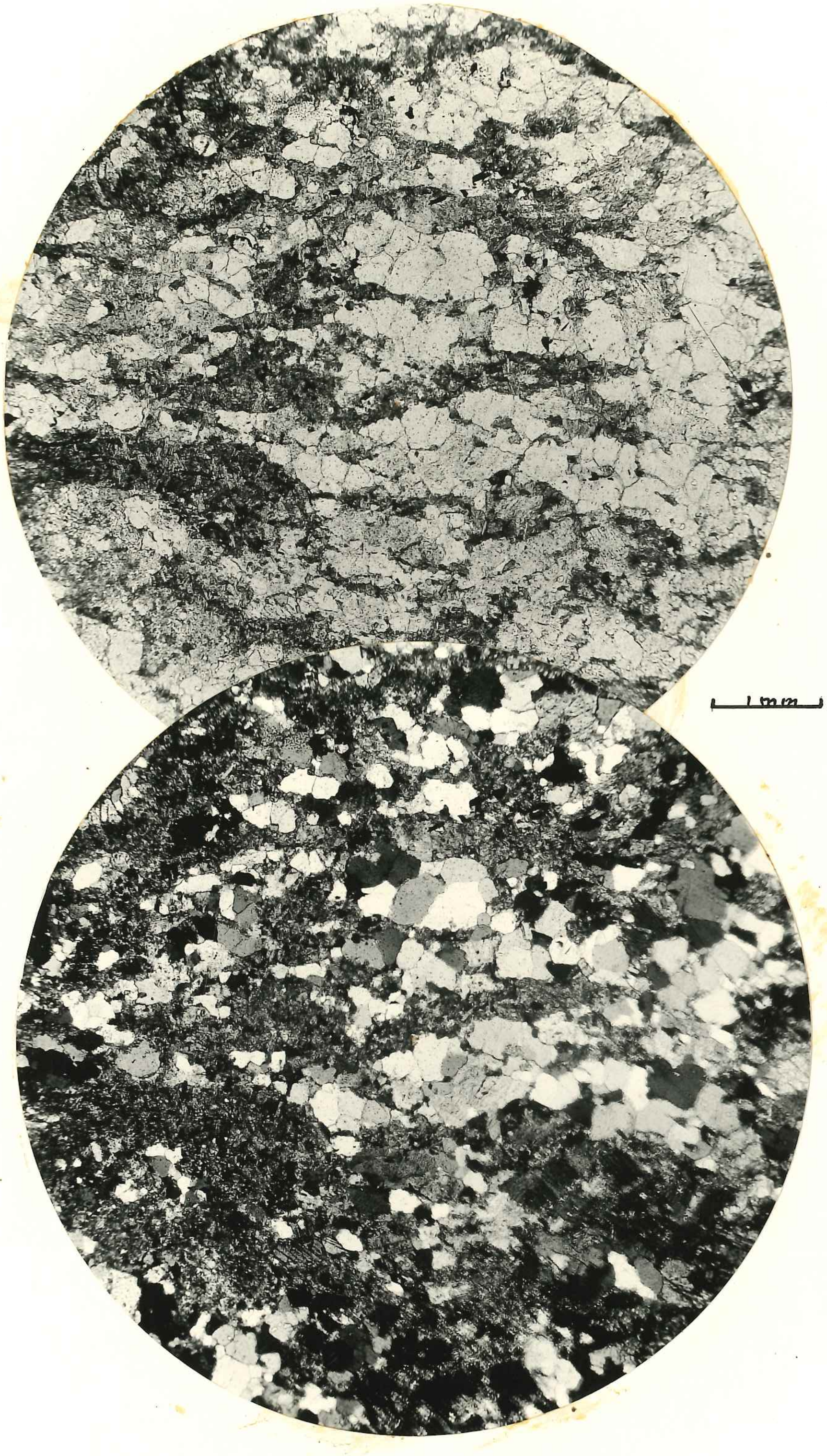

Fig. 9. Photomicrograph of a fairly typical gneiss showing segregation of quartz into bands and lenses, separated aggregates of fine-grained biotite. Plane light and crossed nicols.

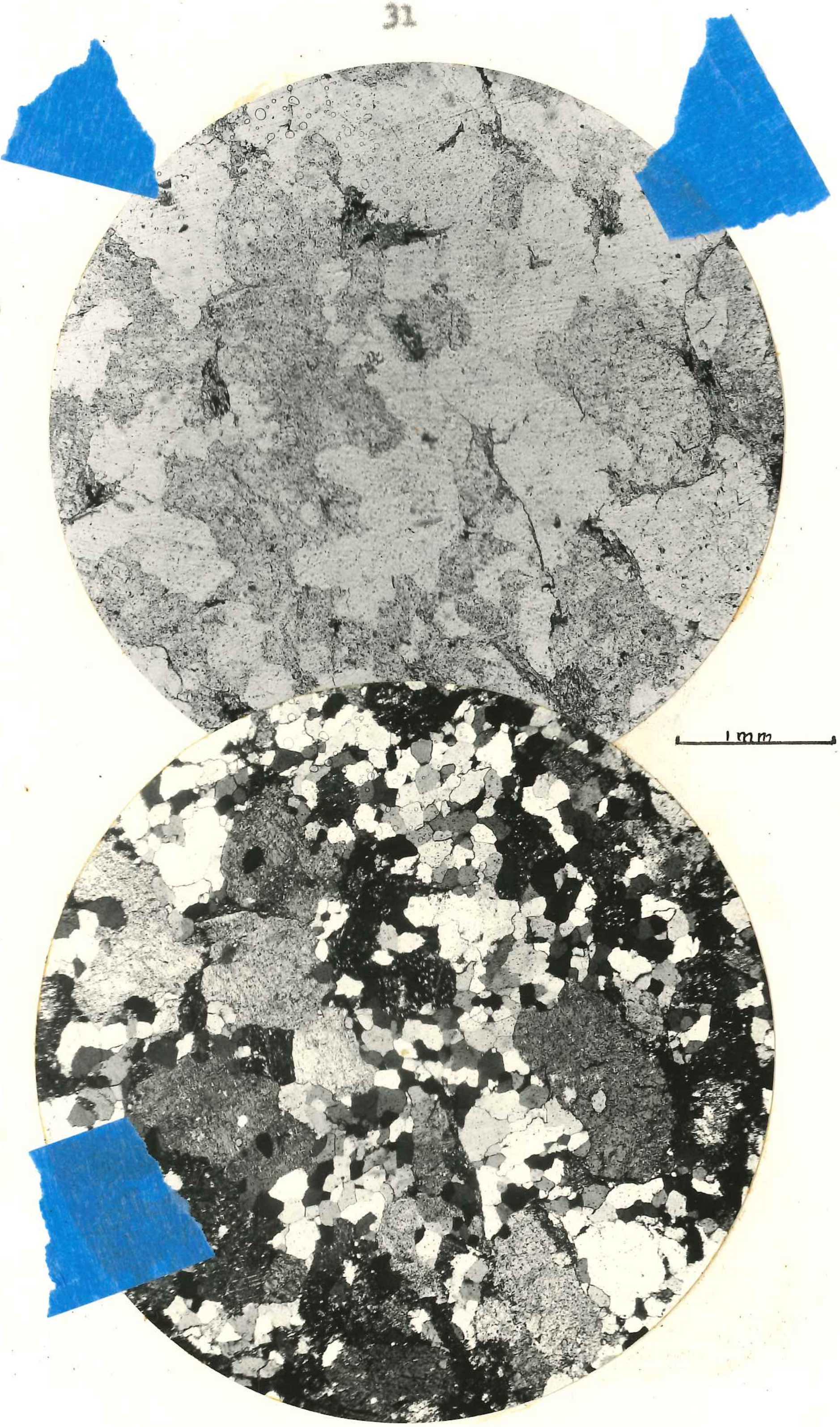

Fig. 10. Photomicrograph of a typical aplitic granulite, poor in biotite, with bands and aggregates of recrystallized quartz. Plane light and crossed nicols.

The plagioclase has anhedral to subhedral forms and distinct crystalloblastic textures. It varies between An_{44} and An_{28}, with an average composition of An_{35}. Normal zoning occurs occasionally, variation being An_{50} in the core and An_{25} at the rim. The plagioclase frequently includes earlier quartz and biotite, as well as some secondary epidote and clinozoisite, with secondary albite occurring only rarely. Minor amounts of early (main assemblage) epidote associated with plagioclase were observed.

The plagioclase has undergone some sericitization. Sometimes it is too greatly decomposed to be identified, but usually it is clear enough to be determined. With an average composition of An_{35}, considerable secondary epidote and clinozoisite should be expected to have formed during alteration in conjunction with the sericite. This is usually not the case and indicates the leaching out of calcium.

Biotite is often considerably altered to chlorite and magnetite. When unaltered, it commonly has a pronounced pleochroism from a dark reddish brown to a light yellow. Late weak shearing has frequently bent and shredded the biotite. Much of the shredded biotite has been recrystallized, although the small grain size has usually been maintained. During this process, some of the biotite has undergone solutional transfer along the shear planes and fractures (see Fig. 11).

Fig. 11. Photomicrograph showing shredded biotite with solutional transfer along late, weak shears and fractures. Plane light and crossed nicols.

The biotite which has developed during synkinematic metamorphism is well aligned, but continued crystallization under static conditions has produced a considerable amount of non-aligned biotite, thereby reducing the degree of the schistosity. There are fairly well defined layers, however, which are richer in biotite than adjacent layers. Within the biotite-rich layers there is usually no very sharp alignment. Thus a certain degree of banding is produced which is mainly compositional.

Late weak shearing has affected most of the area, producing the granulation and mortar structure mentioned above. Wreaths of mortar around plagioclase crystals are not uncommon. Micro shear zones a few mm wide, containing finely granulated minerals, occur either parallel or at angles up to 30 degrees to the foliation (see Fig. 12).

Garnetiferous Biotite Gneiss and Granulite

As in the biotite gneiss and granulite, quartz is usually the predominant mineral, varying from 10 to 65 per cent and averaging about 43 per cent of the total mineral assemblage. Plagioclase, averaging An_{36}, forms 20 to 50 per cent of the rock, averaging about 37 per cent. Orthoclase occurs very infrequently in amounts ranging from 4 to 15 per cent. Wherever it is present, the plagioclase usually decreases in amount to about 25 per cent. Biotite and its alteration product chlorite

Fig. 12. Micro shear zone filled with finely granulated minerals. Here the foliation is horizontal, the micro shear at an angle of about 30 degrees to it. Crossed nicols.

occur in amounts from 5 to 15 per cent. Garnet constitutes 2 to 7 per cent of the rock, averaging about 3 per cent.

Quartz, for the most part, has the uneven extinction and highly crenulated borders typical of the quartz in the ordinary biotite gneiss and granulite. As is common in those rocks, it occurs both as scattered grains and as aggregates or bands which are parallel to the foliation. Occasionally the quartz has recrystallized into clear, equidimensional grains and aggregates.

Plagioclase has anhedral form and crystalloblastic textures, with numerous inclusions of quartz and biotite. Some epidote and clinozoisite have formed from the plagioclase, and late sericitization is very common. Late shearing has caused bending and fracturing of the plagioclase crystals, and locally wreaths of mortar have developed. There has been little or no recrystallization.

Biotite has been bent and shredded along late shear planes and has been partially altered to chlorite. It is fairly well oriented for the most part, but some post-kinematic biotite has formed at angles up to 30 degrees with the foliation planes.

Garnet, occurring as porphyroblasts approximately 2 mm in diameter, has bowed out the layers of surrounding biotite. The garnets have been highly fractured and have been altered along the fractures to biotite and, at a later time, to chlorite. Some plagioclase and epidote are included in the garnets. Secondary sericite often occurs in the biotitized garnets, frequently in considerable amounts exceeding that of biotite (see Fig. 13). Such sericitization of garnet presents the unusual process of leaching of Fe from the garnet, and of such Mg as may have been present in it. This process is combined with the leaching out of Ca from the sericitized plagioclase. The common occurrence of these two alterations indicates a considerable leaching out of Fe and Ca, respectively, difficult though this may be to accomplish in the case of the Fe of the garnets.

The only kyanite found in the entire mapped area occurs in the garnetiferous, biotite-rich gneisses. It occurs as relatively large porphyroblasts (up to 1.5 cm in length) and is fairly fresh, although occasionally it has been highly altered to sericite (see Fig. 14). Richarz (1933) has reported an occurrence of kyanite in the Trinity Tunnel with crystals up to several inches in size. Kyanite is by no means plentiful, however. It may once have been present in greater amounts, as was probably the case with muscovite, but has since been destroyed during Na metasomatism leading to feldspathization. This question is discussed below (cf. Genetic Interpretation).

Apatite, with anhedral to subhedral form, is a common accessory mineral. Secondary magnetite, formed during chloritization of biotite, occurs as a minor constituent of the rocks.

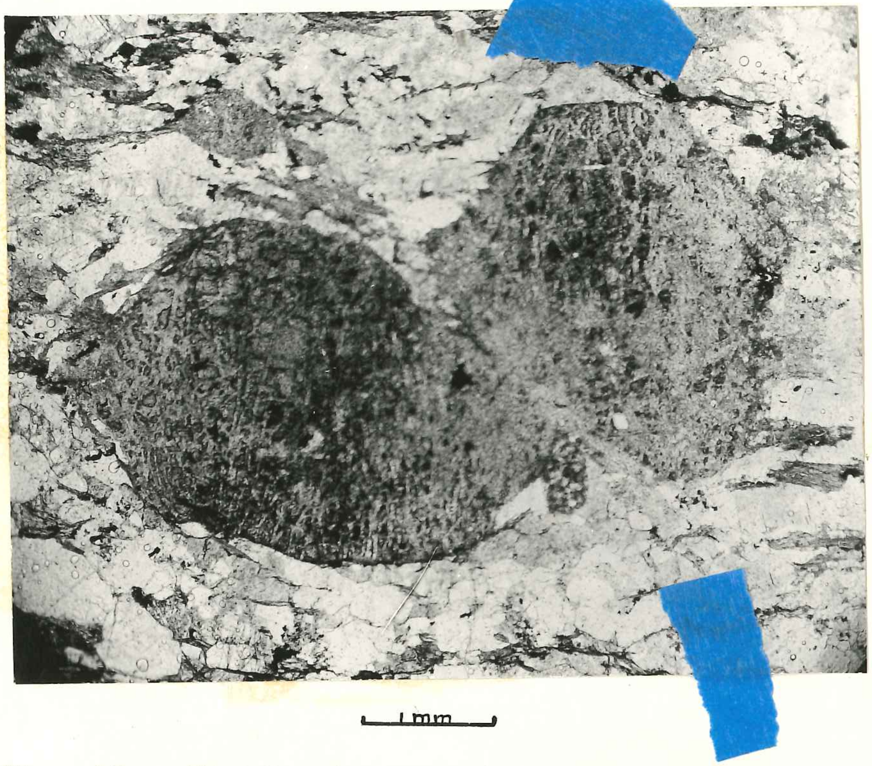

Fig. 13. Highly fractured garnets which have altered to biotite and later to sericite in large part. Plane light.

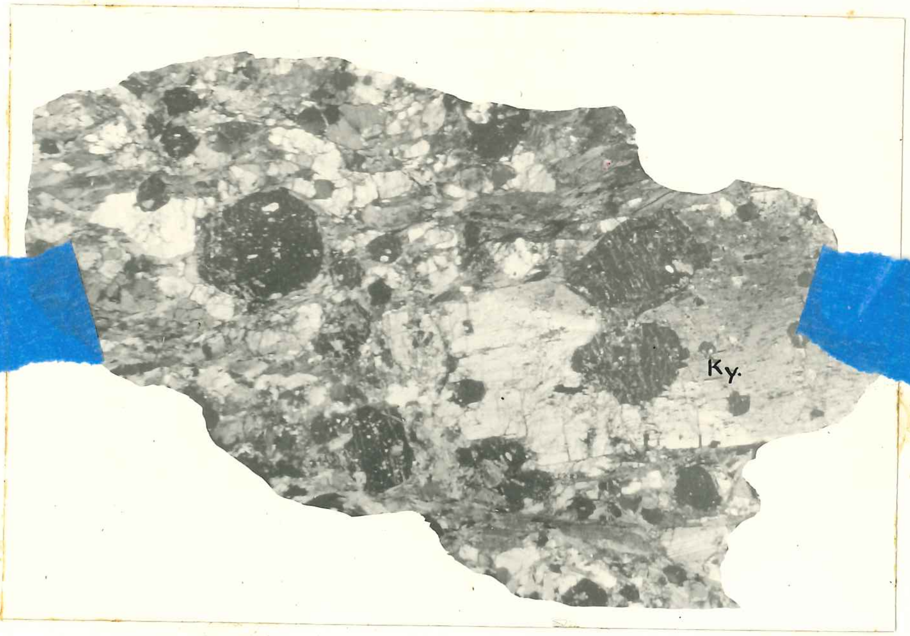

Fig. 14. Large crystal of kyanite (ky) (1.5 cm) associated with garnets in the garnetiferous biotite gneiss. Crossed nicols.

The texture of these rocks is the same as described in the section on Biotite Gneiss and Granulite (cf. above).

Muscovite-Biotite Gneiss and Granulite

The occurrence of muscovite distinguishes this rock type from the biotite gneiss and granulite; otherwise the mineral content is very similar. Quartz is the predominant mineral, ranging in amounts from 45 to 50 per cent. Plagioclase has an average composition of An_{31} and occurs in amount from 35 to 47 per cent, with an average of about 41 per cent. The combined percentage of biotite and chlorite ranges from 3 to 10 per cent, averaging about 7 per cent. Muscovite makes up 1 to 4 per cent of the rock, commonly occurring in amounts of about 3 per cent.

Quartz has the wavy extinction and highly crenulated borders common in the biotite gneiss and granulite. The plagioclase is anhedral in form, with poikioblastic textures often occurring. The biotite is commonly bent and highly granulated without later recrystallization. Very often it is considerably altered to chlorite and magnetite. The biotite has the crude alignment produced by crystallization beginning under synkinematic conditions and continuing after the end of deformation. The muscovite is closely associated with the biotite and often is seen to have formed from the biotite during leaching of Fe and Mg. Many times it has almost completely replaced individual biotite crystals (see Fig. 15). Muscovite is also seen to

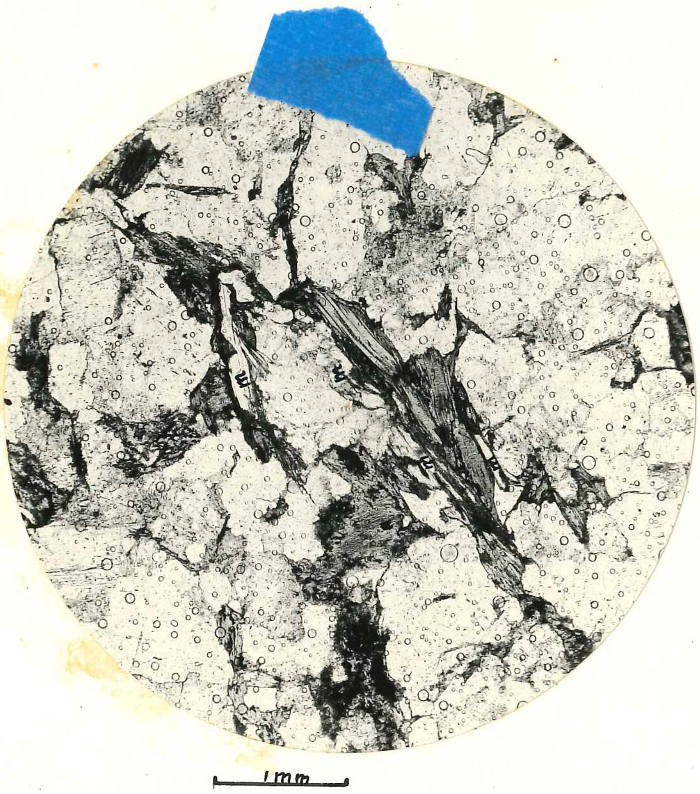

Fig. 15. Photomicrograph of muscovite-biotite gneiss showing muscovite (m) associated with and replacing biotite. Plane light.

occur as separate clear crystals without associated biotite, and in such cases it usually has a haphazard orientation. Much of it has therefore formed after the end of deformation.

Textures are identical with those of the biotite gneisses, being uneven, granular, xenoblastic, and granoblastic with fine to medium grain size.

Genetic Interpretation of the Gneisses and Granulites

The descriptions of the three varieties of gneisses and granulites, given above, indicate that these rocks are products of regional metamorphism which was essentially synkinematic but extended into a late static phase. The occurrence of sodic andesine (averaging An_{36}) with biotite and muscovite and some garnet suggests that the grade is that of the warmer mesozone. This is confirmed by the occasional presence of kyanite.

With regard to the question of the original material from which the rocks were derived, the high quartz content (averaging 45 per cent, but in many cases reaching 60 and 65 per cent), the local occurrence of kyanite and garnet, the great variability in the amount of biotite, and the presence of enough Ca to make sodic andesine even in most of these varieties almost or entirely free of biotite ("alaskitic") are strong arguments for a sedimentary origin of the gneisses and granulites. The entirely crystalloblastic textures of all minerals in these rocks, including their frequently poikioblastic feldspars, may not be conclusive evidence against derivation from an earlier igneous rock (orthogneiss); but other features of these rocks, including those features just described, do constitute such evidence. A direct magmatic origin ("synorogenic intrusion") is definitely excluded by the textures of these rocks.

In determining the type of sediment from which the gneisses have formed, the chemical composition was calculated from the mode. The mineral percentages were estimated by taking five to eight readings across the foliation of each of 60 thin sections, using a low-power objective and an ocular with a graduated crosshair. Because of the considerable variation in percentages of some minerals (particularly quartz and biotite) over the area, a few readings in each of a large number of sections probably gives a more accurate percentage determination than would extensive traversing of only a limited number of sections with an integrating stage. The volume percentages were converted to weight percentages in calculating the chemical composition. The table shown below gives the oxide percentages of the three varieties of biotitic gneisses combined. The compositions calculated separately show very little difference other than a higher SiO_2 content (77%) in the biotite gneiss and granulite as contrasted to 72% in the garnetiferous biotite gneiss and granulite.

Oxide Percentages of the Three Combined
Rock Varieties, Calculated from the Mode

	SiO_2	Al_2O_3	Fe_2O_3, FeO	CaO	K_2O	Na_2O	MgO
Quartz	43.50						
Biotite	2.90	1.17	0.32		0.61		1.70
Chlorite	1.10	0.62					1.20
Plagioclase							
Albite	18.80	5.23				3.16	
Anorthite	6.20	5.28		2.90			
Orthoclase	1.28	0.36			0.33		
Muscovite	0.44	0.37			0.11		
Garnet	0.35	0.20	0.41				
	74.57	13.23	0.73	2.90	1.05	3.16	2.90

In his study of the Swakane gneiss, Waters (1932) concludes that it has been derived from an arkose. The high feldspar content suggests that this might also be the case in this area. Because the plagioclase is andesine, such an arkose would have had to be derived from a quartz diorite or trondhjemite. Such arkoses the feldspar of which is essentially plagioclase, have been found by Misch (personal communication) further to the north in the Cascades.

The occurrence of kyanite, however, is mineralogical evidence of a shaly component rather than an origin from an arkose. The rocks are fairly calcic and an arkose could not supply the alumina excess necessary to form kyanite. The high quartz content and fairly high content of alumina indicate that the sediment probably was on the order of an arenaceous shale or argillaceous quartz sandstone.

In a normal shale, alkalies commonly occur in amounts up to 6 or 7 per cent, with K_2O always dominant over Na_2O. It is important to note in this case, however, that Na oxide occurs in excess of K oxide in proportions of 3 to 1, whereas exactly the opposite should be expected. It is therefore concluded that Na metasomatism has been active during metamorphism. This is supported by the high feldspar content of the rocks and by the replacement texture of the feldspar.

Inasmuch as little or no orthoclase occurs in the rocks, either much of the K has been driven out by the entering Na solutions (which is not uncommon) or it is held in the plagioclase. Although chemical analyses of the feldspar were not made, the lack of anti-perthite suggests that little K occurs in the plagioclase. It is concluded that the Na bearing solutions attacked alumina-rich minerals such as muscovite and drove out K during feldspar formation.

Richarz (1933), in his paper on the geology of the Trinity Tunnel, has proposed a somewhat different origin for the gneisses. It has been shown above, however, that his theory of an injected gneiss does not apply in this case.

QUARTZ LABRADORITE PORPHYRY

General Statement

Quartz labradorite porphyry, a rock of rather unusual composition, occurs in the form of small stocks in the northern and central parts of the area. The Trinity Tunnel at the southern end of the area has exposed a similar body of rock which does not crop out on the surface. The largest of these stocks occurs near the northern end of the area on Red Mountain. It is oblong parallel to the regional strike and is about a mile in length. The other stocks are slightly smaller, having an average diameter of about 1/4 mile. Overburden obscures part of the contacts of these smaller bodies and their relationship to one another is uncertain. Some of them may be part of one larger body. All of these stocks are of similar appearance, composition, and texture and are considered to be of the same origin.

The contacts of these stocks with the gneisses are almost always very sharp. Fairly coarse-grained textures occur throughout the stocks. Chilled borders are developed but are seldom more than 1/8 to 1/2 inch in width (see Fig. 16). Thus the intrusive character of the bodies is usually evident. Occasionally, however, the contacts appear to be gradational over a distance of three or four feet.

The rock as seen in the field is light greenish gray in color and medium to coarse grained. It has a porphyritic

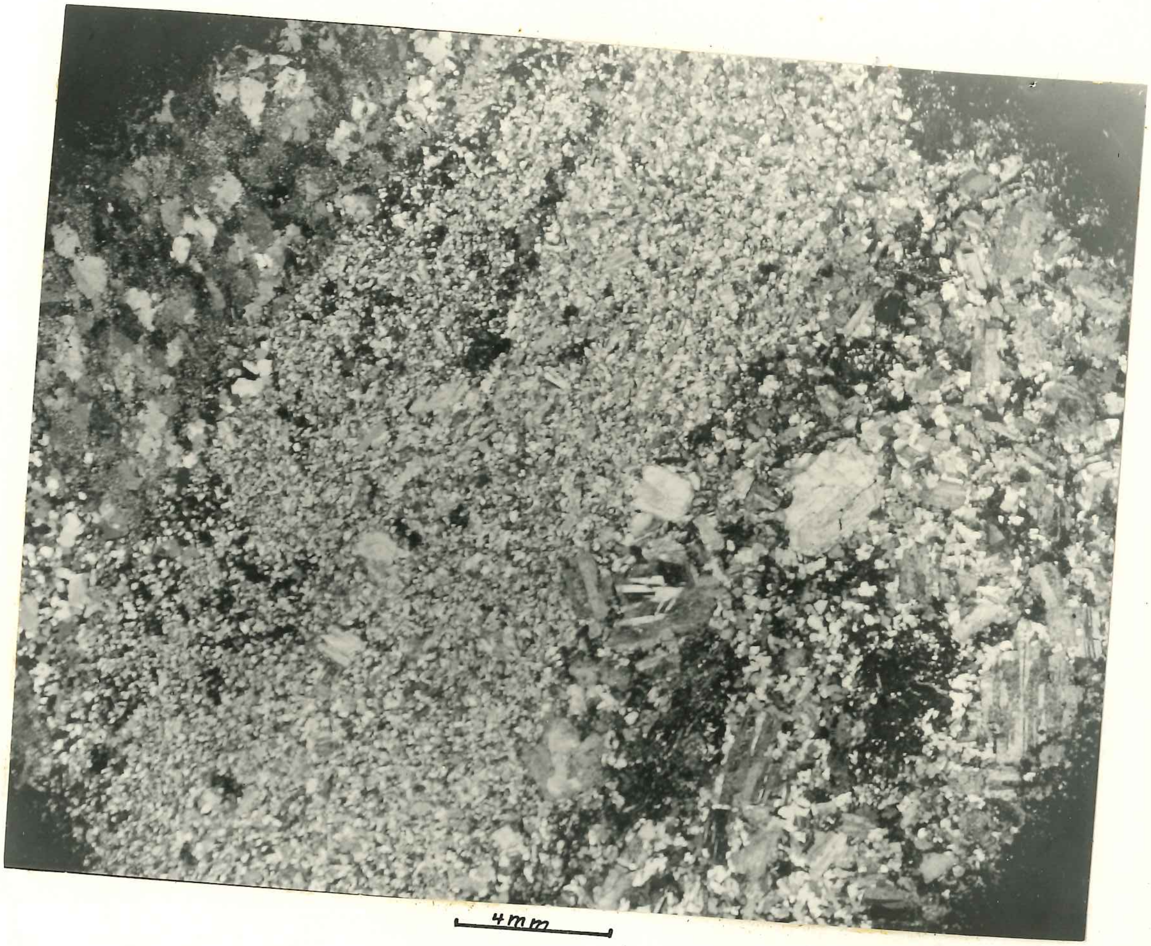

Fig. 16. Photomicrograph of the contact between aplitic granulite (left side of photograph) and quartz labradorite porphyry (right side of photograph), showing the chilled border. Crossed nicols.

texture which is not readily apparent in hand specimen (see Fig. 17). In thin section the plagioclase is seen to form large, square to oblong phenocrysts. Some hornblende occurs as large phenocrysts which are easily seen megascopically.

Although the color and appearance of the rock is largely the same for all the bodies, locally within the largest stock a gradation into patches of darker colored, finer grained rock, poor in phenocrysts, may be seen. These darker, finer grained areas usually are not over 50 to 100 feet in width.

The northern or largest porphyry body is closely associated with remnants of a tectonic breccia and appears to underlie the breccia in most places. Those stocks which occur in the central part of the area commonly have brecciated contacts with the gneisses. These minor breccia zones usually are not over 20 or 30 feet in width. The porphyry body exposed in the Trinity Tunnel, however, has a vertical breccia zone more than 300 feet wide along its contact with the gneiss.

As to the age of intrusion, all that can be said is that the porphyry stocks are younger than the gneisses which they intrude and older than the tectonic breccia, at least 50 per cent of which consists of porphyry fragments. Late minor faulting has offset the contact of the largest stock in a number of places near its southern end. The horizontal offset of the contact, however, is small, usually not over a hundred feet.

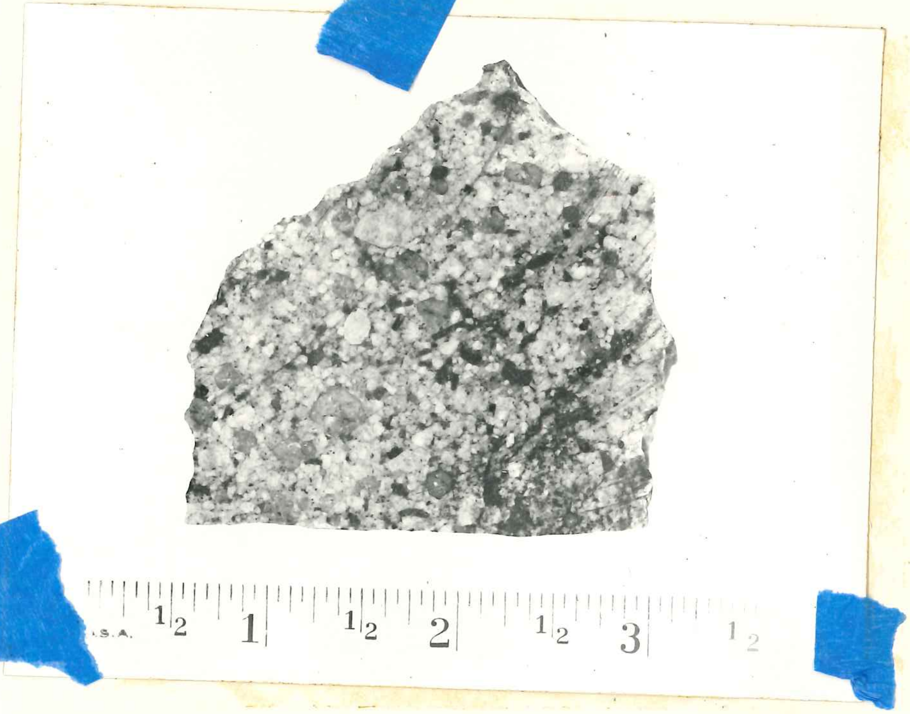

Fig. 17. Specimen of the quartz labradorite porphyry. The porphyritic texture is not as apparent in hand specimen as it is in thin section.

Petrography

The percentage of mineral constituents was determined in each of 16 thin sections with the Rosiwal integrating stage. Traverses in each case were approximately 100 times the diameter of the largest grain. The results of this analysis are as follows:

	Per Cent of Rock	
Mineral	Range in Per Cent	Average Per Cent
Plagioclase	41 - 70	54
Quartz	16 - 41	26
Hornblende	8 - 21	12
Biotite	0.7 - 31	4
Accessories	tr. - 11	3

Plagioclase forms phenocrysts. Occasionally quartz also occurs as phenocrysts. The percentages of these phenocrysts were determined with the integrating stage. They are as follows:

	Per Cent of Rock	
	Range in Per Cent	Average Per Cent
Plagioclase Phenocrysts	31 - 45	37
Quartz Phenocrysts	0 - 13	6
Groundmass (including altered hornblende phenocrysts)	43 - 63	55

Hornblende, which is usually phenocrystic in nature, was grouped with the groundmass inasmuch as it is most often highly altered to felty, fine-grained masses of chlorite and actinolitic products.

The plagioclase phenocrysts range in size from approximately 1.5 mm to 6 mm, with the great majority being about 2.5 mm in length. These and the other phenocrysts are set in a relatively equigranular, fine-grained groundmass composed largely of quartz with variable amounts of plagioclase (see Fig. 18). The grain size in the groundmass is about 0.07 to 0.1 mm. Occasionally the rock becomes uniformly coarse grained and loses its porphyritic nature. This is not common, however (see Fig. 19).

The darker colored, finer grained areas within the largest stock contain a few large plagioclase phenocrysts set in a matrix composed predominantly of well formed plagioclase laths of equal length and have a somewhat diabasic texture. The plagioclase laths in this case average about 0.20 mm in length. Compared to the predominant rock type of the stock, these darker patches have more hornblende and less quartz.

The plagioclase of the porphyry stocks is, for the most part, labradorite with a composition averaging about An_{55}. Very well developed zoning of a normal and oscillatory nature is not uncommon (see Fig. 20). In some cases, the composition ranges from labradorite to oligoclase. The development of albite twinning has aided in the destruction of this zoning,

Fig. 18. Quartz labradorite porphyry, showing its typical textures. Crossed nicols.

Fig. 19. Photomicrograph of the intrusive quartz labradorite rock. Only rarely does it become uniformly coarse grained as shown here. Crossed nicols.

although zoning may be preserved in one twin and destroyed in an adjacent one. All combinations of twinning and zoning can be seen in thin section (see Fig. 21). This greatly complicates the percentage determination of labradorite as compared to the less calcic plagioclase. In many cases a narrow rim of oligoclase surrounds a labradorite core. Fine-grained anhedral plagioclase, which occurs in the groundmass, is usually oligoclase. The great majority of the plagioclase is labradorite, however. The formation of the oligoclase may be due to the action of Na-rich solutions late in the crystallization history.

The plagioclase phenocrysts commonly are of perfect euhedral shape, although locally they may be of subhedral and even anhedral form. In this latter case, the texture often has a metamorphic aspect, in contrast to the typically igneous texture of most of these rocks (see Fig. 22). Tiny inclusions are commonly seen in the phenocrysts. They are usually controlled by zoning and may be clearly delineated by zone boundaries. They are therefore considered to be alteration products controlled by composition (see Fig. 23). Not only do the larger plagioclase phenocrysts mostly have good euhedral shape, but also the smaller phenocrysts display the same degree of form development. The fine-grained groundmass usually contains a moderate amount of anhedral oligoclase, however. This anhedral oligoclase should not be compared with labradorite phenocrysts, but only with their narrow oligoclase rims.

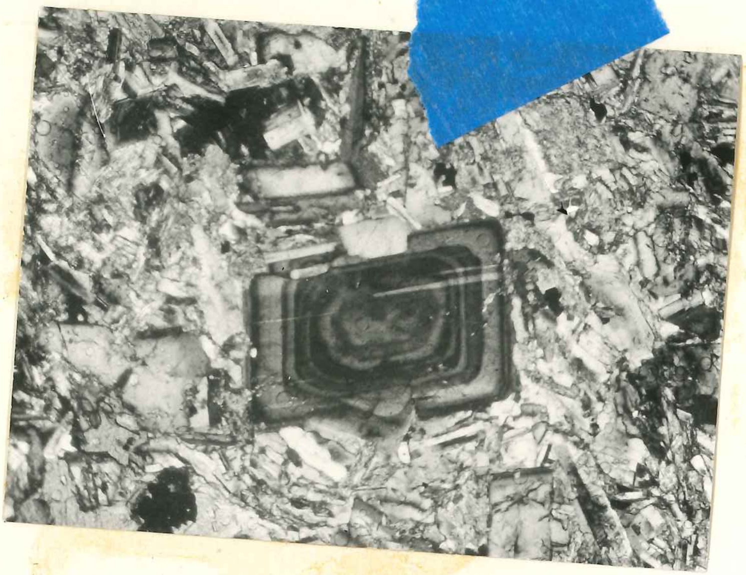

Fig. 20. Exceptionally well developed oscillatory zoning in the plagioclase of the quartz labradorite porphyry. Crossed nicols.

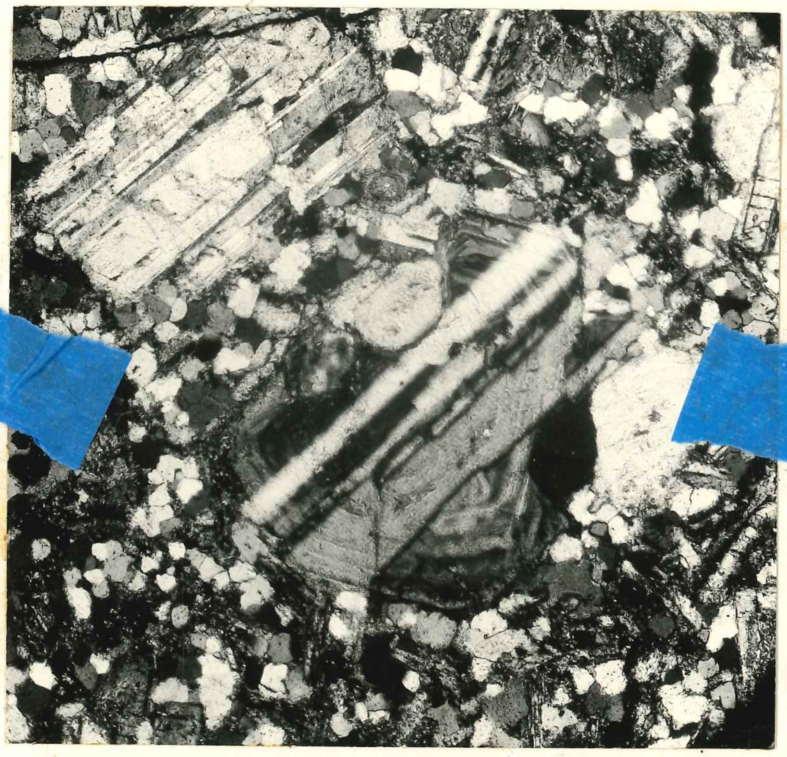

Fig. 21. Photomicrograph showing twinning destroying zoning. Crossed nicols.

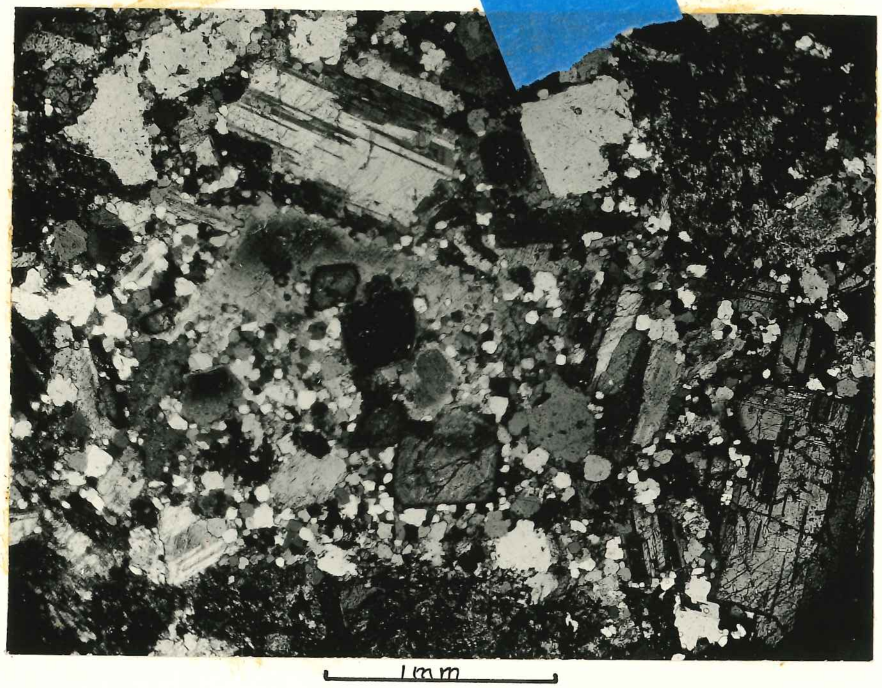

Fig. 22. Photomicrograph showing metamorphic textures such as occasionally seen in this intrusive body. Note the untwinned plagioclase in the center of the photograph with its numerous inclusions. Crossed nicols.

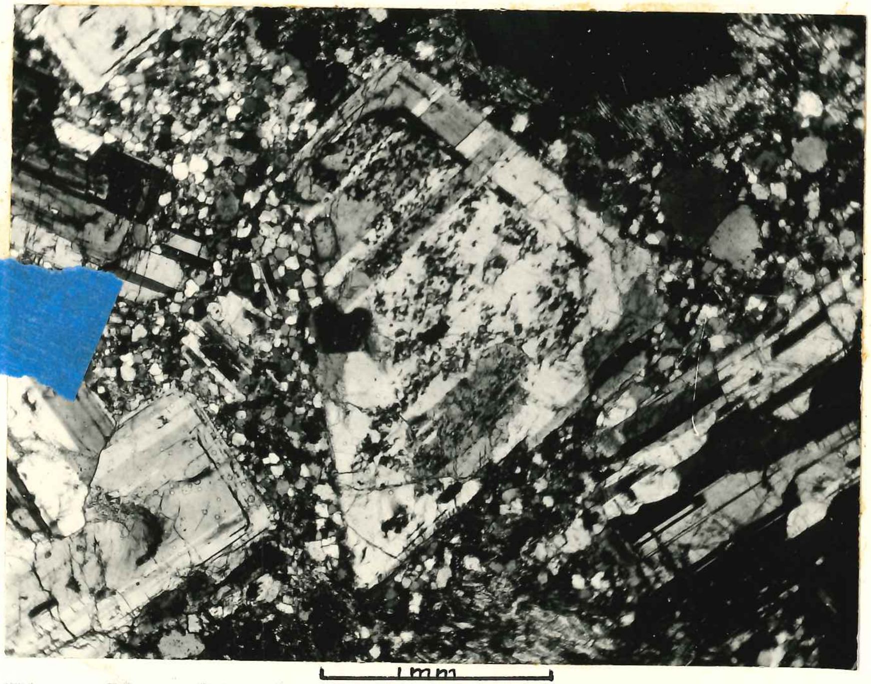

Fig. 23. Plagioclase crystal with numerous small included crystals produced by alteration. The alteration was controlled by former composition boundaries before destruction of zoning by twinning. Crossed nicols.

Distinct rims of iron hydroxide occasionally occur within the plagioclase crystals. They appear to be controlled in part by zone boundaries, and in part are parallel to irregular crystal outlines (see Fig. 24). Their mode of origin is not known. Iron hydroxide also occurs along cleavage planes and cracks in the plagioclase.

As mentioned above, quartz occurs both as large phenocrysts and as small equigranular grains in the groundmass. The large crystals may have a partial development of euhedral form, such as a well developed crystal end (see Fig. 25), but more commonly the large crystals are anhedral. They often exhibit growth characteristics such as uneven borders with pseudopodia-like extensions into the groundmass (see Fig. 26). The majority of the quartz, however, occurs in the groundmass between the euhedral plagioclase crystals as a fine-grained aggregate of equigranular crystals. Occasionally the large anhedral crystals of quartz enclose a number of smaller plagioclase crystals, although some early quartz grains are free of such inclusions. The quartz of the groundmass usually has a pavement texture, but locally it may have highly crenulated borders and may occur in aggregates, looking rather metamorphic in texture.

Hornblende was at one time the main mafic constituent of the porphyry and may occur as fairly fresh phenocrysts up to 1.5 cm in length. Often it is mottled and patchy and has

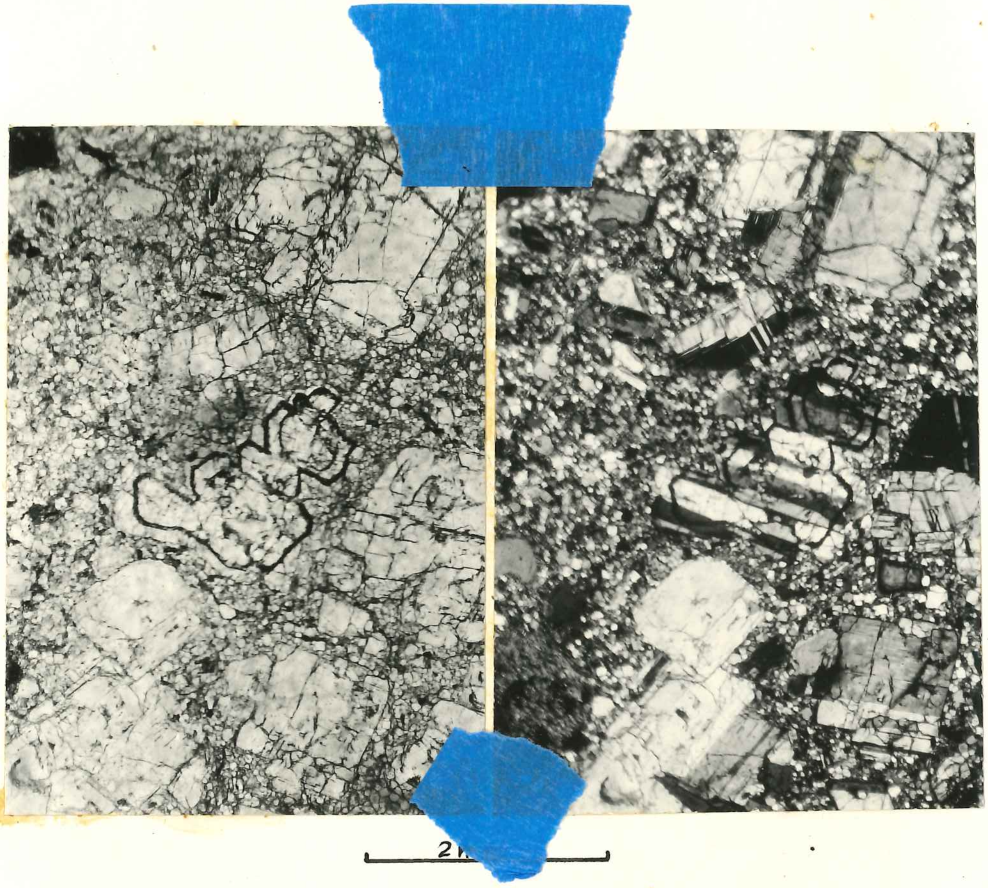

Fig. 24. Photomicrographs showing an iron hydroxide rim which has formed in a plagioclase crystal. The rim formed partly along former zone boundaries (since destroyed), and partly parallel to the crystal outline. Plane light and crossed nicols.

Fig. 25. An early quartz phenocryst in the quartz labradorite porphyry showing well developed crystal form on one end. Crossed nicols.

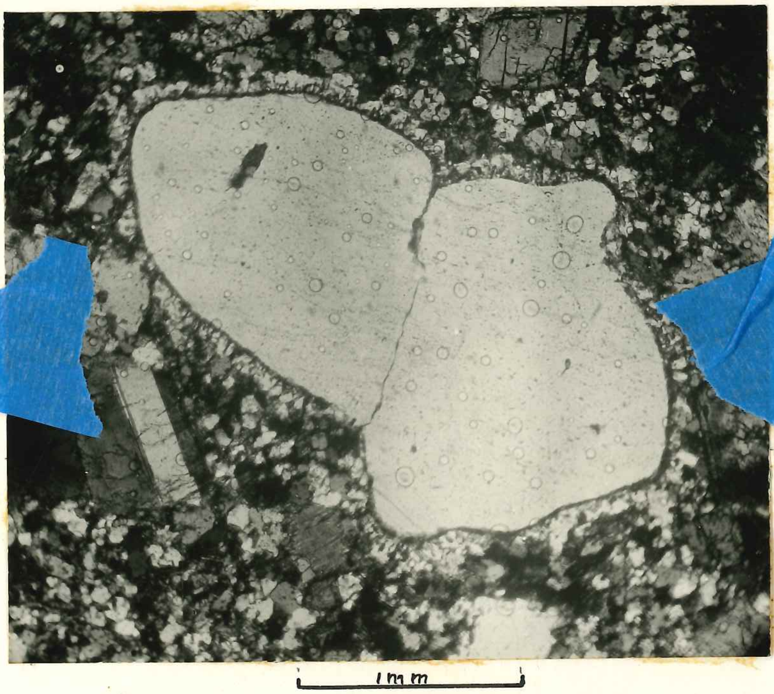

Fig. 26. Quartz phenocryst growing in the porphyry with a rim of pseudopodia-like extensions into the groundmass. The boundary of the main crystal is marked by a rim of chloritic material. Crossed nicols.

associated sphene, suggesting a secondary origin from titaniferous augite or basaltic hornblende. Commonly it is altered to a considerable degree to actinolitic hornblende and large felty aggregates of fine-grained chlorite. Some biotite has formed from hornblende, as shown by the amphibole cross-section being marked by relict iron oxide in the biotite (see Fig. 27). Biotite pseudomorphs after hornblende are also occasionally seen (see Fig. 28).

The biotite is of two generations. Some is primary, but most is secondary from hornblende. It is only rarely in a fresh state, being mostly altered to chlorite. A few specimens show biotite to be the main mafic constituent, although this is by no means common. In some cases the biotite has a metamorphic aspect, occurring both in fine-grained aggregates of anhedral flakes and along the interstices of the quartz and feldspar grains (see Fig. 29). Often it is elongated perpendicular to the cleavage (see Fig. 30).

Accessory minerals include clinozoisite, zoisite, epidote, sphene, and sericite, all forming from plagioclase. Magnetite is common, forming from biotite and hornblende. Some apatite was seen associated with the hornblende.

Tourmaline (schorlite) occurs locally in the largest stock as a zone a few feet wide and a few tens of feet long which consists of almost pure radial masses commonly known as sunburst tourmaline. Sheafs of tourmaline are often seen in

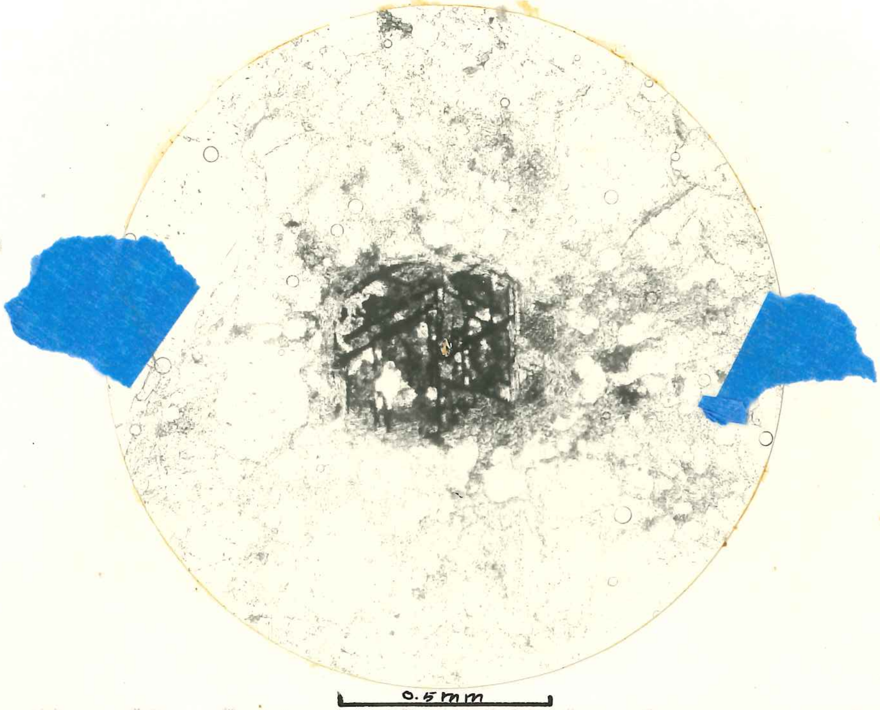

Fig. 27. Pattern of amphibole cleavage marked by relict iron oxide in biotite which is now largely altered to chlorite. Plane light.

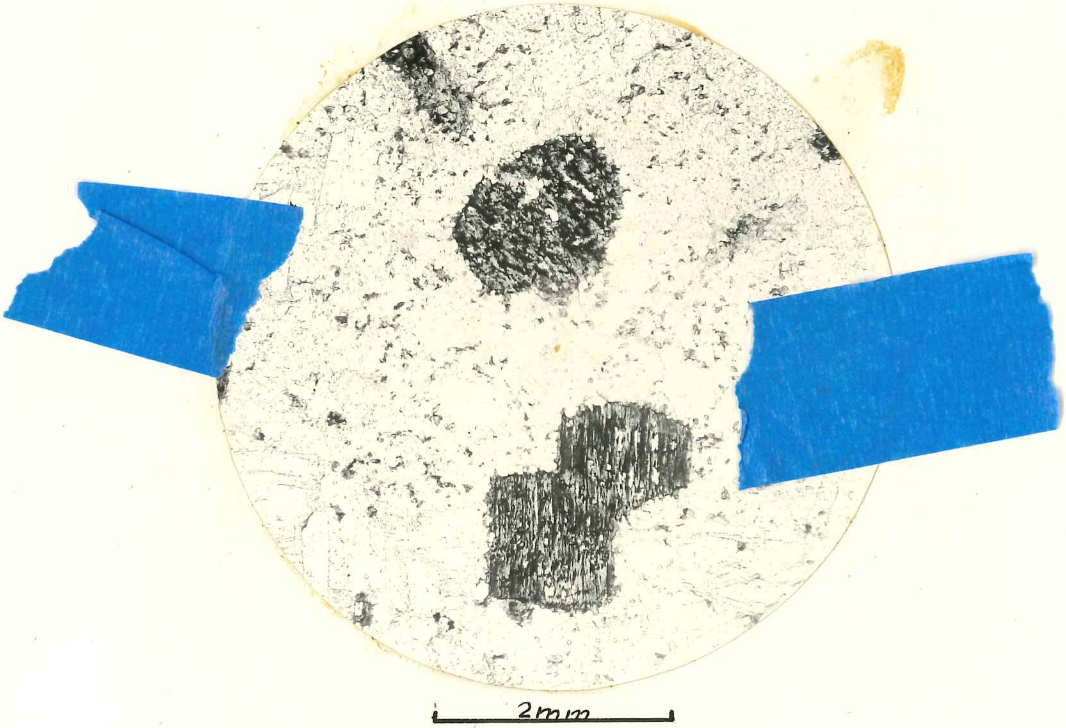

Fig. 28. Pseudomorphs of biotite after hornblende. The biotite is now partially altered to chlorite. Plane light.

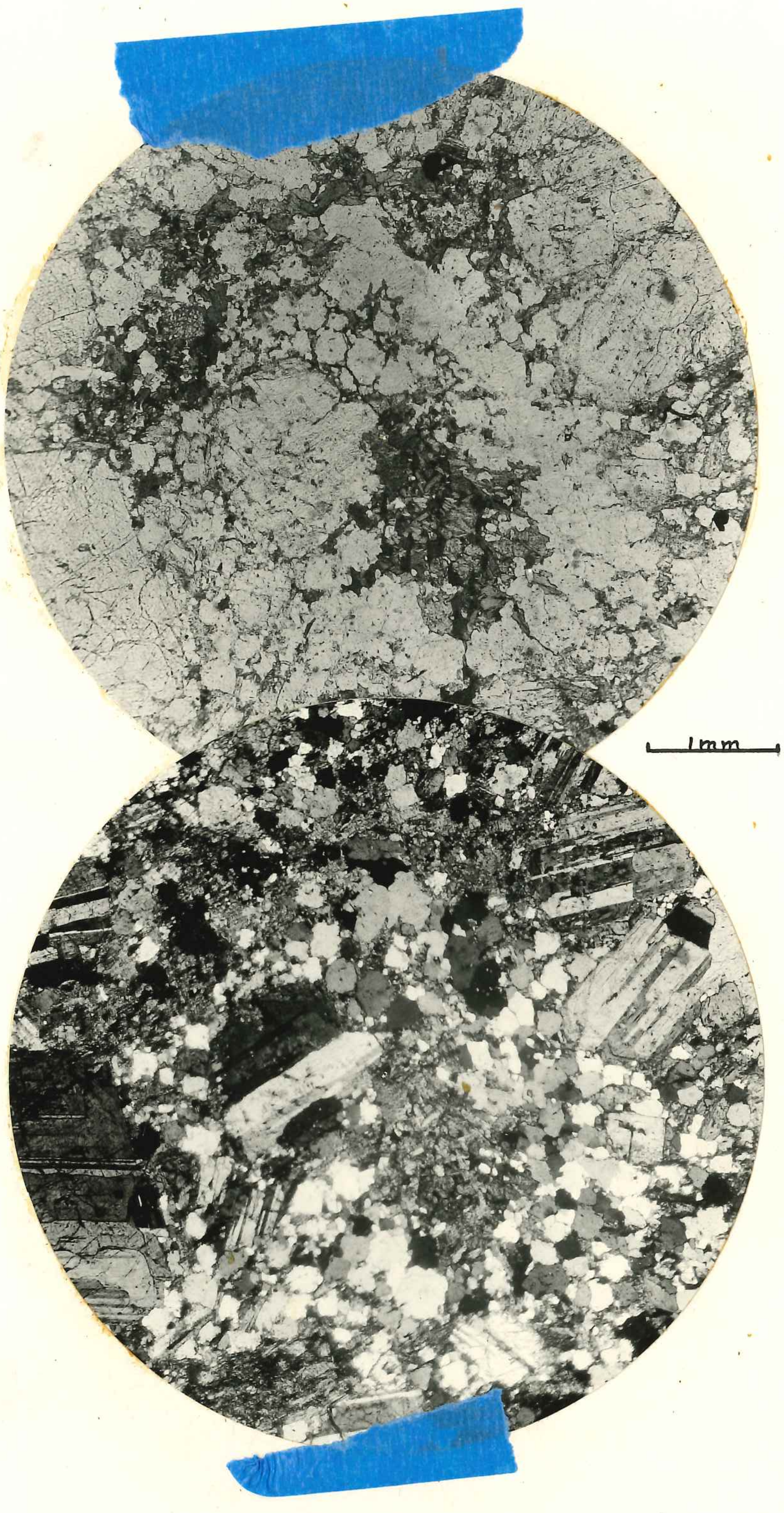

Fig. 29. Photomicrograph showing fine-grained aggregates of biotite, and biotite along the interstices of the quartz and feldspar crystals, giving the porphyry a texture of metamorphic aspect. Plane light and crossed nicols.

widely separated parts of the largest porphyry stock (see Fig. 31). It has some associated scheelite and is thought to be of a late hydrothermal origin.

Concerning the texture, the rock can be said to be idiomorphic to hypidiomorphic porphyritic. The groundmass is fine-grained xenomorphic for the most part, except for some well developed small plagioclase crystals. The rock is completely directionless.

Genetic Interpretation

The origin of a rock of this composition is not easy to explain. Two major points can be definitely established: 1) the rock was intrusive, as shown by the sharp contacts and the existence of narrow chilled borders; 2) the rock was at one time a melt, as indicated by the development of large euhedral phenocrysts of plagioclase as well as many euhedral, smaller plagioclase crystals only slightly larger than the average groundmass grain size. Elongation of some of the biotite perpendicular to the cleavage supports magmatic crystallization. The development of large euhedral phenocrysts must have occurred during a liquid state before the intrusion and quick chilling which produced the fine-grained groundmass.

The quartz labradorite porphyry has all the physical characteristics of an igneous rock. Its composition, on the other hand, is hard to explain. The rock is high in SiO_2

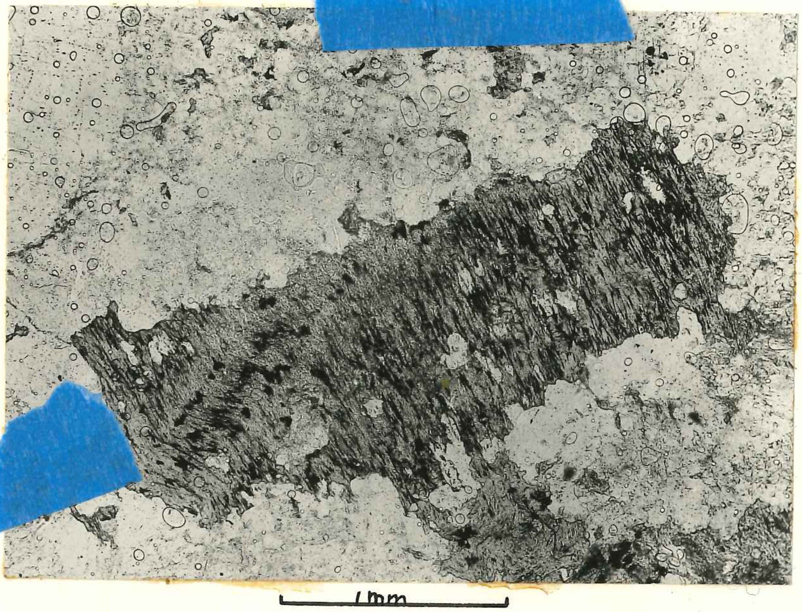

Fig. 30. Photomicrograph of a biotite crystal elongated perpendicular to its cleavage, suggesting growth in a melt. It is now largely altered to chlorite. Plane light.

Fig. 31. Photomicrograph showing sheafs of tourmaline (schorlite) of a late hydrothermal origin in the porphyry. Plane light.

(high quartz content) and low in Mg and Fe (low mafic content), but instead of containing a sodic plagioclase it is very rich in labradorite which indicates a high Ca content. There is no known magmatic rock of this peculiar chemical composition. Nor does it seem likely that a normal magma -- a gabbroic-basaltic magma, for instance, which might be assumed as a source because of the high labradorite content of the porphyry -- could have differentiated into a highly leucocratic, quartz-rich rock containing at the same time a large amount of Ca. Is it possible that the rock was originally a basic one and that its high quartz content is due to secondary, late SiO_2 introduction (deuteric or metamorphic)? The quartz occurs as early phenocrysts, as well as in the groundmass, and therefore the original melt must already have had a high SiO_2 content. Nor do the textures of the rock indicate that quartz introduction has occurred.

If the magma thus had a high SiO_2 content prior to its crystallization, the possibility remains that a basic magma might have assimilated a siliceous rock and thus acquired a high SiO_2 content before crystallization. However, this assumption could not easily account for the disproportionately low Mg and Fe content (low mafic content) compared to the high Ca content.

Inasmuch as a "normal" igneous magma, its differentiation, or its modification by assimilation does not satisfactorily explain the peculiar composition of this rock, the question arises whether there could be a different kind of source of this igneous rock. As mentioned above, metamorphic textures are occasionally seen in samples obtained from different parts of the stocks. These textures are very similar to the metamorphic granulitic textures described in the preceding chapter. These textures may be interpreted as merely being derived from fragments of metamorphic rocks which were carried along in the melt during intrusion. However, the varieties of the porphyry which display these metamorphic-appearing textures have the same composition as the typical igneous porphyry and differ in composition considerably from all of the metamorphic country rocks exposed in the area. Therefore, these metamorphically textured varieties are part of the porphyry itself, and not xenoliths.

The occurrence of these metamorphically textured varieties, together with the peculiar composition of the porphyry, might perhaps be interpreted in the following way. The porphyry magma was the result of the melting of metamorphic rock material, and the metamorphic textures occasionally seen are relict textures preserved in portions which escaped more complete melting. If this interpretation is correct, the metamorphic source rock must have been a limy, sandy argillite. The calcic plagioclase and the biotite and hornblende which occur along with it call for considerable alumina; otherwise alumina-poor calcium silicates should be expected. The source rock must also have been low in Mg, as the mafic content is low and no Mg-Ca silicates (such as diopside) were seen. If relict diopside existed in the rock, such as would be expected from a lime silicate, the hypothetic origin from a melted metamorphic rock would be greatly strengthened. No such relict pyroxene was seen, however.

With the evidence available at the present time, the origin of this interesting rock must remain in some doubt.

TECTONIC BRECCIAS

Tectonic breccias occur near the northern and southern borders of the area. Although the fragments of both the breccias are composed of the same rock types, they differ widely in the character of the matrix. The northern breccia occurs on the western slope of Red Mountain and will be referred to as the Red Mountain breccia. It occurs as a number of scattered patches of an irregular outcrop pattern. The southern breccia occurrence is best exposed in the Trinity Tunnel and drifts branching from it. It also occurs on the lower slope of Phelps Ridge near the St. Francis Mine and is here mostly covered by overburden except where it is well exposed for a short distance in the bed of a small stream. This breccia will be referred to as the Trinity breccia.

Both breccias are the result of tectonic movements along the contact of the porphyry bodies with the gneisses. The breccia in both areas consists of intermingled gneiss and porphyry fragments. The matrix of the northern breccia has formed from the fragments as the result of intense cataclastic action. The southern breccia, however, has a predominantly chloritic matrix.

Red Mountain Breccia

This breccia weathers to a dark gray color. On a fresh surface it is usually medium to light gray. It is relatively resistant, and erosional remnants form knobs and ridges which stand above the surrounding gneiss or porphyry (see Figs. 32 and 33). It contains both gneiss and porphyry fragments, sometimes in fairly equal amounts, although commonly one rock type predominates. Occasionally one rock type may occur exclusive of the other.

The fragments range in size from less than 1/4 inch to over five feet in diameter. Although commonly angular, the fragments are frequently well rounded (see Fig. 34).

In thin section the fragments are seen to be of the same composition as the parent rock, except that the plagioclase is considerably sericitized. In the porphyry fragments, sericitization of the labradorite has been combined with the formation of secondary epidote and/or small amounts of calcite. Feldspar

Fig. 32. Looking southwest to the "wall" of breccia forming part of the crest of Red Mountain.

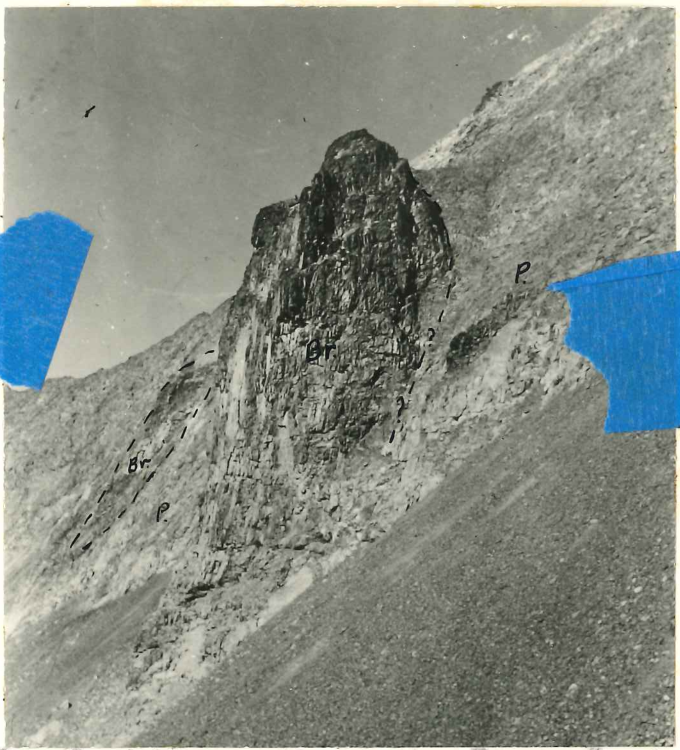

Fig. 33. Looking north at the "tower" of breccia on Red Mountain. The eastern contact of the breccia with the porphyry is shown by the dotted line (Br.-breccia; P-porphyry).

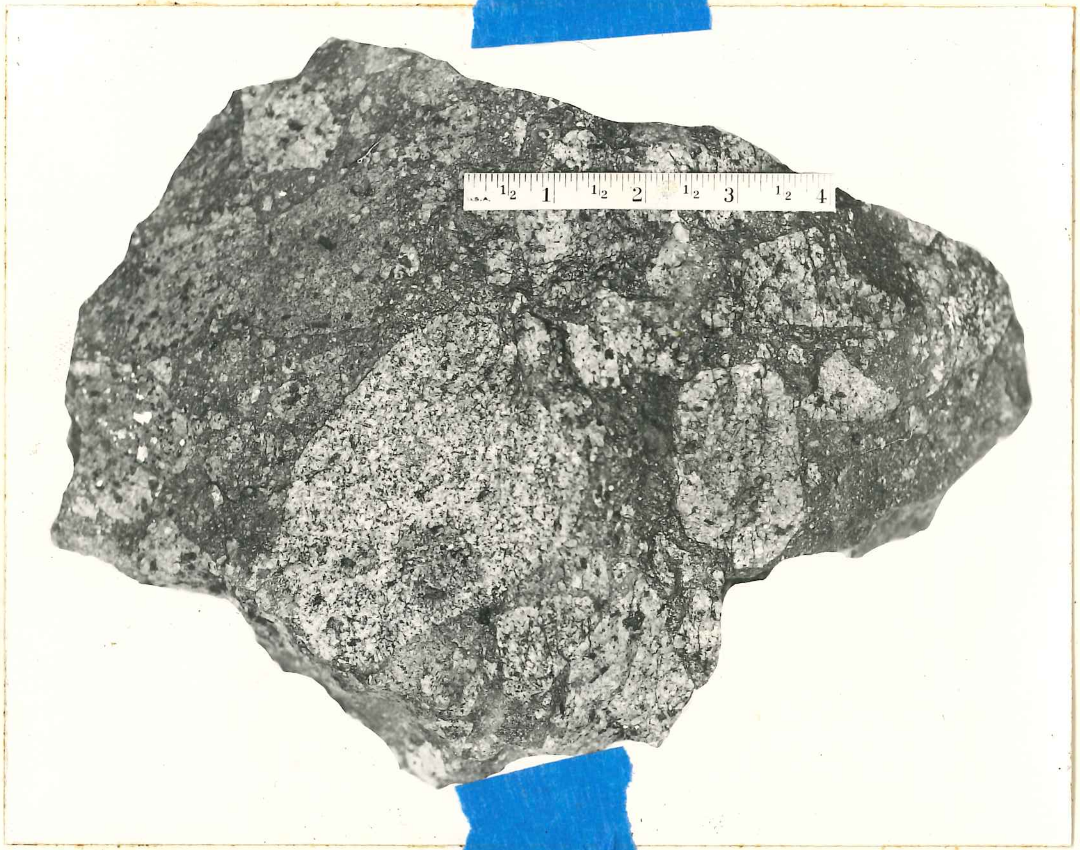

Fig. 34. Specimen of the Red Mountain breccia containing both rounded and angular fragments. Note the compact, fine-grained matrix.

crystals are occasionally bent or broken. The quartz of the porphyry fragments has recrystallized to clear grains with even extinction in some cases, but for the most part the textures are relatively unchanged from their original state. In the case of the gneissic fragments, textures also remain unchanged except for some recrystallization of quartz into clear aggregates. The andesine is considerably sericitized, and some epidote and clinozoisite have developed. Most of the biotite has been altered to chlorite.

The matrix is usually very dense and compact. It is extremely fine grained and is the product of intense cataclastic action. The matrix consists largely of quartz with accompanying chlorite and epidote, as well as finely granulated and sericitized feldspar fragments. Tourmaline has been introduced hydrothermally and locally occurs in considerable amounts as very fine needles which have grown in the matrix, particularly in chlorite but often in quartz and feldspar, also. The tourmaline frequently forms comb structures.

There has been some recrystallization of the matrix but not to a pronounced degree. Some quartz has recrystallized into clear aggregates, but most of it retains its wavy extinction and angular shape produced by fracturing. Locally chlorite forms large, fine-grained aggregates in which quartz has occasionally developed good crystal form, indicating later recrystallization, as do the clear quartz mosaic areas. Locally the quartz is fully recrystallized in the groundmass. There may have been some introduction of quartz into the matrix during brecciation.

The gneisses, granulites, and porphyry fragments have been sheared, mylonitized, and intermixed. With moderate recrystallization of the matrix, the borders of the fragments are often difficult or even impossible to distinguish under crossed nicols (see Fig. 35).

Although the breccia is in large part very compact with the matrix filling in all the space around the fragments, it is in some areas extremely vuggy. The vugs usually are three or four inches across, occasionally being as much as a foot across. Most of these vugs have well developed quartz crystals, averaging an inch in length, growing into them. Chlorite and epidote occasionally fill the smaller vugs. In a few cases considerable calcite, in aggregates of well formed crystals an inch or so across, has formed in the larger vugs.

Occasionally there is a suggestion of a directional element in the alignment of oblong, slab-like fragments. For the most part, however, the breccia is completely directionless.

Contacts of the breccia are in some places sharp and elsewhere, gradational. Figure 36 shows the contact of the breccia with the underlying porphyry. Here the porphyry is somewhat fractured, but the contact is sharp. In other places an unfractured porphyry is seen to become increasingly fractured

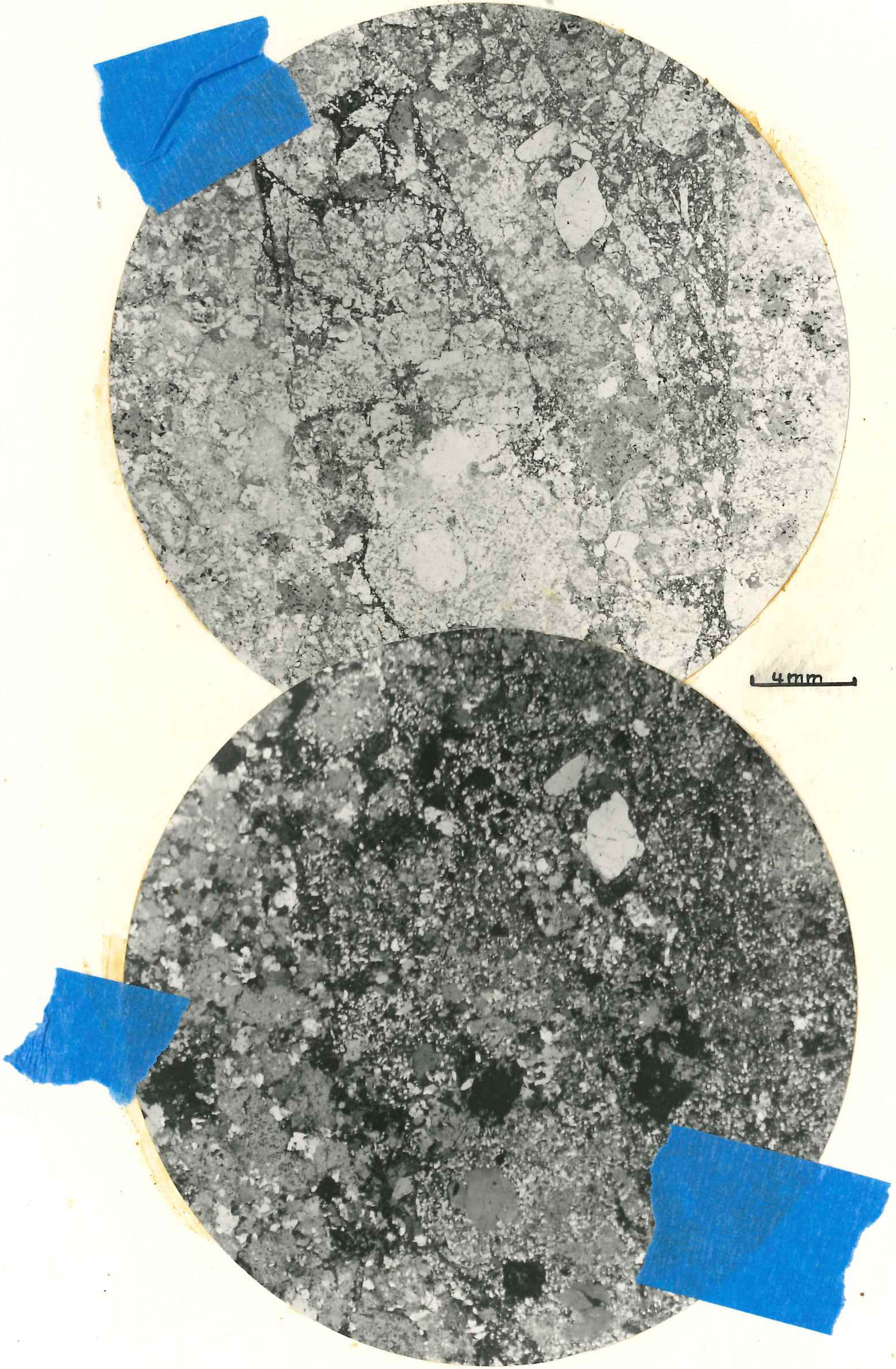

Fig. 35. Photomicrograph showing the mylonitic matrix of the Red Mountain breccia. Plane light and crossed nicols.

Fig. 36. The sharp contact of the breccia with the porphyry on Red Mountain is shown by the dotted line. The breccia overlies the porphyry, the contact being very sharp. Note the late small shear plane dipping to the south in the breccia (Br-breccia; P-porphyry).

over a distance of a few to a hundred feet or more, gradually passing into typical breccia. In such cases, it appears that with intense fracturing and sufficient movement the grinding action between fragments has produced the mylonitic matrix. The southern contact of the "wall" of breccia shown in Figure 32, which is the only large breccia occurrence on the crest of Red Mountain (cf. Plate 2), is both sharp and steep where it crosses the ridge top and angles southwesterly down the slope. The western contact of this area of breccia, however, is dipping at an angle only a few degrees less than that of the slope. The breccia unit here is seen to be a remnant of a large sheet which lies on the western slope of the mountain. Figure 33 shows the eastern contact between the northernmost area of breccia (cf. Plate 2) and the porphyry. Here the contact is also seen to be steep.

To the southwest of this "tower" of breccia, a strip of gneiss extending across the ridge from the east is seen to overlie the breccia locally. Due west from the "tower" of breccia, however, a small creek has exposed the gneiss-breccia contact for a hundred feet or more, and here the gneiss is seen to underlie the breccia. The gneiss, then, has been observed both to overlie and to underlie the breccia. In each of these cases, the contacts are of low dip and the breccia is believed to be essentially a gently dipping plate. Steep faults cross the breccia in a few places and have complicated the structural picture. There seems to have been some downfaulting locally, producing the steep contacts mentioned.

Wherever a breccia outcrop exists near gneissic country rock, the fragments usually are predominantly gneiss. Porphyry fragments predominate in those areas of breccia near a porphyry outcrop. A mixing of fragments is very common, however; and even in areas of breccia surrounded by porphyry, with fragments consisting mostly of porphyry, some gneissic fragments often exist. There has been sufficient movement to produce considerable mixing of fragments.

Trinity Breccia

This breccia exposed in the Trinity Tunnel is approximately 300 feet in width and, although difficult to trace on the surface, is thought to extend for a distance of at least 2,000 feet. The zone is vertical and occurs along the contact of the gneiss and porphyry. On the surface it weathers to a dark, somewhat iron-stained mass.

The fragments of the breccia consist of both gneiss and porphyry and have been highly altered. Hydrothermal solutions which deposited sulfide ore minerals in the breccia are thought to be the agent producing the alteration. The plagioclase in both rock types is completely sericitized, accompanied by the production of considerable calcite. The mafics have been leached out of the fragments, possibly being replaced by introduced quartz. The result is fragments which are now essentially quartz-rich, sericitic rocks. The quartz percentage is estimated to range from 80 to 90 per cent. It has recrystallized into clear crystals and aggregates with even extinction, often with numerous inclusions of sericite, and some chlorite. Other minerals in the fragments besides the sericite, quartz, and moderate amounts of calcite are minor amounts of such accessories as apatite and that part of the chlorite which has not been removed.

Unlike the Red Mountain breccia to the north, which has a dense matrix formed almost entirely by a crushing of the rock fragments, this breccia has a matrix consisting essentially of fine-grained chlorite, with some calcite and only minor amounts of crushed material (see Figs. 37 and 38). Sulfide ore minerals form the matrix locally (cf. Economic Geology, below). Frequently the chlorite (penninite occurring in radial clusters) has a large amount of associated calcite scattered through it, producing a patchy or mottled appearance in thin section. The amount of chlorite in the matrix is surprisingly large. It is estimated that at least 15 per cent of the breccia consists of the chlorite occurring in the matrix (see Fig. 39).

Occasionally quartz forms perfect crystals in the chlorite. Locally the matrix may be largely calcite. This local increase in calcite is more pronounced on the porphyry side of the breccia. The calcite forming from the sericitized

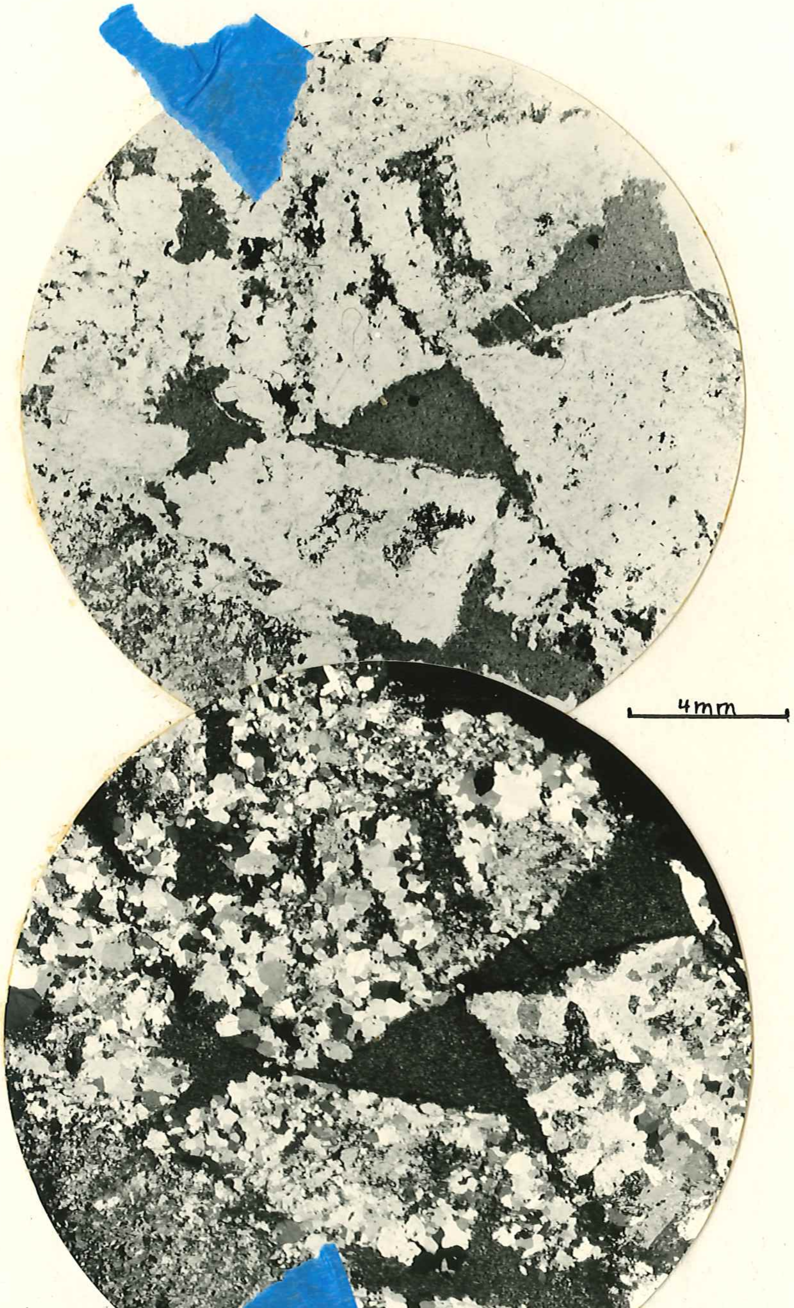

Fig. 37. Photomicrograph of the Trinity breccia showing the chloritic matrix. Plane light and crossed nicols.

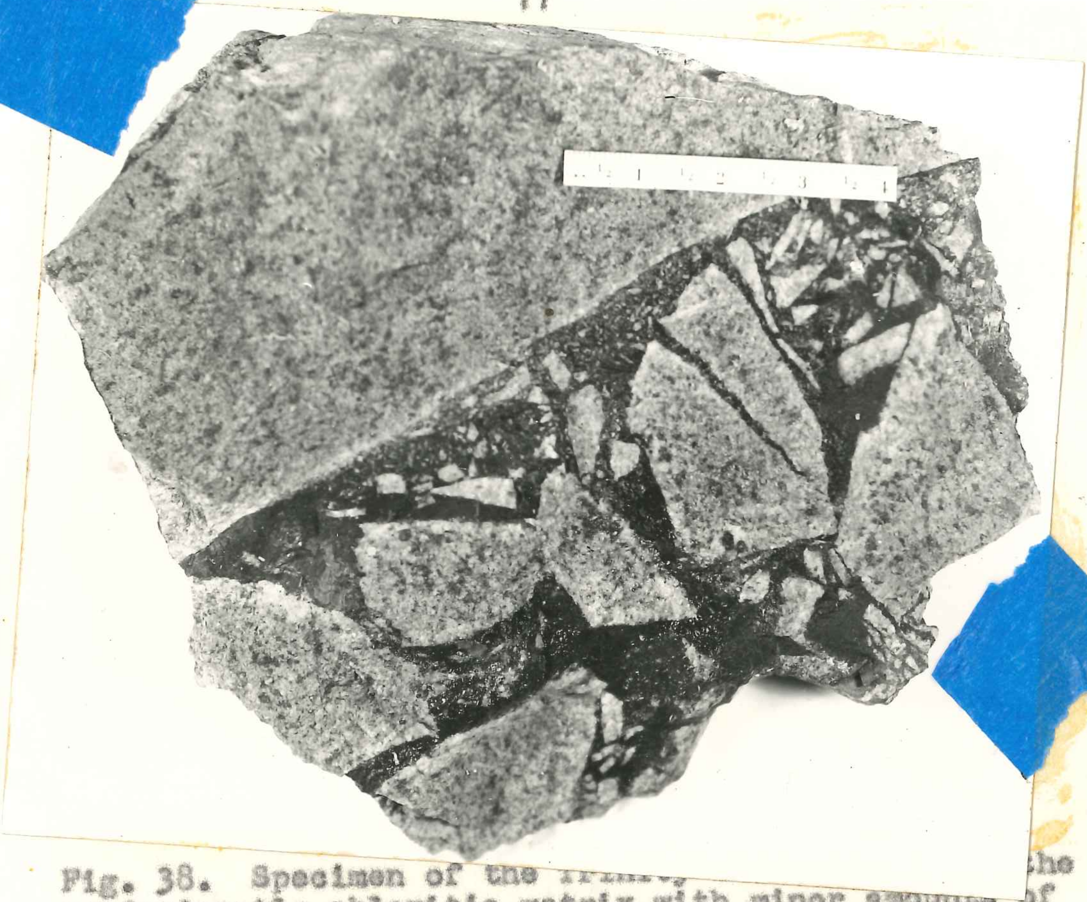

Fig. 38. Specimen of the Trinity, [illegible] the predominantly chloritic matrix with minor amounts of crushed rock fragments. Note the chlorite veinlet in the fractured fragment.

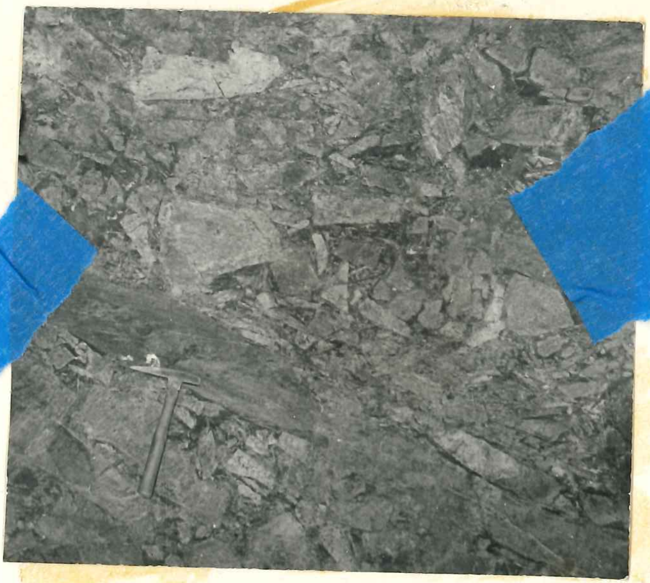

Fig. 39. Photograph of the Trinity breccia in the Red Mountain Mine, showing the large amount of chlorite in the matrix. Note the predominantly angular fragments.

plagioclase of the quartz labradorite porphyry fragments may account for much of this increase.

The contact of the breccia and gneiss in the Trinity Tunnel is fairly sharp. The breccia-porphyry contact is somewhat gradational, however, as it is to the north on Red Mountain. There has been some mixing and rounding of fragments, but for the most part the fragments are quite angular (see Fig. 39). They range in size from less than an inch to over four feet in diameter. Near the gneiss, the fragments are predominantly composed of gneiss and near the porphyry, mostly of porphyry. In the central portion of the breccia there is considerable mixing of fragments. This mixing probably reflects the approximate position of the original porphyry-gneiss contact.

Genetic Interpretation

The breccias described above are tectonic in origin, resulting from intense cataclastic action. In the case of the Red Mountain breccia, the intense crushing of the rocks has produced a mylonitic groundmass composed of finely crushed material from the breccia fragments. There has been a moderate amount of recrystallization but not enough to obscure the relationship between the fragments and the groundmass by any means. The Trinity breccia has not undergone the extreme crushing as was the case of the Red Mountain breccia. Rather than a mylonitic matrix, it has an introduced chloritic matrix.

From the cross-sections (see Plate 3) it can be seen that the Red Mountain breccia occurs only on the west side of Red Mountain. The breccia can be seen to be underlain by gneiss and porphyry. It occurs above these units as remnants of a plate, much of which has been eroded off. A thrust movement best explains the origin of this gently inclined plate of breccia. Because the porphyry is a distinctive rock type which occurs only in the area of the breccia, it is evident that the thrust movement which caused the fracturing and brecciation did not involve much displacement, or the porphyry fragments would have been carried away from the area and their place been taken by gneissic fragments from an adjacent area. The movement apparently was only sufficient to cause extensive rounding of part of the fragments and production of the mylonitized matrix. It may have been less than a few hundred feet.

The gradation from unfractured to highly fractured porphyry and finally to typical breccia observed at some places also suggests lack of any large displacement of the upper plate. Larger scale thrusting would have produced sharp boundaries between a thrust breccia and its substratum.

The breccia is thought to represent the approximate upper contact of the porphyry stock with its roof of gneiss, because fragments of both types are frequently intermingled and because locally the breccia was seen to be both overlain and underlain by gneiss.

On first observation the breccia with its tight, fine-grained matrix, and particularly its occurrence in the "tower"-like form, might lead one to believe that this is an intrusive breccia. However, the vuggy nature, the entirely mylonitic character of the matrix derived from the fragments themselves, the fact that no flowage of the matrix material can be observed, and the low-temperature mineral assemblage newly formed in the breccia all disprove such an interpretation.

The Trinity breccia with its chloritic matrix differs somewhat in origin from the Red Mountain breccia. The intrusive porphyry has been considerably fractured, as has the gneiss, but there has not been the extreme crushing and grinding action which produced the fine-grained matrix typical of the Red Mountain breccia. The lack of grinding up of fragments is probably due to the fact that this breccia occurs in a vertical fracture zone in which actual displacement apparently was insignificant and along which no very intense compressional action occurred.

The chlorite in the matrix of the Trinity breccia can be attributed in part to the alteration of the fragments and the transfer of the chlorite into the open spaces of the breccia. The fragments have lost the major portion of their mafics, but these may not have been precipitated as chlorite immediately next to the individual fragments. Much of the chlorite has probably been carried up from altered fragments at depth by hydrothermal solutions. That these ascending solutions were relatively hot (in terms of ore zones) can be shown by the fact that hypothermal ore minerals such as scheelite and molybdenite, as well as considerable pyrrhotite, were deposited in the breccia (cf. Economic Geology, below). Sericitization has produced some calcite from the plagioclase, and this probably has greatly contributed to the calcite of the breccia cement. Much of the chlorite and calcite may be of a strictly hydrothermal origin, however, brought up from great depth by the ore bearing solutions.

The great quantity of chlorite of the matrix, then, is considered to be derived primarily from alteration of the breccia fragments and concentrated in the zone exposed by the Trinity Tunnel where the hydrothermal solutions were cooled.

The intrusion of the porphyry masses probably prepared the way for the brecciation by causing extensive fracturing. The porphyry itself is a brittle rock forming a resistant knot from a regional standpoint, and it is not surprising that the brecciation has been concentrated between the resistant gneiss and the brittle porphyry.

The age of brecciation can only be said to be later than the intrusion of the quartz labradorite porphyry, inasmuch as both gneiss and porphyry form the breccia fragments. The specific time cannot be determined but may have been during the Cretaceous or Tertiary tectonic movements of the Cascades.

TERTIARY(?) DIKES

Fine-grained basic dikes have intruded both the gneisses and the quartz labradorite porphyry. These dikes consist of plagioclase and hornblende or biotite, with quartz occurring only in minor amounts. The plagioclase occurs partly as euhedral laths and partly as subhedral to anhedral crystals, the average grain being about 0.20 mm in length. The plagioclase often has a pronounced normal zoning ranging in composition from labradorite, An_{53}, to oligoclase, An_{22}. The hornblende, averaging about 0.20 mm in size, is subhedral to anhedral and occupies the spaces between the earlier formed plagioclase crystals, thus constituting a diabasic texture. The hornblende is often partially altered to biotite.

Most of the dikes have a width of 5 or 10 feet, although the largest one seen has a maximum width of approximately 70 feet. The dikes commonly have an east-west strike, although a few strike north-south. All of them have steep dips ranging from 55 degrees to vertical.

Tertiary dikes are common in the northern Cascades, and it is presumed that these dikes are also of Tertiary age. This cannot be definitely established, however, since they only intrude considerably older rocks.

ECONOMIC GEOLOGY

ST. FRANCIS MINE

The discovery of the St. Francis ore body was made on the eastern slope of Phelps Ridge, in a small stream bed which exposes the breccia referred to as the Trinity breccia. It has been described in the preceding section on Tectonic Breccias. A short crosscut about 40 feet in length was driven into the breccia at the discovery point. This location is near the eastern contact of the breccia with gneiss. The St. Francis Mine was established as a result of this discovery at a point about 200 feet down the slope, 3,800 feet above sea level. It is located only a short distance above the valley floor of Phelps Creek.

The portal of the St. Francis Mine was caved at the time of this investigation and could not be entered. According to information obtained from the files of the Washington State Division of Mines and Geology, however, the mine consists of an adit about 650 feet in length, trending approximately S42W, and a 350-foot drift driven about N40W from the crosscut, at a point 460 feet from the portal. The country rock in the adit for the first 192 feet from the portal is the quartz labradorite porphyry previously described. Beyond this point the adit is in the breccia. The breccia consists of porphyry fragments for approximately 100 feet, beyond which most of the fragments are in gneiss. The breccia zone in the St. Francis Mine is about 250 feet wide. The ore occurs in the matrix of this breccia. No large concentration of ore minerals was reported.

RED MOUNTAIN (ROYAL) MINE

Following the development work in the St. Francis Mine, the Trinity adit of the Red Mountain Mine was driven by the Royal Development Company, the object being to cut the St. Francis ore body at depth and to provide a transportation tunnel. The adit strikes N18E for 10,020 feet where it turns to N55E, ending at 10,957 feet. It is connected with the St. Francis Mine by an 850-foot raise at a distance of 10,644 feet from the portal. A number of drifts have been driven to the southeast in the breccia from the main transportation adit (see Plates 3 and 4).

The underground mapping was done by compass and tape and was of a reconnaissance nature rather than detailed, the main purpose being to study the breccia zone because it is poorly exposed on the surface.

Chalcopyrite constitutes the chief ore mineral of the Red Mountain Mine, and, as mentioned above, the ore occurs in the breccia which has been referred to above as the Trinity breccia. The breccia zone is here 300 feet in width. The sulfides form part of the matrix of the breccia and have in part replaced the breccia fragments. Huntting (1943) reports an assay of a trace to 1.9 per cent copper, 0.61 to 5.38 per cent silver, and a little gold per ton.

A 250- to 500-ton mill was constructed in 1930, but had only a small amount of production that year. Some ore was taken out in 1935, 10,000 tons of ore were milled in 1936, and 5,825 tons in 1937. The mine was closed on March 1, 1937, and has not been operated since then. According to hearsay, most of the production came from the 150-foot level which was not accessible during the investigation.

The metallic minerals in the ore zone of the breccia exposed by the Trinity adit and adjoining drifts consist predominantly of pyrrhotite and chalcopyrite with associated sphalerite, pyrite, arsenopyrite, galena, and very small amounts of molybdenite. Scheelite was discovered in 1943 by the Washington State Division of Mines and Geology as reported by Huntting (1943). It occurs as small grains scattered throughout the breccia but not in commercial quantities. The pyrrhotite and chalcopyrite have formed in the matrix with the chlorite and calcite, occasionally as roughly orbicular masses 1 to 2 or more inches in diameter (see Fig. 40). The occurrence of pyrrhotite and molybdenite places the ore body in a high-temperature or hypothermal classification.

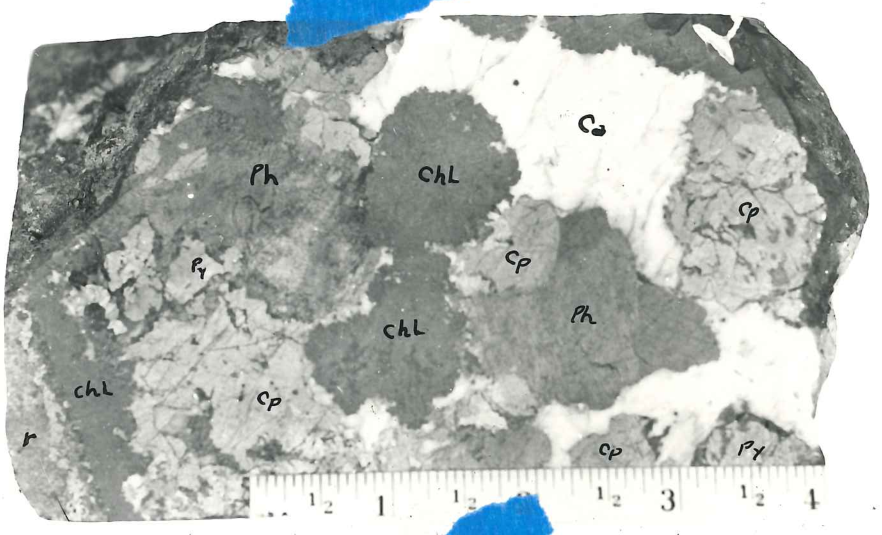

Fig. 40. Photograph of an ore sample from the Red Mountain Mine. The sulfides occur as part of the matrix of the Trinity breccia, sometimes forming the roughly orbicular masses shown above. The sulfides have mostly replaced calcite without affecting the chlorite to any extent. (Ca-calcite; Chl-chlorite; Cp-chalcopyrite; Ph-pyrrhotite; Py-pyrite; r-rock fragment).

The sequence of events in the ore zone is relatively complex. The brecciation and the alteration of the fragments, as well as the production of the chloritic matrix, have been described in the section on Tectonic Breccias. Either during or after this alteration, sulfide bearing solutions entered the breccia, and pyrrhotite associated with chalcopyrite was deposited in the open spaces as well as replacing the carbonate and locally the rock fragments. According to Richarz (1933), the pyrrhotite and chalcopyrite were followed by quartz and arsenopyrite. No polished sections were made, and the time of deposition of the other sulfides has not been determined.

The chlorite and carbonate are closely associated and it appears that they were deposited first, inasmuch as the carbonate, and possibly some of the chlorite, has been replaced by the sulfides. The large amount of chlorite may be the product of alteration of the breccia fragments over a considerable vertical extent by hydrothermal solutions which transported it into the zone of the Trinity adit.

As mentioned above, the main ore body of the Red Mountain Mine occurs at the 150-foot level which was inaccessible at the time of the present investigation, and the factors controlling the ore deposition are not known here. The limited amount of ore in the level of the transportation tunnel seems to favor replacement of carbonate. Whether or not this is generally true of the larger ore body cannot be said. Without more information on the controls of ore deposition, predictions as to the possible occurrence of other ore bodies cannot be made. All that can be said is that the large brecciated zone is a favorable place for ore deposition.

PROSPECTS

There are a number of prospects in the thesis area, two of which are located on the eastern slope of Phelps Ridge. One of these is situated near the head of Phelps Creek; it consists of a 441-foot adit driven S65W in the amphibolite and migmatitic hornblende gneiss described above. Little or no mineralization was observed. This prospect hole is believed to have been driven by the Una Mining Company.

The other prospect on the eastern slope of Phelps Ridge, the Leprechaun Mine, is located near the confluence of Phelps and Leroy Creeks, at an elevation of 4,150 feet. The portal was caved at the time of the visit and could not be entered. From the size of the dump, it is estimated that there are over 1,500 feet of workings. No appreciable amount of mineralization was observed in the waste rock, although there is considerable iron staining.

A number of prospects are located on the upper western slope of Red Mountain. One of these, the Midnight Queen, is located in the porphyry on a tourmaline zone. It consists of an adit 146 feet long, trending N75E. The tourmaline zone is

2-1/2 feet wide at the portal but pinches and swells along the adit. It narrows to a few inches in width about 50 feet from the face and finally disappears into the wall rock to the south. Investigation with a fluorescent light showed the tourmaline to have an appreciable amount of scheelite. The scheelite is scattered throughout the tourmaline as small grains, in places forming aggregates one or two inches in area. It apparently was introduced hydrothermally in association with the tourmaline, and very little occurs within the porphyry itself. The prospecting should therefore be confined to the tourmaline zone. This zone is of relatively small extent and probably does not contain sufficient volume of scheelite for appreciable commercial production.

A few shallow prospect pits and short adits are located in small concentrations of chalcopyrite occurring within the porphyry and breccia of Red Mountain. In all the occurrences, arsenopyrite is the major constituent. There are no areas of copper mineralization which appear to be worthy of further development.

GLACIATION

The last major event in the geologic history of the area was Pleistocene glaciation. Both the Chiwawa and the Phelps Creek valleys are typically U-shaped (see Fig. 41). I. C. Russell (1900) first reported on the glaciation of the area and named the glacier the "Chiwahwah" glacier. Glaciers from the Chiwawa, Phelps, and Buck Creek valleys joined to form this glacier, which flowed 30 miles down the Chiwawa valley to the vicinity of Fish Lake where it became a tributary of the Wenatchee glacier. Russell states that the Chiwawa glacier was 1-1/2 miles in width and 2,000 feet thick in the lower 10 miles of its course.

The Chiwawa glacier had its source in part in the Chiwawa Basin, a large amphitheater about 2-1/4 miles across at its crest. Small amounts of glacial debris exist in both the Chiwawa and Phelps valleys. In places the Chiwawa River has cut through this debris into bedrock. Phelps Creek, a smaller stream, has not yet cut through the glacial material.

A bench and shoulder type of topography occurs locally at an elevation of approximately 5,500 feet, about 1,000 feet above the floor of the upper Chiwawa and Phelps valleys (see Fig. 42). A cirque on the western side of the Chiwawa valley,

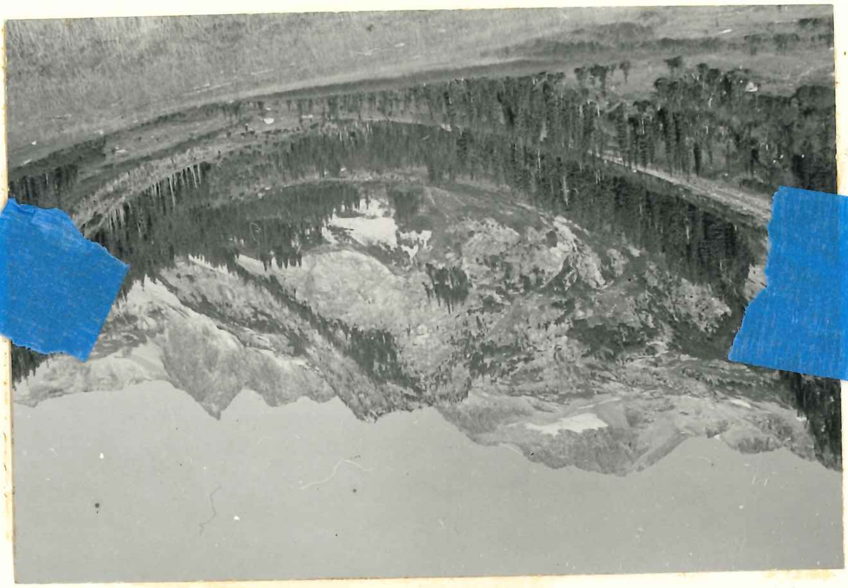

Fig. 41. Looking north along the U-shaped valley of Phelps Creek.

Fig. 42. Looking south along the Phelps Creek valley, showing its local glacial produced bench and shoulder topography in the lower left corner of the photograph.

in which Massie Lake occurs, has its floor at an elevation 1,600 feet above that of the valley floor. Across the valley from Massie Lake an incipient cirque was formed at an elevation 1,000 feet above the valley floor.

The topography of this area suggests that during the maximum period of glaciation only the higher ridge tops stood above the glacier. The bench and shoulder topography and cirque development may represent either a waning or sub-stage of the Wisconsin glaciation, or possibly the highest level of Wisconsin glaciation.

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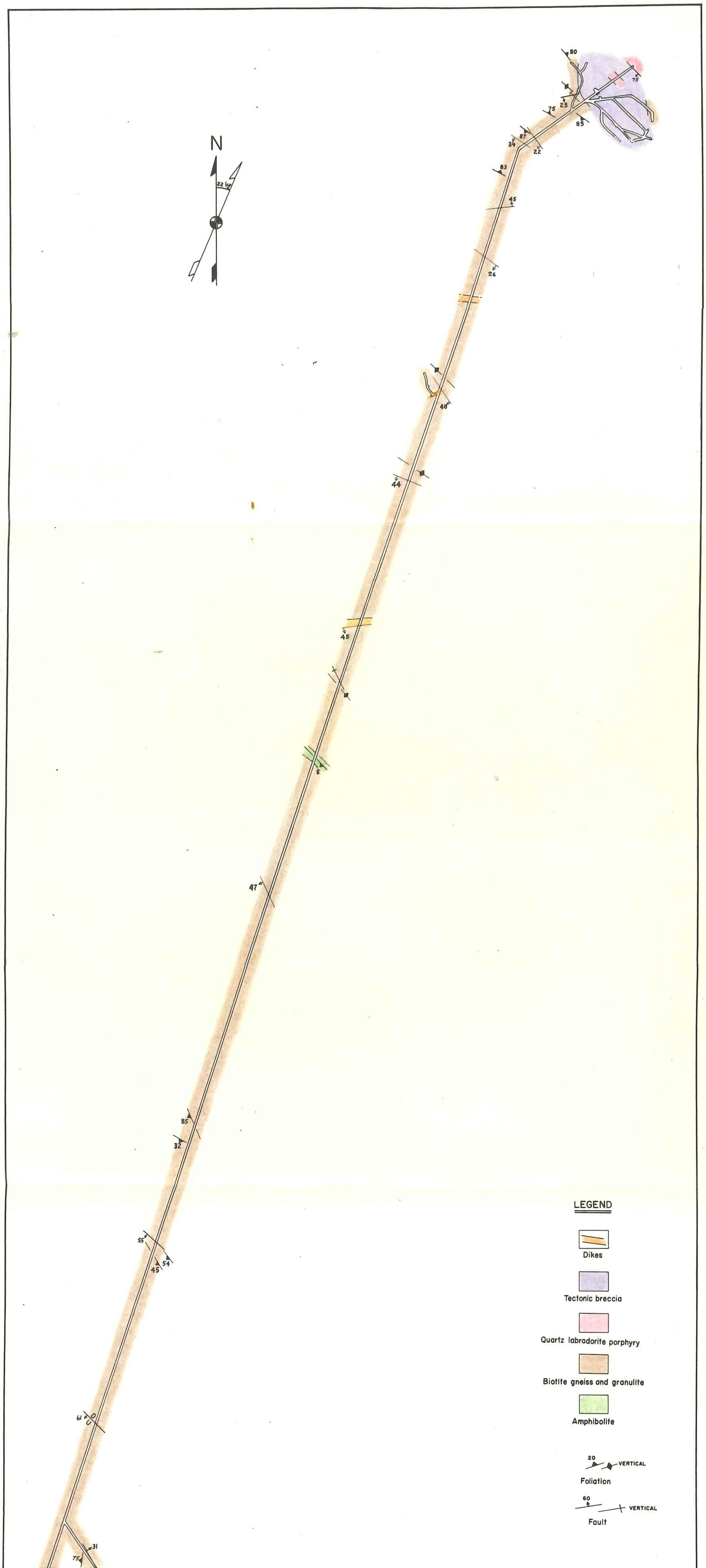
PLATE 4


N
22½°
80
75
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83
45
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8
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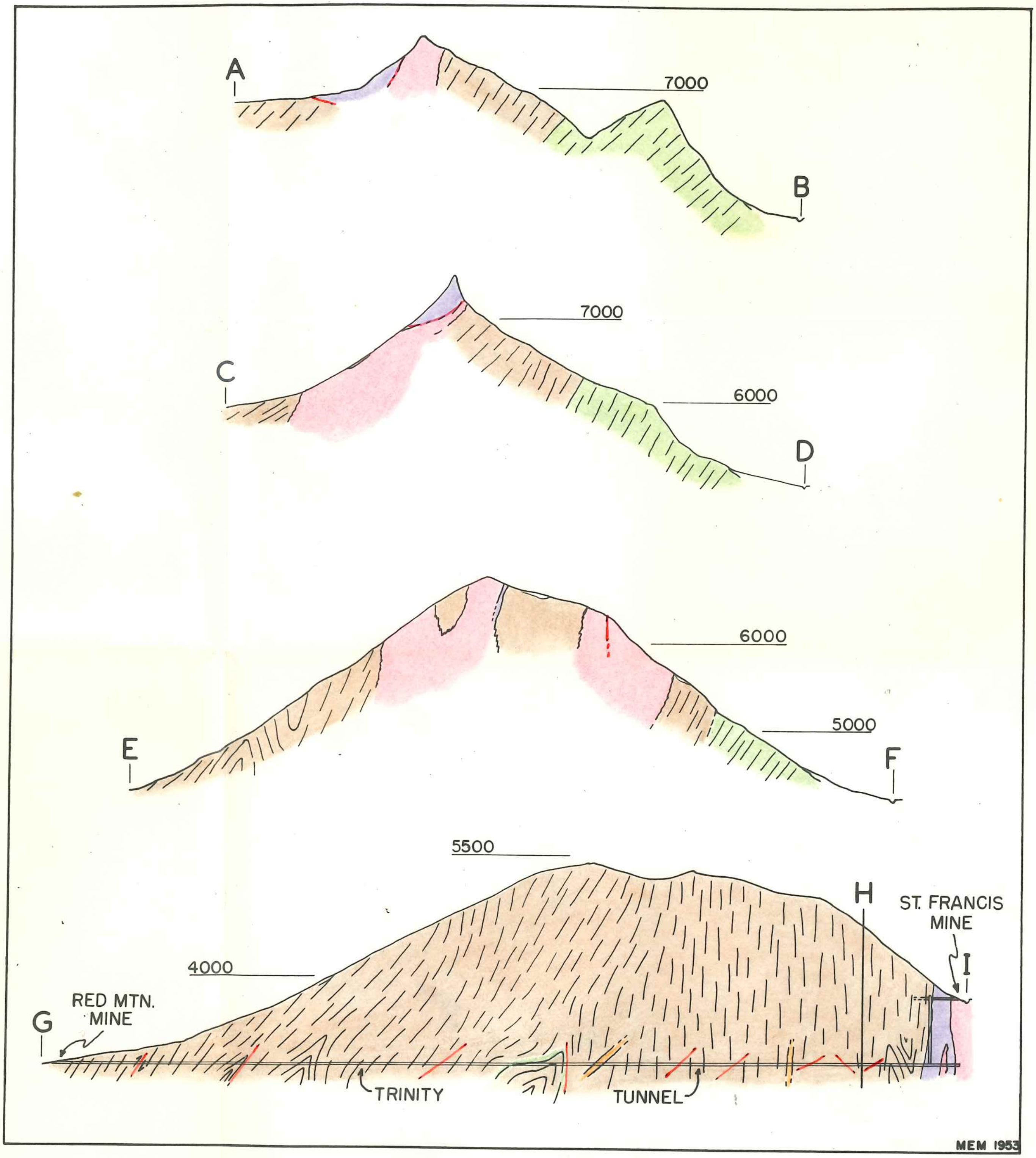
85
32
55
54
45
61
D
U
31
75
LEGEND
Dikes
Tectonic breccia
Quartz labradorite porphyry
Biotite gneiss and granulite
Amphibolite
20
VERTICAL
Foliation
60
VERTICAL
Fault

PLATE 3



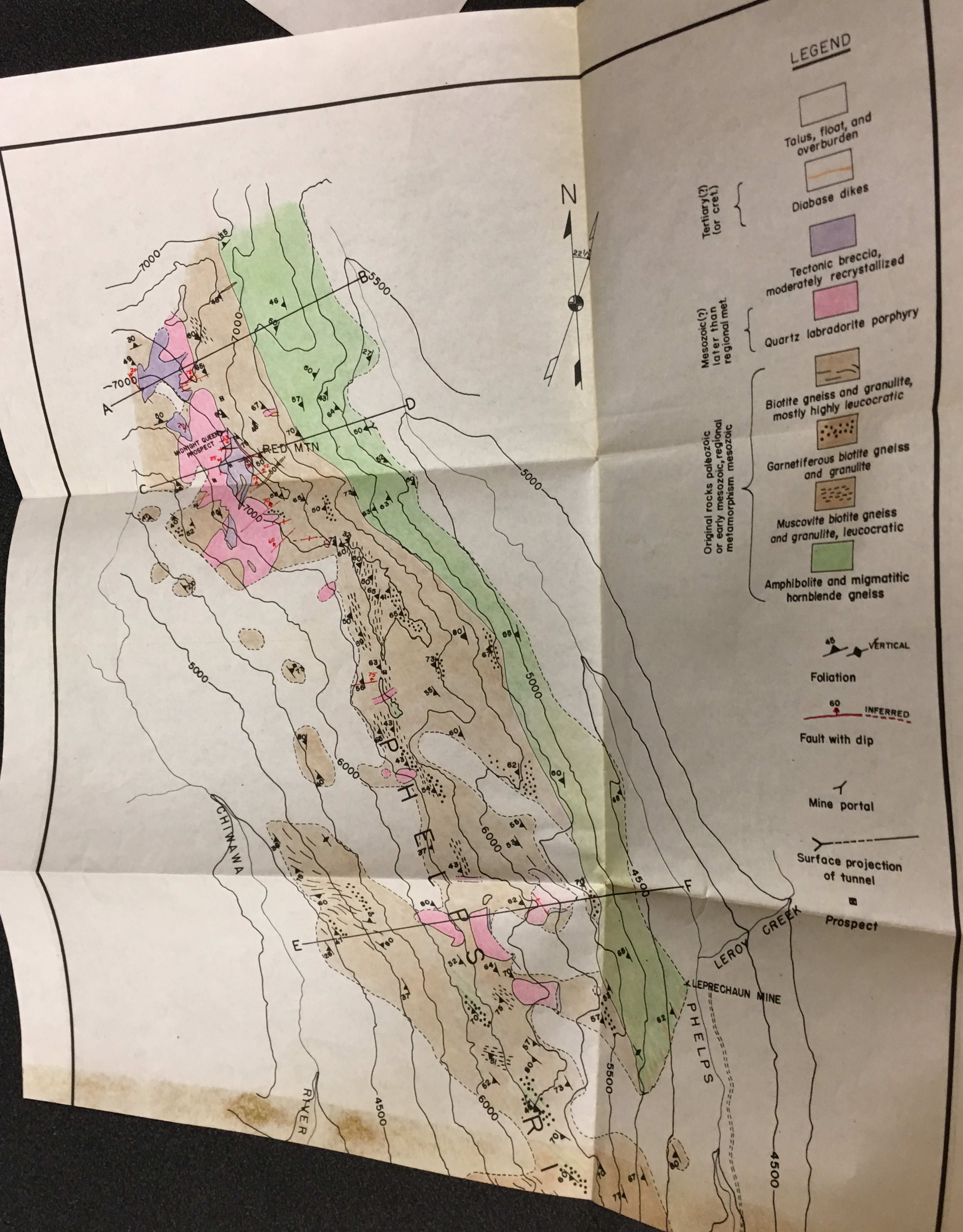
GEOLOGIC SECTIONS OF PHELPS RIDGE - RED MTN. AREA

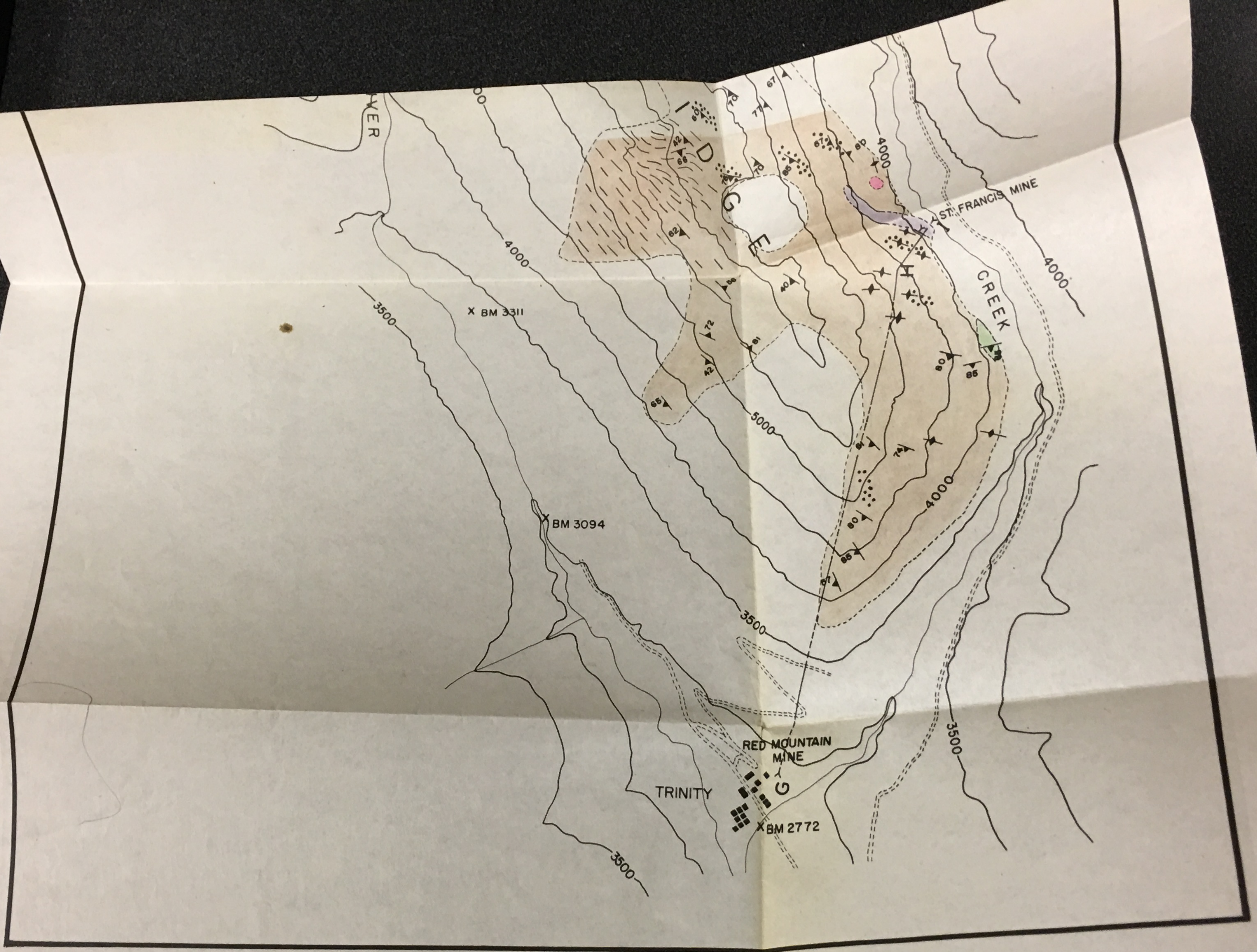
SCALE

SAME SCALE AS MAP

(SEE MAP FOR LEGEND)

PLATE 2


LEGEND
Talus, float, and overburden
Tertiary(?) (or cret.)
Diabase dikes
Tectonic breccia, moderately recrystallized
Mesozoic(?) later than regional met.
Quartz labradorite porphyry
Original rocks paleozoic or early mesozoic, regional metamorphism mesozoic
Biotite gneiss and granulite, mostly highly leucocratic
Garnetiferous biotite gneiss and granulite
Muscovite biotite gneiss and granulite, leucocratic
Amphibolite and migmatitic hornblende gneiss
45
VERTICAL
Foliation
60
INFERRED
Fault with dip
Mine portal
Surface projection of tunnel
Prospect
N
22½°
A
B
C
D
E
F
MIDNIGHT QUEEN PROSPECT
RED MTN
P H E L P S
R I
CHIWAWA
RIVER
PHELPS
LEROY CREEK
LEPRECHAUN MINE
7000
5500
5000
6000
4500



GEOLOGIC MAP OF PHELPS RIDGE - RED MTN. AREA

CHELAN COUNTY, WASH.

BY

M. E. MORRISON

SCALE

0 1/8 1/4 1/2 3/4 1 MILE

CONTOUR INTERVAL 500 FEET

1953

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

UNITED STATES
DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS

HOLDEN QUADRANGLE
WASHINGTON
15 MINUTE SERIES (TOPOGRAPHIC)

Mapped, edited, and published by the Geological Survey
Control by USGS
Topography from aerial photographs by multiplex methods
Aerial photographs taken 1944
Polyconic projection. 1927 North American datum
10,000-foot grid based on Washington coordinate system, North zone

TRUE NORTH
MAGNETIC NORTH
22½°
APPROXIMATE MEAN DECLINATION, 1946

SCALE 1:62500

1 ½ 0 1 2 3 4 MILES

3000 0 3000 6000 9000 12000 15000 18000 21000 FEET

1 .5 0 1 2 3 4 5 KILOMETERS

CONTOUR INTERVAL 100 FEET
DASHED LINES REPRESENT HALF-INTERVAL CONTOURS
DATUM IS MEAN SEA LEVEL

FOR SALE BY U. S. GEOLOGICAL SURVEY, WASHINGTON 25, D. C.

ROAD CLASSIFICATION

HARD-SURFACE ALL WEATHER ROADS
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Medium-duty 4 LANE | 6 LANE
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DRY WEATHER ROADS
Improved dirt
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