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Metamorphism and the Origin of the Granitic Rocks in the Northgate District, Colorado

by

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This report and accompanying illustrations are preliminary and have not been edited or reviewed for conformity with U. S. Geological Survey standards and nomenclature.

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ABSTRACT

The Northgate district is in Jackson County, Colorado, near the northern end of North Park, a broad intermontane basin between the Medicine Bow Mountains and the Park Range of the southern Rocky Mountains. The district is largely on the western flank of the Medicine Bow Mountains, but also includes the northeast corner of North Park.

The pre-Cambrian rocks in the Northgate district consist of a gneiss complex invaded by a granitic stock. A few andesite porphyry dikes cut the gneiss complex and are older than the stock.

Regional metamorphism converted the parent rocks of the gneiss complex into a hornblende-plagioclase gneiss (hornblende gneiss), and was closely followed by widespread metasomatic transformation. Alkali and silica metasomatism converted relatively large masses of hornblende gneiss to quartz monzonite gneiss in the northern and southeastern parts of the district; smaller bodies of quartz monzonite gneiss were formed through the central part of the district where they are associated with abundant pegmatite having similar replacement relations. Biotite-garnet-quartz-plagioclase gneiss (biotite-garnet gneiss) is a common associate of the pegmatite and was formed by local hydrothermal metamorphism of hornblende gneiss in a zone peripheral to the main zone of alkali metasomatism. Hydrothermal metamorphism of small ultramafic bodies developed a number of zoned deposits of chlorite, tremolite-actinolite, and vermiculite.

Shearing during and after granitization reduced much of the rock in the gneiss complex to mylonite along an east-trending zone in the vicinity

of Pinkham Creek. Farther north, where shearing was less intense, only hornblende gneiss was much affected and irregular bodies of hornblende-biotite-quartz-plagioclase gneiss (hornblende-biotite gneiss) were formed.

Some quartz monzonite gneiss in the large bodies in the northwest and southeast parts of the district became mobile after transformation and invaded the surrounding rocks. Relations are clearest near the northwest corner of the district where a funnel-shaped mass more than a mile in diameter forcibly injected and greatly deformed the adjacent rocks.

Several fine-grained andesite porphyry dikes cut the gneiss complex in the vicinity of lower Camp Creek; they definitely are older than the quartz monzonite in the stock. The dikes follow tension fissures that do not conform to the structural pattern shown by the gneiss complex, and the andesite porphyry is believed to be unrelated to the other pre-Cambrian rocks in the district.

Intrusive quartz monzonite forms a stock and associated dikes in the central part of the Northgate district and several related dikes near the eastern edge of the district. As similar rocks, called Sherman granite, are common in the Rocky Mountains of southern Wyoming and northern Colorado, the stock is believed to be a cupola on a much larger underlying body. The original magma, which was dioritic or quartz dioritic in composition, made way for itself by magmatic stoping. After solidification, the dioritic rock was brecciated and invaded by alkali- and silica-bearing late magmatic solutions that converted the main body of the stock into a biotite quartz monzonite. Much of the biotite in the peripheral parts of the stock was chloritized, and the plagioclase here is significantly more sodic than that in the central part of the stock. Wall-rock alteration was minor.

INTRODUCTION

This report deals largely with the progressive regional, metasomatic, and dynamic metamorphism, culminating in local rheomorphism, of a layered series of rocks, and with the later, unrelated emplacement of a dioritic stock and the deuteric alteration of this rock to quartz monzonite. All of these metamorphic and igneous rocks are of pre-Cambrian age; they comprise about two-thirds of the rocks exposed in the Northgate district, Colorado.

The Northgate district is in Jackson County, Colorado, near the northern end of North Park, a broad intermontane basin between the Medicine Bow Mountains and the Park Range of the southern Rocky Mountains (see Fig. 1). The district is largely on the western flank of the Medicine Bow Mountains, but also includes the northeast corner of North Park. The area covered by this report — about 65 square miles — is bounded on the north by the Colorado state line, on the west by the North Platte River, on the south by the township line between T. 10 N. and T. 11 N., and on the east by the range line between R. 78 W. and R. 79 W., sixth principal meridian.

This report presents part of the results of an investigation by the U. S. Geological Survey centering on the fluorspar deposits of the district. The work began in 1943 as a Strategic Minerals Investigation, when D. C. Cox, assisted by J. O. Fisher and J. W. Odell, made a preliminary study of the larger fluorspar deposits of the area. The vein zones were studied in more detail during 1944 and 1945 by D. C. Cox and W. E. Benson, assisted by D. M. Henderson. The writer visited the area briefly during the winter of 1945-1946, and spent about 11 months during the field seasons of 1946, 1947, and 1948 studying the regional geology and fluorspar deposits. R. B. Johnson,

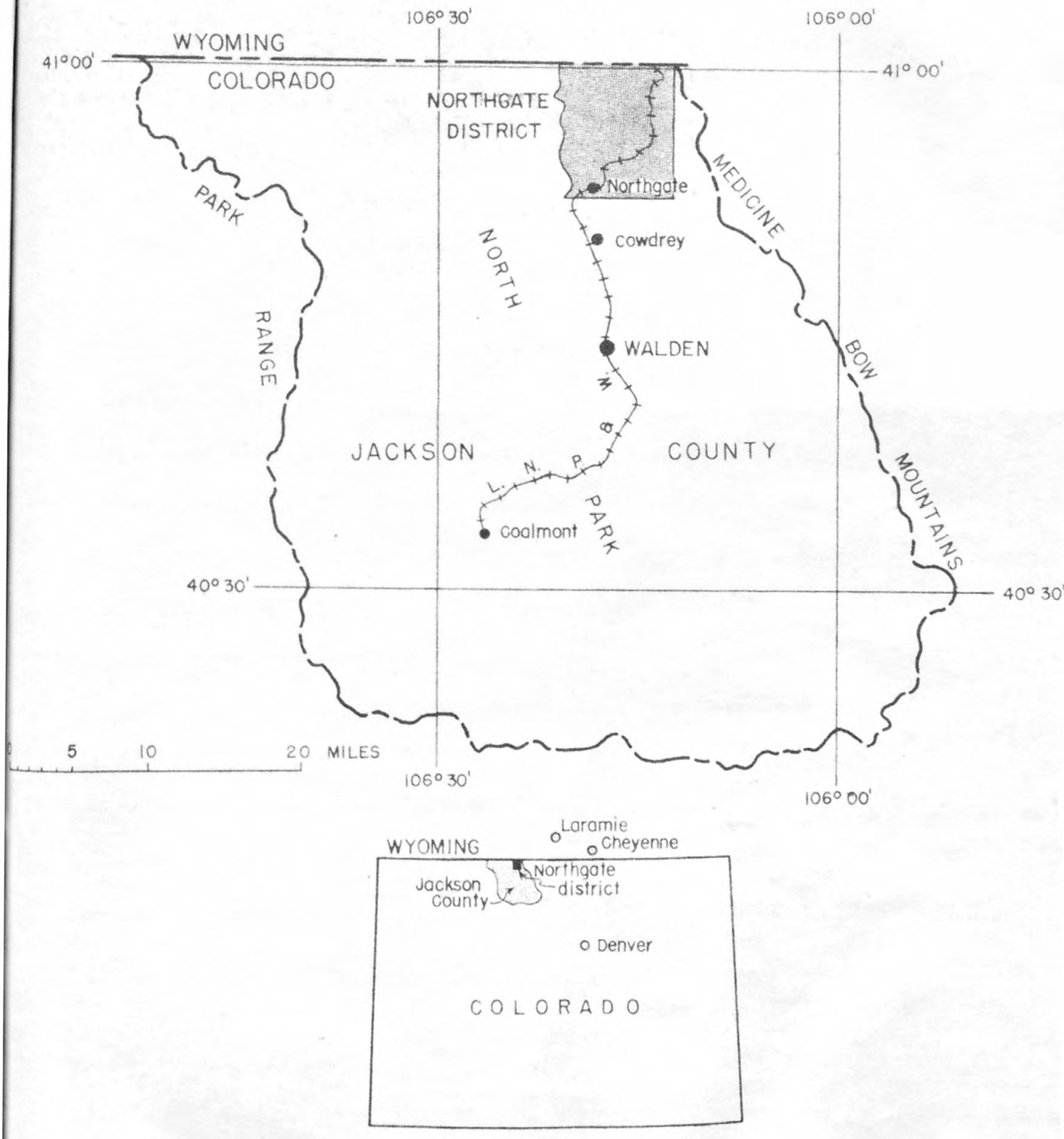

FIGURE I. INDEX MAP SHOWING THE LOCATION OF THE NORTHGATE DISTRICT, COLORADO

This map is preliminary and has not been edited or reviewed for conformity with U. S. Geological Survey standards and nomenclature.

A. L. Bush, and G. W. Weir assisted in this work. The results of a U. S. Bureau of Mines exploratory program were published in 1947 (Warne, 1947), and geologic maps of the fluorspar deposits and a brief preliminary report were issued by the Geological Survey in 1948 (Cox, et al., 1948).

Prior to the present investigation, almost no detailed geologic work had been done on the pre-Cambrian rocks in the vicinity. The broader features of North Park and the surrounding mountains were described briefly in 1877 by Hague (1877, pp. 94-141) as part of the general reconnaissance carried out between 1867 and 1873 by the U. S. Geological Exploration of the Fortieth Parallel. The coal resources and general geology of North Park were described by Beekly (1915), and although the report was based on only one season of field work that was done without an adequate base map, it is still the most complete account of the geology of North Park. In 1934, Miller (1934) published the results of a more detailed study of the McCallum anticlines in east-central North Park. The fluorspar deposits have been described briefly by Ladoo (1923, pp. 28-31, 1927, pp. 116-119), Burchard (1933, pp. 12-14), Cox (1945, p. 277), and Cox et al., (1948). A note on the mineralogy of one of the fluorspar deposits was published by Goldring (1942, pp. 717-719).

At the time of field work there was no adequate base map covering the Northgate district. Therefore the writer did most of the regional mapping on enlarged U. S. Forest Service aerial photographs taken in 1937; some mapping in 1948 was done on aerial photographs taken for the Geological Survey in 1947. Section corners set during the General Land Office resurvey made in 1938 and 1939 were located in the field, and a planimetric map was constructed using the General Land Office township plats for control. Unfortunately the resurvey did not cover the northern part of the Northgate district, and here the radial line method was used for map compilation. Control along the northern edge of the map area is based upon the Colorado state line which was located in the field.

ACKNOWLEDGMENTS

On behalf of the U. S. Geological Survey geologists who have taken part in this investigation, the writer expresses appreciation for the help and cooperation given by the staffs of Kramer Mines, Inc., Western Fluorspar Corp., and Colorado Fluorspar Corp. Requested information was freely given, and living accomodations were furnished, first by Western Fluorspar Corp. and later by Colorado Fluorspar Corp. The writer is especially appreciative of the many courtesies shown by M. P. Cloonan, Resident Manager, and C. E. Mitchell of Colorado Fluorspar Corp.

The writer spent several profitable days reviewing the fluorspar deposits with R. E. Van Alstine, of the U. S. Geological Survey, during the summers of 1946 and 1948. Two days spent in the company of P. O. McGrew and S. H. Knight of the University of Wyoming contributed greatly to the writer's understanding of the Tertiary stratigraphy of the area. A. H. Koschmann, M. N. Bramlette, Q. D. Singewald, and Ogden Tweto, all of the U. S. Geological Survey, each spent a day in the Northgate district reviewing the general geology.

The help and stimulation received from many discussions with fellow graduate students and members of the faculty of the Department of Geology, University of California, Los Angeles, are gratefully acknowledged. The report was prepared under the guidance of Prof. James Gilluly, who critically read the manuscript.

Pre-Cambrian rocks

The pre-Cambrian rocks in the Northgate district consist of a gneiss complex invaded by a granitic stock. A few andesite porphyry dikes cut the gneiss complex and are older than the intrusive stock. The rocks of the gneiss complex were formed under progressively changing conditions of metamorphism during a single orogenic period. Regional metamorphism converted the original rock to a hornblende-plagioclase gneiss (hornblende gneiss), which later was transformed by shearing and metasomatic replacement into various biotite- and quartz-bearing gneisses and schists and into quartz monzonite gneiss and pegmatite. The chief agents of metasomatic transformation were alkali- and silica-bearing solutions which permeated the hornblende gneiss during a period of shearing that closely followed regional metamorphism. Some of the rock in the larger bodies of quartz monzonite gneiss became mobile after most of the metasomatic transformation.

Several fine-grained andesite porphyry dikes cut the gneiss complex near lower Camp Creek; They definitely are older than the granitic stock and apparently are unrelated to the other pre-Cambrian rocks in the district.

A stock and associated dikes composed of quartz monzonite cut the gneiss complex in the central part of the district, and several related dikes occur near the eastern edge of the district. The abundance of similar rocks, called Sherman granite, in the Rocky Mountains of northern Colorado and southern Wyoming indicates that the stock is probably a cupola on a much larger underlying body. The rock was emplaced as a dioritic magma which made way for itself by magmatic stoping. After the dioritic rock solidified it was brecciated and then invaded by alkali- and silica-bearing late magmatic solutions. The main body of the stock was converted to a biotite-microcline-oligoclase-quartz monzonite; in the peripheral zones, biotite commonly is chloritized and most of the plagioclase is albite. Wall-rock alteration was minor.

Permian and Mesozoic rocks

Folded Permian and Mesozoic sedimentary rocks underlie the basin of North Park but they are largely covered by Quaternary terrace gravel, alluvium, and dune sand. The sedimentary rocks were described by Beekly (1915), and Miller (1934) closely followed Beekly's description in a more detailed study of the McCallum anticlines in east-central North Park. In the present report some of the earlier subdivisions are revised to conform more closely with the stratigraphic units now differentiated in neighboring areas.

The following chart summarizes the Permian and Mesozoic stratigraphy in the Northgate district:

Table 1. Permian and Mesozoic rocks in the Northgate district, Colorado

AGE	FORMATION	THICKNESS (feet)	LITHOLOGY
Upper Cretaceous	Pierre shale	Over 60	Dark gray fissile shale.
Upper Cretaceous	Niobrara formation	895	Yellow to gray, limy siltstone and shale.
Upper Cretaceous	Benton shale	635	Dark gray, thin-bedded shale.
Upper Cretaceous	Dakota sandstone	200-320	Pebbly sandstone and conglomerate, sandstone, and shale.
	UNCONFORMITY		
Upper Jurassic	Morrison formation	445	Variegated shale with minor interbedded sandstone, and shale.
Upper Jurassic	Sundance formation	145	Gray to brown sandstone and shale, minor amounts of limestone.
	UNCONFORMITY		
Permian and Triassic	Chugwater formation	690	Red silty shales and sandstone.
Permian	Forelle limestone	8-15	Pink to light gray, laminated limestone.
Permian	Satanka (?) shale	0-50	Red silty shales.
	UNCONFORMITY		
Pre-Cambrian			Gneisses, schists, and igneous rocks

The upper part of the Pierre shale and the Eocene Coalmont formation that are exposed elsewhere in North Park do not crop out in the Northgate district.

Laramide orogeny

Two distinct stages of the recurrent compressive deformation that affected the Rocky Mountain area at the close of the Cretaceous and through early Tertiary time can be recognized in the Northgate district. The oldest recognizable Laramide deformation compressed the sedimentary rocks into a series of north-trending folds that roughly parallel the long axis of the North Park basin. Reverse faults cut and displace many of these folds. The largest of these faulted folds in the Northgate district is the Sentinal Mountain-Dean Peak anticline, which is unique in that it is cut by both east-dipping and west-dipping reverse faults. Many other folds have similar trends, but none of them appear to be more than minor wrinkles on the flank of the larger synclinal structure of North Park.

The northern end of North Park is marked by the fault-line scarp along the Independence Mountain fault, a north-dipping reverse fault that cuts almost at right angles across the trend of the earlier Laramide structures. The earlier structures, which in part were cross-folded along this later, second-stage zone of deformation, show no evidence that they are diminishing in size, and it appears that the original structural basin once continued to the north for a significant distance.

Several faults cutting the pre-Cambrian crystalline rocks have altered rocks associated with them that are identical with altered rocks along known Laramide faults. These faults are clearly pre-Oligocene and probably were formed during one of the stages of the Laramide orogeny.

Tertiary rocks

White, tuffaceous clays and silts belonging to the White River group of Oligocene age occupy old valleys in the pre-Cambrian terrane. The topography during White River alluviation apparently was fairly rugged. The partly exhumed valleys show fairly steep walls, and many channels are so narrow that any flat valley floors must have been narrow. Cross-warping of the mid-Tertiary stream channels shows that the area was deformed after alluviation.

Sandy silts and clays of the North Park formation occupy an old, northwest-trending valley that carried the late Tertiary drainage of ancestral North Park. This formation has tentatively been considered as Miocene (?) in age (Wilmarth, 1938, p. 1514), but P. O. McGrew in an investigation of the Tertiary stratigraphy and paleontology of the Saratoga basin, Wyoming, has found early Pliocene vertebrate fossils in beds he believes were at one time continuous with those in the Northgate district (personal communication, 1950). The North Park formation has few remnants in the mapped area of the Northgate district, but it is widely exposed to the northwest and in the south-central part of North Park. Some old stream gravels in the northeast part of the Northgate district are believed to be related to the North Park formation. These gravels give the only evidence for postalluviation deformation in the area mapped for they appear to have been downwarped. In the central part of North Park, however, the North Park formation forms a syncline with dips as steep as 35° along the flanks.

Fluorspar occurs along minor faults that cut White River sedimentary rocks and are beveled by a post-early Pliocene (?) erosion surface. It is not known to which of the middle or late Tertiary periods of minor deformation these faults belong.

GNEISS COMPLEX

The gneiss complex comprises a varied group of rocks formed under progressively changing conditions of metamorphism during a single period of orogeny. Hornblende gneiss formed as the result of regional metamorphism and was subsequently transformed by metasomatism to quartz monzonite gneiss, biotite-garnet gneiss, and pegmatite. Local shearing concurrent with the metasomatic transformation converted the other rocks in the gneiss complex to hornblende-biotite gneiss and mylonite which subsequently recrystallized. Some quartz monzonite gneiss in the northwestern and southeastern parts of the district became mobile or rheomorphic subsequent to transformation.

Hornblende gneiss

General features and distribution — The hornblende gneiss consists essentially of hornblende and intermediate plagioclase; minor amounts of quartz, biotite, and diopsidic augite occur locally. Hornblende gneiss grades into almost all other rocks in the gneiss complex, and field and petrographic relations indicate that most of the other rocks were derived from it, either by metasomatic transformation or by shearing.

Hornblende gneiss is most abundant in the northern and northeastern parts of the district, where masses a mile or more in diameter are relatively free of any associated pegmatite or quartz monzonite gneiss (see Pl. 1). To the west and south, where replacement by pegmatite and quartz monzonite gneiss was more complete, the hornblende gneiss forms irregular, relict masses of various sizes. The larger bodies commonly are interconnected, but many of the smaller bodies are isolated inclusions in pegmatite or quartz monzonite gneiss.

In the central and southeast parts of the district the hornblende gneiss grades into biotite-garnet gneiss, apparently formed from the hornblende gneiss by hydrothermal metamorphism. Near Pinkham Mountain and eastward the hornblende gneiss shows transitions to hornblende-biotite gneiss and mylonite gneiss, seemingly derived from it by shearing. Hornblende gneiss is widespread in all these places, and the surrounding rocks generally appear to have been derived from it.

Small pods of massive chlorite occur sporadically in hornblende gneiss, and in the northwestern part of the district several irregular bodies of chloritic serpentine are 100 feet or more in diameter. Near these bodies, hydrothermal metamorphism was particularly effective and produced complexly zoned chlorite-tremolite-vermiculite bodies along the margins of some serpentine masses, and talcose rocks along some chlorite pods. A separate study is being made of the mineralogy and genesis of these deposits.

Lithology — The dark, medium-grained hornblende gneiss crops out in blocky layers or "beds" that range in thickness from several inches to several feet. The grains generally are less than 2 mm long, but some hornblende grains are 5 mm or more long. The layering is due to variations in bulk composition of the several layers rather than to mineral banding on the scale of individual grains. In most of the rock, hornblende and plagioclase are present in roughly equal amounts and fresh surfaces have a distinctive pepper- and-salt appearance. Some layers a few inches to several feet thick, however, differ greatly. Where hornblende greatly predominates, the rock has a dark greenish-black cast and the scattered plagioclase crystals are glossy and in places almost colorless; in lighter-colored varieties, the more abundant plagioclase tends to be white, although still quite glassy, and hornblende is in scattered crystals or clots of crystals. The long axes of hornblende prisms roughly parallel the plane of larger-scale layering, but the minerals generally are not segregated into bands and the foliation is poor. Hornblende prisms are fairly well alined in some gneiss; but mineral lineation is weak or absent in much of the rock. Most plagioclase grains tend to be equidimensional, but some are elongate in the plane of layering.

The layering of the gneiss appears to have been an original feature of the rocks and is not due to metamorphic differentiation. Not only do the layers show minor crenulations and drag folds, but individual "beds" can be traced around the crests and troughs of larger folds. Some layers of light-colored plagioclase- and quartz-rich hornblende gneiss as much as 1 1/2 feet thick are interbedded with the common, more mafic varieties. These rocks show no evidence of a secondary origin, and in all probability they originally had contrasting compositions.

Small chloritic pods, from a few feet to nearly a hundred feet in length and up to 20 feet wide, are widespread and range from relatively pure, massive chlorite to variable mixtures of chlorite and hornblende. Grain size ranges from medium to very coarse. The small serpentine bodies in the northwest part of the district are dense, greenish-black rock that encloses abundant small aggregates of tremolite and olivine. Much of the serpentine is altered to chlorite. Thin rims made up almost entirely of hornblende commonly separate the chlorite and serpentine bodies from normal hornblende gneiss. These rims grade irregularly into both the hornblende gneiss and the chlorite or serpentine bodies, and apparently were formed by reaction between the hornblende gneiss and the more mafic pods.

Petrography — The gneissic structure is even less apparent in thin section than in hand specimen, and hornblende and plagioclase grains form crystalloblastic aggregates with little mineral banding. Almost all inequidimensional grains are elongated in the plane of foliation. Hornblende has a strong parallel orientation in some rocks, but more commonly the orientation is imperfect and in some rocks the texture is almost granoblastic.

Proportions of the component minerals vary so widely that an average composition has little meaning. Hornblende forms 5 to 100 percent and plagioclase up to 70 percent of the rock, but in most specimens plagioclase is somewhat more abundant than hornblende. Diopsidic augite is rare, and where it occurs it generally makes up less than 5 percent of the rock, although as much as 15 percent of this mineral was seen in one specimen. Minor amounts of quartz and biotite are widely distributed, but in most places these minerals do not appear to be primary. Accessory minerals make up less than 1 percent of the hornblende gneiss. Of these, apatite is most abundant; sphene and magnetite are very subordinate.

Strongly pleochroic hornblende crystals are in irregular grains and rough prisms. Acicular crystals are rare, and few prisms are more than 3 or 4 times longer than they are thick. Most grains are anhedral and interlock irregularly with surrounding grains of hornblende and plagioclase. In hornblende-rich varieties some crystals are up to 2 cm long, but generally the prisms are less than 3 mm long. Some very fine grained varieties have few crystals more than 0.5 mm in diameter.

The plagioclase in most of the hornblende gneiss is calcic andesine (An_{40-45}), but the composition ranges between sodic andesine (An_{55}). The more calcic plagioclase is generally in hornblende-rich gneiss, but some rocks with roughly equal proportions of hornblende and plagioclase also contain labradorite. Most plagioclase is in clear, roughly equidimensional crystals that range from 0.5 mm to 2 mm in diameter.

Diopsidic augite forms small, irregular grains, generally less than 1 mm in diameter, that are closely associated with hornblende. Some augite grains are irregular-rimmed by pale, actinolitic amphibole, but these rims are not common.

Rounded blebs of quartz embay both hornblende and plagioclase and in places form abundant small poikiloblastic inclusions in hornblende. Small, cuspate grains of quartz associated with minor amounts of microcline apparently replace in part the earlier, larger crystals. Some quartz may be an original constituent of the gneiss, but most appears to have been introduced after the hornblende and plagioclase crystallized.

Biotite generally is associated with hornblende and in places forms imperfect pseudomorphs after it. More commonly biotite forms flakes and sheaves along cleavage planes or crystal margins of hornblende. No biotite was found in augite-bearing hornblende gneiss. Some biotite may have been original in the gneiss, but most of the biotite apparently formed during the period of hydrothermal alteration and shearing that followed regional metamorphism. Grains range in size from approximately that of the associated hornblende (1 to 3 mm) to very fine (less than 0.5 mm).

Small, stubby prisms of apatite are scattered through almost all hornblende gneiss, but they nowhere exceed a fraction of a percent of the rock. Magnetite and sphene are even less abundant, and in places appear to be secondary. Secondary epidote is in small, irregular grains and aggregates scattered through the rock.

Some chlorite pods clearly were formed from hornblende-rich masses of gneiss and all stages in the alteration can be seen. Hornblende was altered to chlorite, magnetite, and epidote-clinozoisite; the subordinate plagioclase was highly saussuritized and sericitized, and commonly was almost completely altered. Many of the chlorite pods retain little evidence of their origin, but consist of medium to coarse chlorite with small amounts of magnetite (commonly titaniferous), epidote, and green spinel.

The serpentine bodies are made up in large part of very fine grained fibrous chrysotile with abundant dusty to granular magnetite and hematite. Irregular and partly serpentinized aggregates of tremolite and olivine with abundant accessory magnetite and spinel are scattered throughout the serpentine, and scattered flakes of chlorite with associated magnetite cut both the serpentine and the tremolite-olivine relicts. Prismatic tremolite and rounded to irregular olivine grains occur in crystalloblastic aggregates that are clearly older than the serpentine. Olivine was more easily altered than tremolite, and in many of the partly altered rocks olivine was largely replaced by pseudomorphs of chrysotile. In the more completely altered rocks tremolite also was serpentinized, spinel disappeared during serpentinization, and magnetite was largely recrystallized.

Structure -- Although the hornblende gneiss is distinctly layered, it lacks key beds or distinctive horizon markers. It was so highly involved in later shearing and metasomatic transformations that so much of the evidence for determining the detailed structure of the rocks has been lost. Foliation and layering trend easterly and northeasterly and generally dip steeply north. Locally the rocks are considerably folded. Foliation parallels the layering on many folds, but in some places the foliation transects the axial parts of folds.

All fold axes in the regionally metamorphosed hornblende gneiss plunge steeply, generally about down dip. The orientations of 31 random fold axes plotted on a Schmidt equi-area net (Fig. 2) fall within a relatively small area, and it is significant that no measurement deviates far from the regional trend. Lineation shown by oriented prismatic hornblende crystals conforms to the same pattern, and the orientation of 18 random measurements also is shown on Fig. 2. Thus the mineral lineation is parallel to the tectonic axis defined by the fold axes, and according to interpretations widely but not universally accepted the direction of tectonic transport was largely horizontal. Lineations developed during the subsequent dynamic metamorphism and rheomorphism are parallel to lineation in the regionally metamorphosed hornblende gneiss; apparently the same stress field persisted after isoclinal folding and regional metamorphism ceased.

Origin — Similar hornblende-rich rocks from many other places in the pre-Cambrian of Colorado and southern Wyoming have been described. According to Blackwelder (1910) the most abundant metamorphic rocks in the Laramie and Sherman quadrangles are dark greenish hornblende schists; they are very abundant on Jelm Mountain along the western edge of the Laramie quadrangle and 12 to 15 miles northeast of the Northgate district. From Blackwelder's description, these rocks appear identical with the hornblende gneiss in the Northgate district. By analogy with similar rocks in other districts, Blackwelder suggested that they are metamorposed basic dikes and lava flows.

Ball (Spurr et al., 1908, pp. 45-46) first described hornblende gneiss in the central part of the Front Range, Colorado. He noted that the rock occurred as sheets and dikes and believed it to be metamorphosed mafic igneous rocks. Lovering (1935, pp. 10-11) described a similar hornblende gneiss in the Montezuma quadrangle, Colorado, where the hornblende gneiss is essentially conformable with the underlying Idaho Springs formation. Lovering suggested that it originated through the metamorphism of the andesitic flows. Tweto (1947, pp. 47-65) made a detailed study of the hornblende gneiss in the Vasquez Mountains, north of the Montezuma area. Here bands of hornblende gneiss alternate with gneiss and schist of the metasedimentary Idaho Springs formation. After carefully considering the field relations, the variations and limits of composition, and the common association with lime-silicate rocks, Tweto concluded that the hornblende gneiss resulted from the metamorphism of impure dolomite.

Hornblende-plagioclase rocks in other metamorphic terranes are known to have been derived from both igneous and sedimentary rocks. The well-known amphibolites in the Grenville series in New York, Ontario, and Quebec have been attributed (Adams and Barlow, 1910; Buddington, 1939, pp. 11-12; Osborne, 1936, pp. 197-228) to the metamorphism of impure calcareous sediments, gabbros and diorites, and volcanic flows and tuffs.

Hornblende gneiss in the Northgate district is so highly metamorphosed and was so greatly involved with later transformations that any discussion of origin would be largely conjecture. The present structure and mineralogy are due to intense deformation and regional metamorphism of what appears to have been a layered rock originally. The composition shows wide variation similar to that observed by Tweto (1947), but no unequivocal metasedimentary rocks were found. Some dense clinozoisite-epidote-quartz rocks that may have been lime-silicate rocks of sedimentary origin are in the belt of recrystallized mylonites along Pinkham Creek Canyon, but the relations now are too greatly obscured by cataclasis and granitization to be clear. The residual tremolite-olivine-spinel aggregates in the serpentine bodies have been completely recrystallized and no relict texture survives. On the basis of composition, however, these bodies could well represent metamorphosed ultramafic igneous rocks.

Although the composition of the different bands in the hornblende gneiss shows more variation than might be expected in a series of lava flows, it is perhaps even more difficult to envisage a sequence of impure calcareous rocks as thick as that in the Northgate district without some interbedded clastic sediments of distinctive character. The occurrence of serpentine bodies of possible ultramafic igneous origin suggests that the associated hornblende-plagioclase rocks also may have been of igneous origin.

Quartz monzonite gneiss

General features and distribution — Some of the hornblende gneiss in the Northgate district was converted by metasomatism to a granitoid gneiss of quartz monzonitic composition. Abundant pegmatite of similar origin is closely associated with it; many quartz monzonite gneiss bodies have a distinctly pegmatitic facies. The very intricate shapes of the quartz monzonite gneiss bodies shown on the geologic map (Pl. 1) actually are generalizations, as it was found impossible during field work to show all the details on aerial photographs with the approximate scale of 1 inch equals 1,000 feet.

Large bodies of quartz monzonite gneiss form crude zones in the northern and southeastern parts of the district. Numerous small bodies are in the area between, but they are subordinate to the abundant pegmatite. The zoning probably was due to variations in temperature and concentration of the solutions responsible for metasomatism. Except near the masses that became mobile after transformation, the quartz monzonite gneiss was formed without deformation of the surrounding rocks. Remnants of hornblende gneiss abound in the migmatitic rocks, and even in the interiors of some of the larger bodies relict textures can be recognized. The transitions between quartz monzonite gneiss and the metamorphic rocks on one hand and pegmatite on the other are commonly so gradational that many of the mapped contacts are arbitrary. This gradation is particularly common along the strike of foliation from the migmatite bodies; across the strike many of the contacts are fairly sharp. Most of the larger bodies of quartz monzonite gneiss are relatively massive and "granitic" appearing. Many of the smaller bodies mapped (Pl. 1) are incompletley transformed rocks that in the field resembled quartz monzonite gneiss more than the original metamorphic rock. Pervasive solutions altered the original minerals and introduced new minerals along the margins of the older grains; little or no lit-par-lit gneiss or veined gneiss is associated with the large bodies of quartz monzonite gneiss.

Reconnaissance in adjacent areas showed that the large bodies of quartz monzonite gneiss in the northwestern and southeastern parts of the district are parts of much larger masses of these rocks. After transformation from hornblende gneiss to quartz monzonite gneiss, the rock in the northwest corner of the district apparently became mobile and invaded the surrounding rocks. Similar mobilization took place in the southeast part of the district, but on a much smaller scale.

Lithology — Quartz monzonite gneiss includes a variable group of medium-grained pink rocks composed dominantly of feldspar and quartz with minor amounts of biotite or chlorite. The incompletely transformed rocks vary most in appearance, but even thoroughly granitized rocks range widely in texture, grain size, and mineral composition. Most of the rock is layered or gneissose, and three general textural varieties were recognized in the field. The most distinctive variety shows a faint relict texture, but this generally is subordinate to the gneissose or aplitic varieties which have entirely new textures.

All stages of transition between the quartz monzonite gneiss with the faint relict texture and hornblende gneiss were traced in the field. After some familiarity was gained, the rather nebulous resemblance could be recognized more easily. The similarity to the hornblende gneiss lies chiefly in the plagioclase grains which were more or less albitized during transformation but retained their crystal form.

The rock is made up of an aggregate of roughly equidimensional grains of quartz and feldspar up to 2 mm in diameter with small quantities of biotite or chlorite. The gneissic texture is due chiefly to a faint layering owing to variations in grain size and mineral composition, and to the elongation of some quartz grains and aggregates in the direction of foliation. Biotite and chlorite generally are too sparse to effect the foliation, but the few grains present tend to be oriented parallel to the layering shown by the other minerals. Pegmatite layers as much as an inch or two thick are common and generally follow the foliation. The quartz monzonite gneiss with relict texture crops out in blocky layers or "beds" that resemble in form the outcrops of hornblende gneiss.

Relict textures are absent in the other two closely related textural varieties, which are distinguished by their degree of foliation which in turn is controlled largely by the relative abundance of biotite. Where biotite makes up more than 5 percent of the rock, most of the flakes are oriented roughly parallel to the original layering of the metamorphic rocks and the foliation is fair to good; where biotite is very minor or absent, the rock is distinctly aplitic. Biotite generally is rather evenly distributed, but in a few rocks it tends to be aggregated into biotite-rich layers. Quartz and feldspar grains in both the gneissose and aplitic rocks are in even-grained aggregates and show little directional orientation. Some quartz grains are elongate in the direction of foliation but most tend to be equidimensional. As in the rock which shows relict textures, thin bands of coarser gneiss and pegmatite are abundant and generally follow foliation. These rocks appear fairly uniform in hand specimens, but most outcrops show slight textural variations that give the rock a layered appearance.

The several textural varieties are closely associated, and gradations are common. The variety characterized by faint relict textures is absent near quartz monzonite gneiss that became mobile; but where the rocks were relatively undisturbed, different varieties occur in adjacent layers, even in the interior of large masses of migmatite.

In addition to the somewhat coarser bands common in most of the quartz monzonite gneiss, many bodies contain abundant irregular masses of pegmatite; some smaller bodies pass laterally into pegmatite. These bodies were arbitrarily mapped as either quartz monzonite gneiss or pegmatite, depending on the dominant rock type.

Petrography — The textural varieties of quartz monzonite gneiss differ considerably in mineral content. The gneiss with relict textures has significantly less microcline than plagioclase, and biotite or chlorite generally are subordinate. Albite or oligoclase are largely in corroded pseudomorphs after the plagioclase of the original hornblende gneiss; in places such plagioclase grains still make up 30 to 35 percent of the rock. Those rocks with new textures generally have microcline-plagioclase ratios of 1/1 or greater and the gneissose and aplitic varieties differ chiefly in biotite content. Plagioclase occurs as corroded relicts in these rocks too, but more complete replacement has destroyed the original textures of the rock. Quartz ranges widely in abundance but makes up 30 to 45 percent of most rocks.

A study of thin sections of quartz monzonite gneiss disclosed other differences in composition which apparently are related to variations in soda and potash concentration in the alkali- and silica-bearing solutions responsible for transformation. Where potash was predominant, the resulting rock characteristically consists of microcline, sodic oligoclase, quartz, and biotite; where soda was abundant the rock is made up of microcline, sodic albite, quartz, and chlorite. Most quartz monzonite gneiss with new textures and some with relict textures developed under potash-rich conditions; most rocks altered by soda-rich solutions show relict textures. The mineralogic transformations transitional between hornblende gneiss and quartz monzonite gneiss differed greatly between potassic and sodic conditions of origin.

Potash was the predominant alkali involved in the development of most quartz monzonite gneiss. In early stages of the transformation, hornblende was converted to biotite, plagioclase was altered to a somewhat more sodic feldspar crowded with saussuritic and sericitic inclusions, and considerable quartz was introduced. With continued alteration, microcline was introduced along the margins of the older grains, and biotite was progressively replaced. Plagioclase was progressively replaced by microcline and some additional quartz, and was converted to sodic oligoclase and calcic albite with relatively abundant myrmekite. Typical, thoroughly transformed rocks of this origin consist of 25 to 50 percent microcline, 10 to 35 percent sodic oligoclase, 30 to 45 percent quartz, and 0 to 15 percent biotite. Muscovite and garnet locally make up several percent of some quartz monzonite gneiss, but generally are very subordinate or absent.

Where the alterations took place under more sodic conditions, the soda-bearing solutions were most effective early in the period of transformation and were followed by progressively more potash-rich solutions. In early stages of alteration, hornblende was converted to chlorite, in places through intermediate actinolite, plagioclase was altered to sodic albite crowded with saussuritic and sericitic inclusions, and some quartz generally was introduced. Some albite recrystallized during this stage and albite-rich stringers with pegmatite texture are relatively common, but most of the intermediate rock shows excellent relict hornblende gneiss texture. Scattered granules and veinlets of epidote are abundant. With continued alteration, microcline and more quartz were introduced, and the quantity of chlorite diminished markedly with an increase in microcline content. Saussuritic inclusions in plagioclase in the more altered rocks are very irregularly distributed, and clear to partly clear grains are common. Microcline generally makes up only 20 to 30 percent of the quartz monzonite gneiss of this origin and relict textures are common. The rest of the rock typically is made up of 25 to 35 percent sodic albite, 35 to 45 percent quartz, and up to 5 percent chlorite and epidote.

Plagioclase in all varieties of quartz monzonite gneiss forms irregular grains that characteristically are embayed by microcline and quartz. Some crystals are 2 mm in diameter, but most are between 0.5 and 1.5 mm in diameter. The composition in rocks that formed under predominantly potassic conditions ranges between An_8 and An_{15}; the albitized grains in rocks where early soda metasomatism was widespread generally are more sodic than An_5. Saussuritic and sericitic inclusions in plagioclase generally decrease in abundance with an increase in the degree of alteration. This is particularly true in the more sodic plagioclase, but some relatively calcic oligoclase is clear also. Myrmekite is widespread through quartz monzonite gneiss and generally is along the margins of plagioclase grains adjacent to microcline. It is most abundant in those rocks formed by predominantly potassic solutions and is relatively rare in sodic albite-bearing rocks. All plagioclase crystals are highly corroded, and evidence from transitional rocks suggests that most grains are sodic pseudomorphs of the intermediate plagioclase in the original hornblend gneiss.

Irregular grains of microcline range from minor intergranular wisps in incompletely transformed rocks to relatively large pegmatitic crystals an inch or so in diameter that commonly contain abundant residual inclusions of unreplaced plagioclase and biotite. The contacts everywhere indicate replacement relations toward plagioclase and biotite, and all gradations in the progressive replacement have been observed. Most of the textural banding noted in outcrops and in hand specimens of quartz monzonite gneiss is due to greater introduction of microcline along certain layers parallel to foliation. Replacement in most places began along crystal borders and gradually engulfed the adjacent grains; injection apparently had little influence on the development of these layered rocks.

Most quartz was introduced fairly early in the transformation, before significant quantities of microcline were introduced. The later stages of metasomatic alteration generally show only a slight increase in quartz, and considerable recrystallization apparently took place as it is difficult to determine any consistent age relation for quartz and microcline in thoroughly transformed rocks. Quartz typically is in lobate to rounded blebs and grains, and as elongated crystals and aggregates strung out along the foliation. It definitely corrodes and replaces plagioclase and biotite, but some crystallized quite late in the transformation and cuts microcline as well.

Small ragged flakes and grains of biotite are scattered through the quartz monzonite gneiss. The biotite is corroded by microcline and quartz and commonly is associated with abundant dusty to granular magnetite and hematite. In places muscovite is interleaved with biotite or forms discrete flakes. Many of the rocks contain secondary chlorite and magnetite associated with biotite.

Chlorite is most common in the rocks in which early albitization was intense. It is abundant in partly transformed rocks, where it forms pseudomorphs after hornblende; but where transformation was more complete, chlorite rarely makes up more than a few percent of the rock and generally is in ragged shreds with abundant dusty to granular magnetite and hematite. Sphene and epidote are associated with some of the chlorite and are most abundant in incompletely transformed rocks.

Irregular small grains and aggregates of magnetite and hematite are distributed through most quartz monzonite gneiss. They are commonly associated with corroded biotite and chlorite grains and appear to be most abundant where replacement was most complete; it is likely that the scattered grains are residual from the replacement of original ferromagnesian minerals in the rock.

Pink garnet is fairly abundant in some of the smaller bodies of quartz monzonite gneiss. It has the same appearance and index of refraction as garnet found in partly altered metamorphic rock and pegmatite; in all probability it is a residual mineral that survived transformation.

Zircon and apatite occur as very minor accessory minerals.

Origin -- Quartz monzonite gneiss in the Northgate district formed through reaction between hornblende gneiss and silica - and alkali-bearing hydrothermal solutions which permeated the rock after regional metamorphism. Quartz monzonite gneiss is in extremely irregular bodies that do not conform to the highly folded structure of the hornblende gneiss. Although some local control on replacement was exerted by folds in the host rock, almost all medium to large-sized masses transgress the older structures. In spite of the cross-cutting nature of the quartz monzonite gneiss bodies the adjacent rocks show no deformation, and the orientation of foliation in numerous inclusions of hornblende gneiss within quartz monzonite gneiss is parallel to that in the enclosing rock and in the adjacent hornblende gneiss. Even in areas where local control for quartz monzonite gneiss by folds in hornblende gneiss is apparent, the relations are those of incompletely replaced folded rocks rather than of folded granitoid rocks or phacolithic intrusion.

Intermediate stages in the transformation of hornblende gneiss to quartz monzonite gneiss are found thoughout the district. Gradational contacts are common along the strike of foliation from quartz monzonite gneiss, and many smaller bodies show all stages of the transformation. Although marginal transition zones are not conclusive evidence as to the origin of the interiors of such bodies, the presence of relict textures and masses of incompletely replaced rock within large bodies of quartz monzonite gneiss indicates a common origin.

Petrographic study of intermediate stages in the development of quartz monzonite gneiss indicates that most plagioclase is pseudomorphous after the plagioclase in the original hornblende gneiss, and that replacement by quartz and microcline began along grain boundaries and gradually engulfed the adjacent crystals. Hornblende was converted to biotite or chlorite, and the ferromagnesian content gradually decreased as the transformation progressed. Even though foliation was rather poorly developed in most hornblende gneiss, it apparently exercised considerable control on the flow of the hydrothermal solutions;

the layered character of quartz monzonite gneiss is in large part due to differences in degree of replacement, and contacts of quartz monzonite gneiss bodies are commonly sharp across the trend of foliation. The correlation of relict texture with less complete replacement by microcline is particularly significant in verifying conclusions reached in field studies.

Thus field and petrographic evidence indicates that transformation was accomplished by rather tenuous hydrothermal solutions that were capable of penetrating large masses of rock without disturbing the structural continuity of that rock. Lime, magnesia, and iron were largely replaced by potash, soda, and silica, and the bivalent bases were removed in solution. Early conversion of hornblende to biotite and the introduction of quartz, followed by introduction of microcline and more quartz in most of the quartz monzonite gneiss, indicate that potash and silica were very important constituents of the solutions. Albitization was not intense in most of these rocks, and the plagioclase most commonly in sodic oligoclase. This fact suggests that the soda concentration of most of the solutions was relatively low.

Local transformation of hornblende gneiss to albite-chlorite quartz rocks, followed by later introduction of microcline and more quartz, indicates that locally the early solutions were soda-rich but that they gradually became more potassic as transformation progressed. These rocks occur throughout the gneiss complex, even in the interiors of large bodies of quartz monzonite gneiss. No control for this type of alteration was discerned in the field; such alteration however, is particularly abundant in many relatively small bodies of quartz monzonite gneiss. It is suggested that the sodic alteration may have been a local marginal effect of solutions enriched in soda by potash metasomatism of plagioclase feldspars at depth. As granitization progressed sodic alteration would be followed by potash metasomatism.

Biotite-garnet gneiss

General features and distribution -- Irregular bodies of biotite-garnet gneiss (biotite-garnet-quartz-plagioclase gneiss) occur in the central part of the Northgate district, where they are associated with abundant pegmatite, and in the southeast part, associated with quartz monzonite gneiss and minor amounts of pegmatite. The largest bodies of biotite-garnet gneiss are near lower Camp Creek and the North Platte river, where several interconnected masses 1,000 to 6,000 feet long and 500 to 1,500 feet wide crop out. Many smaller bodies are found here and elsewhere throughout the area where pegmatite is abundant; many are too small to be shown on the geologic map (Pl. 1).

The scattered masses of biotite-garnet gneiss were formed through local transformation of hornblende gneiss. They are so closely associated with pegmatite that a genetic relationship is obvious in the field. Most bodies of biotite-garnet gneiss were most completely transformed next to pegmatite, and it locally grades into pegmatite through transitional zones either of lit-par-lit gneiss or by a general coarsening of grain and decrease in biotite content. On the other hand, biotite-garnet gneiss commonly intertongues with hornblende gneiss and grades into it through narrow transitional zones. The contacts are so indistinct and irregular, and the tongues of biotite-garnet gneiss so discontinuous that it is difficult to conceive of any origin other than transformation. Untransformed or partly transformed relicts of hornblende gneiss with similar gradational contacts are common within many biotite-garnet gneiss bodies.

Lithology -- Biotite-garnet gneiss grades from only slightly altered hornblende gneiss to coarsely porphyroblastic augen-gneiss, banded lit-par-lit gneiss, and even pegmatite. Variable grain size and uneven texture characterize the interior of most bodies of biotite-garnet gneiss. In most rocks the different minerals tend to be unevenly distributed, and the degree of segregation increases with the intensity of alteration. Layering is prominent in some rocks, and quartz and feldspar form discontinuous thin layers and lenses interleaved with layers rich in biotite. Red garnets are irregularly distributed through most of the rock. They are most abundant in or near quartz-feldspar layers; elsewhere the garnet aggregates are commonly surrounded by light-colored halos that are poor in biotite. Where layering is not prominent, quartz and plagioclase with minor amounts of biotite form irregular or lenticular aggregates in biotite-rich gneiss. Such biotite-rich and biotite-poor masses of rock intergrade completely and commonly form masses a few inches to a few feet in diameter.

The transition zones between hornblende gneiss and biotite-garnet gneiss are commonly rather narrow and are marked by the appearance and progressive increase in abundance of biotite and quartz. With increasing biotite, the foliation becomes more marked, but in general the rock strongly resembles hornblende gneiss. A short distance from the margins hornblende becomes rare, and biotite, quartz, and plagioclase generally are coarser grained. Some rather even grained aggregates of plagioclase, quartz, and biotite with minor amounts of hornblende make up fairly large bodies, but more commonly such aggregates make up minor facies near the margins of more typical biotite-garnet gneiss.

Where alteration was especially intense, particularly near the large pegmatite bodies, the gneiss varies extremely and the quartz-feldspar layers pass into small pods and stringers of relatively fine-grained quartz-plagioclase-garnet pegmatite. Feldspar augen or small pegmatitic knots of quartz, plagioclase, and garnet occur singly or in beadlike strings along the foliation; in places these knots coalesce into fairly persistent bands several inches thick, or into irregular masses a few inches to a few feet in diameter. With increasing numbers of pegmatitic pods and stringers, the rocks attain a typical lit-par-lit texture; many have a distinctly knotted appearance in outcrop. As the quantity of associated pegmatite increases, the biotite-rich bands become thinner and more discontinuous; and microcline, hitherto a minor constituent, becomes progressively more abundant. All gradations exist between the lit-par-lit variety of biotite-garnet gneiss and many of the larger, microcline-rich pegmatite bodies.

Petrography -- Along the margins of the biotite-garnet gneiss bodies the texture greatly resembles that in the surrounding hornblende gneiss. Hornblende and plagioclase grains closely resemble these grains in hornblende gneiss and apparently are relict. Biotite occurs along the cleavage and crystal margins of hornblende and as separate grains. Where not strung out along later shear zones, biotite tends to be evenly distributed through the rock and is oriented roughly parallel to the layering; the rock is distinctly better foliated than the original hornblende gneiss. Irregular to lobate quartz grains have replacement relations toward the other minerals. A representative rock of this kind is made up of about 40 percent plagioclase (An_{28-35}), 30 percent quartz, 15 percent hornblende, and 15 percent biotite. As much as 5 percent microcline is found in some rocks. Hornblende is absent or is very subordinate to biotite a short distance from the contact, and is introduced quartz is somewhat coarser and more abundant.

The minerals in most of the biotite-garnet gneiss are unevenly distributed, and the texture shows wide variation. In banded varieties the discontinuous quartz-plagioclase layers generally have very indistinct margins and commonly coalesce into irregular masses of quartz-plagioclase rock. The darker, biotite-rich layers generally are somewhat finer grained than the light-colored layers and are thickest and most abundant where alteration was less advanced. Garnet, with associated quartz, biotite, and blue amphibole, forms irregular to rounded aggregates that are commonly 1/2 inch and more rarely several inches in diameter. Most garnet aggregates are in the quartz-feldspar layers or are surrounded by light-colored halos poor in biotite, but in some rocks garnet occurs in nests of coarse biotite. The mineral composition of these different "typical" biotite-garnet rocks varies greatly, but most of these rocks are made up roughly of 40 to 45 percent plagioclase, 25 to 35 percent quartz, 15 to 20 percent biotite, and as much as 15 percent garnet. Relict hornblende in minor amounts is widespread, and several percent of microcline occurs in a few rocks.

Textures near pegmatite and lit-par-lit masses vary even more than in the less altered rocks. Quartz-plagioclase-garnet stringers have a typical pegmatitic texture in which some quartz and feldspar crystals are an inch or more in diameter and associated biotite and garnet are only a little less coarse. The texture of the rock adjoining the pegmatitic stringers is in places very similar to the more normal biotite-garnet gneiss, but commonly it is even more irregular.

Many of these rocks underwent minor granulation during the same period of shearing that elsewhere developed hornblende-biotite gneiss and mylonite gneiss. Quartz stringers and relatively coarse undeformed biotite follow some granulated zones through the rocks, and both quartz and biotite, as well as plagioclase, are ground up and spread out along others. Thus the shearing appears to have been recurrent and to have taken place at about the same time as the transformation.

The composition of plagioclase in biotite-garnet gneiss is remarkably uniform and is generally between An_{28} and An_{35}. A striking feature is that within any given body, the plagioclase has the same composition whether it occurs as relict crystals in the narrow, hornblende-bearing marginal zones; as relict or recrystallized grains in the main part of the body; or as coarse and completely recrystallized grains in the quartz-plagioclase-garnet pegmatite stringers. In several suites of specimens from different biotite-garnet gneiss bodies the range in composition of plagioclase was only 3 or 4 percent of anorthite (close to the limit of accuracy of determination), and the range in individual specimens was nearly as great. The only significant variation in plagioclase composition is in those pegmatitic rocks with 10 percent or more of introduced microcline; in these the plagioclase generally is near An_{25}.

One very significant deviation in plagioclase composition was noted in a specimen of slightly altered hornblende gneiss from the margin of a relatively small body of biotite-garnet gneiss. Most of the specimen is made up of about 45 percent hornblende, 40 percent plagioclase, 10 percent quartz, and 5 percent biotite. Plagioclase and hornblende have the same textural relationship as these minerals have in normal hornblende gneiss; quartz has replacement relations toward the earlier minerals, and biotite is along cleavage planes and margins of hornblende. This slightly altered hornblende gneiss is cut parallel to the foliation by an irregular stringer about 1/8 inch thick of biotite-garnet-plagioclase rock. This stringer of typical biotite-garnet gneiss grades into the adjacent rock and still contains a few ragged hornblende relicts only partly altered to biotite. The composition of 15 plagioclase grains was determined; five grains from the relatively unaltered hornblende gneiss showed an average composition of An_{30}, five grains from the margins of the biotite-garnet gneiss stringer ranged between An_{35} and An_{37}, and five grains from the central part of the stringer ranged between An_{40} and An_{45}. The alteration here developed a distinctly more calcic plagioclase than that in the original rock.

Plagioclase grains have the same appearance and habit in marginal transition zones and in even-grained varieties of biotite-garnet gneiss as in the surrounding hornblende gneiss; apparently individual grains persisted through transformation although the composition changed. In more uneven-textured biotite-garnet gneiss, however, the plagioclase ranges widely in grain size and was largely recrystallized. The large recrystallized grains in the quartz-plagioclase-garnet pegmatite stringers generally embay smaller plagioclase grains. As most of the crystals are rather clear, the change in composition was not due to a saussuritic breakdown of the original plagioclase.

Plagioclase makes up 40 to 50 percent of most biotite-garnet gneiss, regardless of the degree of transformation. This is only slightly less than the average amount in unaltered hornblende gneiss. Only in pegmatitic varieties of biotite-garnet gneiss does the quantity of plagioclase vary significantly; plagioclase commonly makes up 50 to 70 percent of the quartz-plagioclase-garnet stringers and pods, and it is relatively minor where abundant microcline was introduced.

Hornblende is most abundant in the transition zones between hornblende gneiss and biotite-garnet gneiss, where it occurs in irregular grains that commonly are partly altered to biotite. Where biotite is subordinate, the hornblende is very similar to that in adjacent, unaltered hornblende gneiss; as the quantity of biotite increases, the hornblende relicts become smaller, less abundant, and much more irregular. Hornblende within the bodies of biotite-garnet gneiss are in scattered, ragged grains, chiefly in the less-transformed parts, where they are associated with abundant biotite. Hornblende generally is absent in more intensely altered rocks near pegmatite and quartz monzonite gneiss. In a few places along the margins of biotite-garnet gneiss bodies, hornblende gneiss is distinctly coarser grained and hornblende is much more abundant than normal. This is particularly true in the rare places where quartz-plagioclase-garnet pegmatite stringers cut hornblende gneiss. Some of the pegmatitic pods contain hornblende crystals 1/2 inch or more long, and apparently the adjacent rock was considerably enriched in hornblende.

Biotite is closely associated with abundant hornblende in the marginal transition zones and in partly transformed, hornblende-rich inclusions within biotite-garnet gneiss bodies. It is regularly distributed through relatively even grained biotite-garnet gneiss, and the relations with scattered hornblende relicts indicate that the biotite here had the same origin as that in marginal zones. Where transformation was more complete, most biotite is in separate grains that show no trace of their origin, but all relict hornblende crystals have some closely associated biotite. Textures are uneven in thoroughly recrystallized rocks and biotite forms irregular concentrations and stringers that range widely in grain size. Biotite is coarsest where it is most abundant, and in some rocks it forms local concentrations with grains up to 1/2 inch or more in diameter. More commonly it is mixed with variable amounts of plagioclase and quartz or is closely associated with garnet aggregates. Coarse-grained biotite is a minor constituent of many pegmatite pods and stringers.

The total hornblende and biotite content generally decreases with an increase in degree of alteration of the rock. Hornblende comprises 35 percent or more of most hornblende gneiss, and in the marginal parts of biotite-garnet gneiss bodies, combined hornblende and biotite make up 25 to 35 percent of the rock. Biotite generally makes up 15 to 25 percent of those rocks where hornblende is very minor or absent, and as little as 5 percent of much lit-par-lit gneiss and rock cut by abundant pegmatite.

Red garnet is widely but irregularly distributed through biotite-garnet gneiss and associated pegmatite, and in places it is in the adjacent hornblende gneiss near a contact with pegmatite or biotite-garnet gneiss. Garnet is coarsest and most abundant near pegmatite bodies and in many places is found only in thin peripheral zones around pegmatite. In other places, garnets are distributed throughout relatively large masses of biotite-garnet gneiss. Rock with abundant garnet generally has less biotite than similar rock with less garnet. The garnets are completely isotropic and probably belong to the almandine-pyrope group. The index of refraction of garnets in 26 specimens from all occurences was determined. In 24 specimens the index was between 1.79 and 1.80, and in 2 specimens the index was significantly above 1.80. Thus the composition of most garnets in biotite-garnet gneiss and related rocks probably is near $Al_{70}Py_{30}$. The garnet typically occurs as granular, poikiloblastic aggregates with abundant rounded quartz inclusions and variable amounts of closely associated blue amphibole and biotite. All stages in the development of garnet were seen, both in slightly altered hornblende gneiss and in thoroughly transformed biotite-garnet gneiss. Garnets formed from materials derived from the breakdown of both hornblende and biotite. In the earliest stages, alteration was confined to scattered, irregular to rounded spots up to 1/2 inch in diameter, and adjacent hornblende and biotite generally were somewhat corroded. These spots consist of small grains of blue amphibole and biotite with a few small garnet granules set in a very fine mosaic of quartz and sericitized plagioclase. As the quantity of garnet increases, the quantity of blue amphibole, biotite, and plagioclase decreases, and the quartz tends to be aggregated into rounded blebs surrounded by or closely associated with granular garnet. The larger garnets are in rounded to very irregular aggregates with abundant lobate to rounded quartz inclusions and variable quantities of closely associated biotite. The biotite forms peripheral concentrations, scattered inclusions and fracture fillings; some relatively large crystals project haphazardly into or through the garnet. Small grains of blue amphibole are associated with many garnet aggregates but generally are absent where biotite is abundant. The garnets within biotite concentrations are surrounded by thin rims of fine quartz, sericitized plagioclase, and biotite, and the larger adjacent biotite crystals are strongly corroded.

The blue amphibole associated with many garnet aggregates is most abundant where the surrounding rock is rich in hornblende, but it is relatively common even where the hornblende in the adjacent gneiss is insignificant in amount. Most of the blue amphibole is in small, irregular to idioblastic grains that formed as an intermediate step in the development of garnet, but in some hornblende-rich rocks the original hornblende crystals adjacent to the garnet aggregates were partly or entirely converted to blue amphibole. The optical properties of the blue amphibole are almost identical with those of hornblende, but the color is more characteristic of amphiboles relatively rich in alkalies. The pleochroic colors of the blue amphibole are yellow, blue-green and green-blue in contrast with the yellow, grass-green and dark green of unaltered hornblende in hornblende gneiss.

Although biotite is a common associate of garnet, the rock around the larger garnet aggregates commonly is relatively poor in biotite and hornblende, and in places the minerals in these light-colored halos are distinctly coarser grained than those in the rest of the rock. The biotite-poor halos around garnet aggregates and the relatively low percentage of biotite and hornblende in those rocks where garnet is abundant suggest that most of the garnet-forming material was of local origin. The development of garnet undoubtedly accounted in part for the decrease in total biotite and hornblende content with an increase in the degree of alteration. Total biotite and garnet, however, rarely exceeds 25 percent of the more altered rocks and generally is less than 20 percent; consequently these totals represent a significant decrease in the iron and magnesia held in the original hornblende gneiss.

Quartz was one of the earliest minerals introduced during the transformation of hornblende gneiss, and even in marginal zones it comprises as much as 30 percent of some biotite-garnet gneiss. It forms small lobate grains in slightly altered rocks; with an increasing alteration the quartz became coarser, more irregular, and somewhat more abundant. The quantity of quartz in biotite-garnet gneiss ranges widely, but it makes up 20 to 40 percent of most thoroughly transformed rocks. Some quartz undoubtedly resulted from the breakdown of hornblende to biotite and garnet. However, as the quantity of quartz in most biotite-garnet gneiss exceeds that of combined biotite and garnet and is about the same as that of hornblende in the original rock, significant quantities of silica must have been introduced during transformation.

Microcline in wisps and small grains constitutes as much as 5 percent of some typical biotite-garnet gneiss, but in much of the rock it is absent. Some biotite-garnet gneiss, particularly near large microcline-bearing pegmatite bodies, contains 30 percent or more microcline in grains that range from very small up to roughly rectangular augen an inch or more in length. The microcline embays and replaces both biotite and plagioclase and some quartz as well. Myrmekite is widespread in these rocks, and many microcline crystals are crowded with unreplaced inclusions of the older minerals. Some of these inclusions are aggregates that show the normal relations of biotite-garnet gneiss. The microcline was evidently introduced after the hornblende gneiss was transformed to biotite-garnet gneiss.

Accessory minerals in original hornblende gneiss make up only a fraction of a percent of the rock; apatite is the most abundant of these, but sphene is fairly widespread as well. Both apatite and sphene, as well as variable amounts of secondary epidote, are much more abundant in the biotite-garnet gneiss, and appear to increase in abundance with the degree of transformation. Zircon and magnetite also are fairly common in biotite-garnet gneiss, but they are greatly subordinate to apatite, sphene, and epidote.

Origin -- Abundant evidence indicates that biotite-garnet gneiss originated by transformation of hornblende gneiss. Contacts between these two rock types are gradational and irregular, many untransformed or incompletely transformed residuals of hornblende gneiss occur throughout the biotite-garnet gneiss; and many details of the transformation can be observed under the microscope. The close association with pegmatite and minor amounts of related quartz monzonite gneiss and the evidence for recurrent shearing during transformation indicate that the transformation was a phase of the general dynamic and metasomatic metamorphism that affected the gneiss complex shortly after regional metamorphism.

Although progressive mineralogic and textural changes clearly indicate the replacement origin of most biotite-garnet gneiss, the origin of quartz-plagioclase-garnet pegmatite is not so obvious. Bodies of this rock range from small knots a few inches in diameter through thin, discontinuous stringers in lit-par-lit gneiss to relatively persistent, veinlike bodies a few inches thick and up to several tens of feet long and irregular masses up to several feet or more in diameter. Because of their coarse grain and low biotite content these rocks appear quite distinctive; but the bodies do not displace their walls, and the contacts characteristically are gradational. Although present in different proportions, the minerals are the same as those in the wall rocks; and neither plagioclase nor garnet shows any change in composition across the contacts of the pegmatitic bodies. Evidently the quartz-plagioclase-garnet pegmatite resulted from the same alteration that developed the adjacent biotite-garnet gneiss.

Except for alterations accompanying the relatively late introduction of microcline, (changes more closely related to the origin of microcline-rich pegmatite discussed in the following section), the transformations produced chiefly minerals containing considerable lime, magnesia and iron. Abundant introduced quartz is the only significant exception. Normal hornblende gneiss, having roughly equal proportions of intermediate plagioclase (An_{30-55}) and hornblende, was converted to a rock composed of biotite, garnet, quartz, and plagioclase (An_{28-35}). Total ferromagnesian content shows a slight but progressive decrease with increased alteration; magnesia apparently was lost more rapidly than iron, as the ratio of relatively iron-rich garnet to biotite increased with the degree of alteration.

To accomplish these changes some silica was needed for the quartz in excess of that derived from the breakdown of hornblende to biotite and garnet, and sufficient potash was required to permit the development of biotite from hornblende. Potash concentration in early stages was apparently low, for little microcline was then introduced. The other alterations required removal of small amounts of lime, magnesia, and iron. These changes contrast notably with those in the adjacent and deeper zones where quartz monzonite gneiss was formed. Here large quantities of lime, magnesia and iron were replaced by alkalies and silica as the plagioclase of the hornblende gneiss was converted to sodic oligoclase or albite and the ferromagnesian minerals were largely destroyed.

Although the minerals of the biotite-garnet gneiss are generally considered to originate at higher temperatures than those in quartz monzonite gneiss, geologic conditions suggest that this was not the case. Biotite-garnet gneiss occurs with abundant pegmatite in a crude zone peripheral to the large quartz monzonite gneiss bodies, a zone where the temperature should have been somewhat lower.

More probably the differences in reaction were related to differences in concentration of the various materials in solution. Evidently most alkalies in the hydrothermal solutions were precipitated in the development of quartz monzonite gneiss, a precipitation Wegmann (1935, p. 326) postulates as taking place within a narrow zone or "front." As the solutions were impoverished in alkalies they undoubtedly were enriched in displaced lime, magnesia, and iron. Thus the alteration of the rock above the granitization "front" would take place in a hydrothermal environment relatively low in alkalies and rich in the bivalent bases (lime, magnesia, and iron). There was no precepitation of these materials in the biotite-garnet gneiss to form a "basic front" (Reynolds, 1944, pp. 234-238; Read, 1948, pp. 11-12); rather there is evidence for slight removal. However, the uniformity of composition of plagioclase and garnet suggests that these minerals approached equilibrium with solutions considerably richer in lime, magnesia, and iron that those in deeper zones.

Pegmatite

General features and distribution -- Microcline-quartz-plagioclase pegmatite is very abundant in a crude zone between the large masses of quartz monzonite gneiss in the northern and southeastern parts of the Northgate district. Small bodies of quartz monzonite gneiss are associated with the abundant pegmatite, but they are largest and most numerous to the north, where the pegmatite and quartz monzonite gneiss zones overlap. The largest pegmatite bodies are in the west central part of the district where they range from small pods to very irregular masses more than 2 miles long and 2,000 feet wide. Biotite-garnet gneiss is associated with the abundant pegmatite through the central part of the pegmatite zone, where quartz monzonite gneiss is subordinate. In the southern part of the pegmatite zone relations have been greatly obscured by igneous intrusion, Laramide faulting, and Tertiary alluviation; but pegmatite appears to be much less abundant here than farther north. It forms numerous small bodies on Pinkham Mountain and eastward where shearing appears to have been active during the period of metasomatic alteration (see following section), and the southern margin of the pegmatite zone coincides roughly with an irregular belt of mylonite gneiss near Pinkham Creek. Some pegmatite is associated with the large masses of quartz monzonite gneiss both north and south of the pegmatite zone, but is distinctly less abundant here than in the central part of the district.

Although some of the smaller pegmatite lenses clearly displace their walls and apparently represent injected material, most of the larger bodies show replacement relations. Rocks surrounding the complexly branching pegmatite masses are not displaced or deformed, and the foliation in the wall rock and in numerous undigested inclusions of country rock in pegmatite shows the same orientation. In some places contacts of pegmatite bodies are fairly sharp, but elsewhere pegmatite grades into such diverse rocks as hornblende gneiss, hornblende-biotite gneiss, biotite-garnet gneiss, and quartz monzonite gneiss. Minor amounts of pegmatite are associated with almost all quartz monzonite gneiss, and many smaller bodies range from quartz monzonite gneiss in one part to pegmatite in another, pegmatite and quartz monzonite gneiss generally appear contemporaneous, but where an age sequence can be determined pegmatite is always the younger.

Lithology -- With few exceptions, pegmatite in the Northgate district shows little mineralogic or textural zoning, but is a simple aggregate of quartz and feldspar with subordinate muscovite, biotite, garnet, and magnetite or hematite. The texture characteristically is uneven, and some grains are as much as several inches in diameter. Very coarse pegmatite is quite rare.

The pegmatite ranges widely in composition from plagioclase-rich, microcline-poor through all gradation to those in which nearly all the feldspar is microcline. Where plagioclase is abundant the rock generally is white to gray and is relatively finegrained for pegmatite. Garnet and biotite are most abundant in these rocks, and microcline is chiefly in scattered pink crystals. Where microcline is more abundant, the rock is distinctly pink and generally coarser grained. In microcline-rich pegmatite, plagioclase is in scattered grains and in irregular, granular aggregates. In places quartz and the associated feldspar show the same range in grain size but more commonly the quartz is in irregular aggregates between larger feldspar grains. Muscovite is abundant in a few bodies, but is very scarce or absent in most. Magnetite, or martite, is widespread in the pegmatite, and in places make up several percent of the rock.

Most contacts of pegmatite with quartz monzonite gneiss and biotite-garnet gneiss are completely gradational. In quartz monzonite gneiss the pegmatite occurs either as narrow bands parallel to foliation or as irregular masses of various shapes and sizes. Most contacts are indistinct and the two rocks appear to be of about the same age; in some places pegmatite cuts quartz monzonite gneiss with fairly sharp contacts and is younger. Biotite-garnet gneiss grades into microcline-rich pegmatite through an abrupt increase in introduced microcline, a decrease in biotite, and a general increase in grain size. The change is most marked in the medium-grained even-textured biotite-garnet gneiss, but more commonly the transition is with the lit-par-lit variety, where much of the adjacent rock already had a pegmatitic or near pegmatitic texture. Scattered grains and augen of pink microcline mark the first stage in the transformation to pegmatite. With an increase in the quantity of microcline, the biotite content decreases and the gneissic texture is gradually lost. The grain size increases significantly, even in rocks that already had a pegmatitic texture.

The relations between pegmatite and hornblende gneiss are considerably more varied. Some contacts are fairly sharp but more commonly a narrow, epidote-rich transition zone exists between the two rocks. Chlorite, pink plagioclase (albite), garnet, and specularite are common associates of epidote in the transition zone; microcline is progressively more abundant toward the pegmatite. The transition zone is highly variable in texture and ranges from pseudomorphic hornblende gneiss through structureless aggregates to distinctly pegmatitic textures.

Late in the period of pegmatite development, the leaching of quartz was widespread in both pegmatite and quartz monzonite gneiss. Most of the masses of leached rock are only a few feet or tens of feet in diameter and make up only a small part of the affected bodies. The leaching was erratically distributed; and except for a slight localization near the bulbous ends of pegmatite bodies, no structural control was discerned. In some places numerous partly leached relicts occur through the more cellular rock. Many of the cavities contain scattered to numerous flakes of specular hematite and a few of the holes are lined with small, euhedral quartz crystals.

Petrography -- The abundance of different minerals in the pegmatite varies widely from quartz-plagioclase-garnet pegmatite with subordinate microcline to quartz-microcline pegmatite with little or no plagioclase or garnet. Quartz makes up 20 to 30 percent of almost all of the pegmatite, and in most of the rock microcline is significantly more abundant than plagioclase. Garnet, generally with some associated biotite, is relatively abundant in those rocks where plagioclase is abundant, but it is rare and irregularly distributed in microcline-quartz pegmatite. Muscovite is abundant in a few places but generally is quite rare. Minor quantities of magnetite and martite are widespread.

Plagioclase generally occurs in an irregular aggregate with quartz, and rocks where plagioclase is the most abundant feldspar are finer grained than the more common, microcline-rich pegmatite. Microcline grains range from small, intergranular wisps that corrode and replace the adjacent plagioclase to large, irregular grains that contain numerous partly absorbed plagioclase inclusions. The inclusions have irregular embayed margins and commonly several adjacent inclusions have the same crystallographic orientation. Some quartz appears to be more or less contemporaneous in origin with plagioclase, but other grains clearly corrode the plagioclase and were either recrystallized or were introduced at about the same time as the microcline.

Many pegmatite bodies have a distinct megascopic foliation shown by numerous elongate quartz aggregates, or, more rarely, by muscovite-covered folia. Under the microscope, the quartz aggregates appear as stringers and veinlets along recrystallized cataclastic zones. Granulated feldspar and quartz along these zones have recrystallized to a fine interlocking aggregate of irregular grains, and are cut by the larger quartz stringers which definitely are later than the shearing. Where present, muscovite forms small grains in the recrystallized cataclastic aggregate and larger flakes and layers associated with the late quartz stringers. Both varieties crystallized after shearing. Sheared and foliated pegmatite is most abundant in the same general area where hornblende-biotite gneiss and mylonite gneiss are most abundant.

Plagioclase was one of the earliest minerals in the pegmatite to crystallize, and it is generally corroded and partly replaced by microcline and quartz. In those bodies where plagioclase makes up more than a few percent of the rock its composition generally ranges between An_{20} and An_{30}. Some grains are quite clear but most are somewhat saussuritized; a few grains are very heavily crowded with saussuritic and sericitic inclusions. Little correlation exists between composition and degree of alteration. Where plagioclase is a very minor constituent of the pegmatite, it tends to be distinctly more sodic and commonly ranges between An_{10} and An_{15}. Most of these grains are highly saussuritized.

Mymekitic borders are common on plagioclase grains where considerable replacement by microcline has taken place.

Microcline ranges from small crystals between the plagioclase grains to large, irregular to roughly rectangular crystals that commonly contain abundant corroded relicts of plagioclase. In plagioclase-rich pegmatite, the microcline clearly was introduced into a previously existing rock, and all degrees of replacement can be seen from these early rocks to rocks in which the feldspar is largely microcline.

Quartz occurs in irregular to lobate grains and aggregates that are unevenly distributed through the rock. Where plagioclase is abundant the associated quartz appears to be approximately contemporaneous, but where microcline is the predominant feldspar much of the quartz is corrosive toward the plagioclase and appears to be of about the same age as the microcline. As quartz in the plagioclase-rich pegmatite, and in the, microcline-rich pegmatite is about equally abundant, the apparent difference in relative age may be due in large part to recrystallization of quartz already present. This recrystallization is further suggested by a general increase in grain size of quartz with an increase in introduced microcline.

Garnet has about the same index of refraction in pegmatite as it has in the adjacent biotite-garnet gneiss. The irregular to rounded grains and aggregates have a typical sieve texture, with abundant blebby quartz inclusions and variable quantities of closely associated biotite. Garnet is most abundant and the associated biotite is most common in pegmatite that is rich in plagioclase; garnet is relatively minor and biotite is absent in pegmatite where replacement by microcline was more complete.

The garnet grains appear to have been inherited in large part from an earlier stage in the transformation and replacement of hornblende gneiss.

The contacts between pegmatite and hornblende gneiss are marked in many places by abundant epidote and various associated minerals. Some of these rocks show good relict texture of the original hornblende gneiss, with chlorite pseudomorphs of hornblende set in a dense matrix of epidote. More commonly the alteration product is a dense green rock composed of predominant granular to prismatic epidote with variable quantities of pink albite (An_{2-5}). Sphene, chlorite, and hematite are common accessory minerals. In places the epidote-albite rock is quite coarse-grained and has a pegmatitic texture. Garnet is fairly common in hornblende gneiss near pegmatite and in the transition zones, and in one place a dense garnet-clinozoisite-scapolite-albite-sphene rock occurs along a pegmatite-hornblende gneiss contact.

<u>Origin</u> -- The large pegmatite bodies are extremely irregular and contain numerous inclusions of metamorphic rocks. With few exceptions the wall rocks and inclusions show no evidence of deformation, and the foliation in the inclusions and the wall rocks generally has the same orientation. Many of the contacts are gradational. Some of the smaller pegmatite bodies clearly displace their walls, but most of the pegmatite in the larger masses evidently replaced rather than intruded the metamorphic rocks. This conclusion is further suggested by the progressive replacement of plagioclase by microcline as well as the occurrence of relatively calcic plagioclase (An_{20-30}) and garnet even where microcline is relatively abundant.

Microcline in all the pegmatite, even in the central part of large pegmatite bodies, bears replacement relations toward plagioclase, and in marginal zones of the pegmatite bodies microcline clearly was introduced after the biotite-garnet gneiss was formed. These same relations are found in the gradational contacts of biotite-garnet gneiss inclusions within pegmatite as well. The composition of most plagioclase in the pegmatite in the Northgate district is more calcic (An_{20-30}) than is common in quartz-feldspar pegmatite, and garnet in the pegmatite has about the same composition as garnet in adjacent biotite-garnet gneiss. Apparently both the plagioclase and garnet are relict. Biotite-garnet gneiss and pegmatite bear no constant relation to each other in space. Although biotite-garnet gneiss generally is most completely transformed near large pegmatite bodies, many thoroughly transformed masses of biotite-garnet gneiss have relatively little closely associated pegmatite, and many pegmatite bodies have no associated biotite-garnet gneiss.

Although a distinct sequence in time between biotite-garnet gneiss and pegmatite is implied by the late introduction of microcline, it seems quite likely that the two rocks were formed about contemporaneously, but that the biotite-garnet gneiss developed ahead of the advancing pegmatite "front." This hypothesis is consistent with the common close association of pegmatite with the more thoroughly transformed biotite-garnet gneiss and the apparently continuous local sequence in time between the two rocks. No unequivocal example of concentric zoning of biotite-garnet gneiss around a large mass of pegmatite was observed, and in many places a pegmatite body grades into highly altered biotite-garnet gneiss on one side and into hornblende gneiss on the other. Hydrothermal solutions changed during the course of transformation from those carrying abundant lime, magnesia, and iron to those rich in potash. Where the later solutions followed the same general channels as the earlier solutions, biotite-garnet gneiss and pegmatite are very closely associated; where new channels developed or old channels shifted during transformation, the alteration products occur either alone or with minor intermixing.

Hornblende-biotite gneiss

General features and distribution -- The hornblende-biotite gneiss includes a group of well-foliated rocks made up of varying proportions of hornblende, biotite, quartz, and plagioclase. Small amounts of microcline are widespread, and irregular bodies of quartz monzonite gneiss and pegmatite replace some of these rocks. The rocks form complexly interlayered series that range from unaltered hornblende gneiss to fine-grained mylonite gneiss. Foliation in the hornblende-biotite gneiss parallels the layering in adjacent hornblende gneiss, and the different rocks appear to be interbedded. The mixed rocks do not persist along the strike, however, but the layers feather out and grade into hornblende gneiss. The hornblende-biotite gneiss is very erratically distributed, and it is not separated from hornblende gneiss on the geologic map (Pl. 1).

These rocks are most abundant and most biotite-rich on the southern part of Pinkham Mountain and along Pinkham Creek, where they are associated with mylonite gneiss. Some hornblende-biotite gneiss occurs south of the belt of mylonite gneiss, but relations are obscured by large masses of quartz monzonite gneiss and by Laramide faultings. Farther north, hornblende-biotite gneiss alternates with larger and larger masses of normal hornblende gneiss. No hornblende-biotite gneiss was seen in the north and northwest parts of the district.

Lithology — Horneblende-biotite gneiss varies widely from place to place as it is made up of a completely gradational series of rocks. Where hornblende is abundant the rock has a grain size roughly comparable with that in the associated hornblende gneiss and commonly has a similar appearance. Biotite may be fine-grained, but in places it is almost as coarse as the associated hornblende and plagioclase. The foliation generally is considerably more distinct than that in horneblende gneiss.

With increasing biotite and quartz, the rock becomes finer-grained and more closely foliated. Some hornblende and plagioclase occur in slightly larger grains, but the rock loses the distinctive salt-and-pepper aspect of hornblende gneiss and acquires a more even, dark gray color. Although closely foliated, the rock does not split evenly along a single plane; the fracture is hackly, and megascopic foliation appears to be a compromise direction between several planes of mineral orientation. As the grain size becomes smaller, the gneisses grade into dense, uniform to banded gray rocks characteristic of mylonite gneiss.

Feldspar augen and irregular quartz-feldspar stringers are abundant in many places, particularly near bodies of quartz monzonite gneiss or pegmatite. The quartz and feldspar are generally strung out parallel to the foliation, although in places they form irregular, cloudy masses. The contacts are characteristically indistinct, and the stringers and masses appear to result from replacement or transformation rather than injection.

Petrography -- Hornblende-biotite gneisses are more or less granulated rocks intermediate in texture between hornblende gneiss and mylonite gneiss. Fine-grained quartz and biotite with abundant accessory minerals occur along shear zones and in recrystallized, cataclastic aggregate that surrounds the larger, relict grains of plagioclase and hornblende; the quantity of quartz and biotite is directly related to the degree of granulation of the rock. Biotite tends to be oriented along the various shear planes, and the foliation is much stronger than that in normal hornblende gneiss. In places a single set of shear planes is dominant and in such rocks even relatively biotite-poor gneiss has good megascopic foliation. Most of the hornblende-biotite gneiss shows several sets of shear planes that intersect at low angles in the direction of megascopic foliation, as well as considerable granulated rock between the larger crystals. In these rocks the strength of foliation depends both on the quantity of oriented biotite and on the angles of intersection of the shear planes. In some rocks cataclasis took place only between the grains; these rocks have almost no foliation. No generalization can be made concerning the relation of strength of foliation with the degree of comminution.

Hornblende and plagioclase occur as ragged, relict grains set in finer, granulated rock. Broken grains of plagioclase are abundant in the surrounding granulated rock, but fine-grained hornblende is uncommon. The grain size of the larger crystals is comparable with that in normal hornblende gneiss, and in some of the less broken rocks, remnants of hornblende gneiss are common. Hornblende relicts generally are not abundant as plagioclase relicts, and they are commonly altered in part to biotite. Where there was significant granulation, the plagioclase is distinctly more sodic than that in the associated hornblende gneiss, and generally is either sodic andesine or calcic oligoclase. Most grains are considerably sericitized and saussuritized, but relatively clear grains also are abundant. In general, plagioclase is about as abundant in the resulting rock as it was in the original hornblende gneiss.

Although a small quantity of biotite is commonly associated with the relict hornblende grains, most of it occurs with quartz and plagioclase in fine-grained crystalloblastic aggregate along the shear zones and between the larger plagioclase and hornblende crystals. Biotite forms irregular to well-formed platy crystals that range from very fine grained to nearly as coarse as some of the hornblende crystals. Many of the biotite plates are oriented along the shear planes, but a large number also show random orientation in the granulated rock between the relict crystals. Depending largely on the degree of shearing, biotite ranges in abundance from practically zero to 20 percent of the rock.

Quartz forms small, roughly equidimensional grains associated with the recrystallized biotite and plagioclase between the larger crystals and somewhat larger grains in elongated aggregates along shear zones. Quartz makes up as much as 30 percent of some rocks; it is generally most abundant where biotite is most abundant.

Microcline occurs in minor wisps and irregular grains in the recrystallized cataclastic zones of some of the gneiss. Small quantities of microcline are widespread, but it is most abundant in the vicinity of quartz monzonite gneiss and pegmatite bodies where concentrations make up the augen and granitic-appearing stringers. Microcline replaces relict hornblende and plagioclase grains, as well as biotite and plagioclase in the cataclastic mortar. Several poikiloblastic microcline grains were observed that cut across granulated zones and contained biotite inclusions oriented in the direction of the shear plane; these microckine grains obviously crystallized after shearing. The transition from hornblende-biotite gneiss to the associated quartz monzonite gneiss takes place chiefly by an abrupt increase in the quantity of introduced microcline. Although microcline definitely was introduced along some granulated zones, in many places it was broken by later shearing.

Apatite, sphene, and magnetite are much more abundant in hornblende-biotite gneiss than in unsheared hornblende gneiss. They commonly make up several percent of the biotite- and quartz-rich gneiss, and in some specimens they constitute about 5 percent of the rock.

Irregular grains of epidote are scattered through most of the rock. They are erratically distributed, and generally in quite minor amounts, although in places epidote forms as much as 15 percent of the gneiss.

Origin — The transition from hornblende gneiss to mylonite gneiss through intermediate hornblende-biotite gneisses and schists is marked by progressively more intense shearing and granulation. In all of these rocks, only hornblende and plagioclase occur in the relatively large relict crystals; the groundmass consists essentially of a fine aggregate of crystalloblastic biotite, quartz, and feldspar. The transformation involved granulation of the original hornblende gneiss by penetrative movement and shearing. Plagioclase was broken and altered to a somewhat more sodic feldspar, but the quantity of plagioclase in the rock did not change appreciably. Hornblende, on the other hand, was broken down and the constituent materials recrystallized as a mixture of biotite, quartz, and the lime-bearing accessory minerals apatite, sphene, and epidote. These new minerals did not form pseudomorphs after hornblende but occur scattered through the granulated part of the rock.

As indicated by the relations of microcline along granulated zones in the rock, the shearing took place during regional granitization. The additional potash required by biotite could have been derived from this source, and perhaps some quartz also may have been introduced. As most biotite in the granulated zones shows no obvious relation to broken hornblende remnants and quartz is unevenly distributed, the recrystallization of materials derived from sheared hornblende involved some movement in solution. Possibly this accounts for the varying quartz-biotite ratio and the erratic distribution of the lime-bearing accessory minerals.

Mylonite gneiss

General features and distribution — The mylonite gneiss is made up of very fine grained crystalloblastic rocks that originated through intense shearing and granulation, followed by moderate recrystallization, of the different rocks in the gneiss complex. These rocks vary widely in composition, depending on the composition of the original gneiss, on the intensity of shearing, and on the degree of recrystallization. Many of the rocks are strongly streaked, and rounded to lozenge-shaped augen are common. Following the nomenclature in the glossary compiled by Waters and Campbell (1935, pp. 478, 481) these rocks are called mylonite gneiss; some rocks that have been so intensely sheared that all original textures were destroyed are classed as ultramylonite.

Mylonite gneiss is most abundant along the walls of Kings Canyon and Pinkham Creek Canyon; smaller areas of this rock are exposed in the core of Sentinal Mountain and along the front of the Medicine Bow Mountains northeast of Sentinal Mountain. Mylonite gneiss is most abundant where the original rock was dominantly hornblende gneiss; it dies out to the east and south, where large masses of quartz monzonite gneiss are present. Some large quartz monzonite gneiss bodies show considerable megascopic evidence of shearing along the margins, but this is lost away from the contacts where shearing produced intergranular cataclasis on a microscopic scale only. Irregular, relatively unsheared remnants of hornblende gneiss occur even in the areas of most intense movement.

Lithology — Mylonite gneiss derived from hornblende gneiss generally is a very fine grained medium- to dark-gray micaceous rock that is closely foliated and in part strongly streaked. The streaks are due to alternating biotite-rich and feldspar-rich layers that are commonly folded and crenulated on a small scale. Hornblende crystals occur in bands along the folia of some of these rocks. The foliation is uneven, and fractures commonly sparkle with reflections from abundant fine biotite. Rounded feldspar augen are relatively common, and in places they are strung out along layers like series of beads.

A dense, white to greenish gray, slightly greasy-appearing rock that may have been either a lime-silicate rock or a normal hornblende gneiss occurs along the flanks of Pinkham Creek canyon. This rock is made up of a very fine aggregate of epidote and clinozoisite with minor amounts of quartz. Much of it is megascopically structureless, but the more quartz-rich varieties show faint streaks parallel to the foliation of the adjacent gneiss.

Quartz monzonite gneiss was more resistant to shearing than hornblende gneiss, and even in the zones of greatest movement only the marginal parts of larger bodies were reduced to mylonite. Many of the smaller bodies, however, were ground up to a very fine grained, pinkish gray rock with a distinct quartzitic appearance. These siliceous-appearing rocks commonly show color banding parallel to the foliation of adjacent rocks. Where granulation was not so complete abundant rounded to ovoid pink feldspar grains are set in a thin-layered, vitreous groundmass. The crinkled layers bend around the augen much as flow bands in lava bend around phenocrysts. Moderately sheared quartz monzonite gneiss is distinctly finer grained and better foliated than normal quartz monzonite gneiss, but the cataclastic texture is not generally obvious.

Most mylonite gneiss derived from pegmatite has a distinctive appearance. Abundant rounded to lozenge-shaped augen of pink feldspar up to several inches in diameter are surrounded by a fine groundmass with a strongly streaked, pseudofluidal texture. The contrasting colors of the pink to gray "flow bands" that branch and bend around the pegmatite relicts and augen are due largely to the tendency of quartz and feldspar to aggregate into separate layers. Minor amounts of biotite and muscovite occur along some of the folia and accentuate the banding. Where the original rock was completely ground it is difficult to tell whether the light gray to pink ultramylonite was derived from quartz monzonite gneiss or from pegmatite.

Petrography -- The common dark gray mylonite gneiss derived from hornblende gneiss shows an excellent recrystallized cataclastic texture under the microscope. Rounded and broken plagioclase augen, generally calcic oligoclase, are set in a fine, crystalloblastic groundmass of feldspar, quartz, and biotite. Hornblende crystals are few or absent in most specimens, but they are abundant in some mylonite gneiss and tend to be concentrated along relatively hornblende-rich layers. Some hornblende occurs in recrystallized, poikiloblastic grains that are distinctly coarser than the fine groundmass. Curving streaks, or "flow bands," marked by abundant biotite flakes, branch and bend around the rounded feldspar augen. Those rocks that were reduced to a fine cataclastic aggregate with very few larg grains, later recrystallized to fairly even textured, dense rocks composed of biotite, feldspar, and quartz grains that are generally 0.2 mm or less in diameter. The megascopic banding is commonly indistinct under the microscope. Much quartz occurs in the recrystallized cataclastic rock, but some aggregates and microscopic veinlets string out along the curving bands. Epidote, apatite, and sphene are common accessory minerals. This rock is the cataclastic end member of the transitional series called hornblende-biotite gneiss that grades from slightly sheared hornblende gneiss to mylonite gneiss.

The fine-grained, white to greenish gray rock of uncertain parentage that occurs along Pinkham Creek Canyon is composed largely of clinozoisite and epidote with lesser quantities of quartz. Clinozoisite is much more abundant than epidote, but all gradations exist between the two minerals. Some epidote and clinozoisite crystals are 1 mm long; most grains are less than 0.5 mm in diameter. Quartz generally makes up only 10 to 20 percent of the rock, but in places it is much more abundant and tends to occur in bands or streaks. Sphene is a common minor accessory mineral.

All gradations exist between slightly sheared quartz monzonite gneiss and fine-grained ultramylonite. Some rocks that appear in hand specimen to be relatively fine grained quartz monzonite gneiss show marked intergranular cataclastic texture in thin section. Where shearing was not intense, granulation was confined to relatively thin zones along grain margins. With an increase in degree of shearing, the zones of intergranular brecciation became wider, and integrated shear zones cut through the rock. These shear zones generally intersect at relatively low angles in the direction of megascopic foliation. Where the mylonite stage was reached, most of the original grains were milled out to a fine cataclastic aggregate, and one of the several intersecting shear planes generally is dominant. The relict feldspar augen that survived are rounded and fractured, in places giving the appearance of having been rolled. Some of the larger grains show the external form of augen, but under crossed nicols they appear almost as brecciated as the groundmass. With extreme granulation all the original grains were broken down, and shearing tended to separate the different minerals in the groundmass into quartz-rich and feldspar-rich bands that bend around the ovoid feldspar augen. Most of the recrystallized grains in these rocks are less than 0.3 mm in diameter.

The composition of plagioclase apparently was not altered much by the granulation of quartz monzonite gneiss. Although plagioclase in the groundmass is too fine to determine accurately, it appears to have roughly the same index of refraction as the associated augen, which are either calcic albite or sodic oligoclase. Biotite was broken down into chlorite and sericite, which occur as scattered wisps and shreds through the rock. Although the cataclastic origin of the rocks is obvious, the present texture is crystalloblastic. Quartz apparently recrystallized most easily and is distinctly coarser than the feldspar. All grains have irregular, interlocking contacts.

Pegmatite underwent the same general changes as quartz monzonite gneiss. The augen tend to be much larger than those in comparable sheared quartz monzonite gneiss, but the streaked groundmass in both rocks has the same aspect.

Structure — Foliation in both hornblende-biotite gneiss and mylonite gneiss is parallel to that in the associated unsheared rocks, and lineation shown by minor fold axes and mineral elongation conforms closely to that in hornblende gneiss (see Fig. 3 A). Apparently the same general stress field persisted through regional metamorphism and dynamic metamorphism, but the type of deformation changed from isoclinal folding to more localized shearing and granulation.

Only the northern margin of the belt of sheared rocks is well exposed in the Northgate district; the rest of the belt is largely covered by younger sedimentary rocks in North Park, and relations are further confused by Laramide reverse faults. The northern margin of mylonite gneiss is irregular but fairly sharp, and generally is roughly parallel to the regional trend of foliation. An adit at a small copper prospect along Pinkham Creek near the eastern edge of the district cuts across the structure in a mass or relatively unsheared rock that projects into the mylonite gneiss and is nearly surrounded by it. Surface exposures suggest that the rock is unaltered, but careful inspection of the walls of the adit disclosed that numerous narrow bands of granulated rock cut the otherwise unsheared hornblende gneiss. Apparently the irregularities on the north margin of the mylonite gneiss were due to local concentration of the movement into narrow zones. The hornblende-biotite gneiss which is north of the zone of most intense shearing, resulted from relatively minor, scattered movement.

Mylonite gneiss merges to the east into large masses of quartz monzonite gneiss. The margins of these large bodies generally show intense granulation, but this feature is lost a short distance from the edge of the bodies where the rocks are similar in appearance to the quartz monzonite gneiss in the rest of the district. Evidently the large bodies of quartz monzonite gneiss were massive enough to resist penetrative shearing that reduced the weaker rocks to mylonite.

The apparent offset of the northern margin of the belt of mylonite gneiss across the Independence Mountain fault zone near Kings Canyon probably is misleading, as this offset is the reverse of that expected along a north-dipping reverse fault. More probably the broad zone of mylonite gneiss contains relatively large masses of ungranulated rock, or is made up of several distinct bands of mylonites, and the actual northern margin may not be exposed south of the Independence Mountain fault.

Origin — Mylonite gneiss resulted from the intense granulation of all rocks in the gneiss complex during the same period of shearing that developed hornblende-biotite gneiss. As pegmatite and quartz monzonite gneiss bodies which were formed at an earlier stage in the shearing were reduced to mylonite, the belts of intense granulation apparently developed late in the period of shearing. The relative movement between the rocks in the northern and southern parts of the district appears to have become more and more localized along certain zones as the shearing progressed.

Rheomorphic quartz monzonite gneiss

General features and distribution — Some quartz monzonite gneiss in the northwest and southeast parts of the Northgate district shows evidence that it became plastic and moved after it was transformed. The banded texture of normal quartz monzonite gneiss was largely destroyed, and a more uniform, aplitic texture was developed. Where movement was not great, highly contorted original banding still can be recognized; and this banding is commonly cut by a new, less distinct foliation. The trends of unreplaced hornblende gneiss inclusions show great departures from the regional east and northeast trend of foliation and layering, and reflect the larger-scale features of the deformation resulting from movement of mobile quartz monzonite gneiss.

Relations are clearest in the northwest corner of the district, where a funnel-shaped mass of quartz monzonite gneiss about 1 1/2 miles long by 3/4 mile wide intruded and deformed the rocks in the adjacent gneiss complex. Relict features and the differences in composition of adjacent layers in rheomorphic quartz monzonite gneiss suggest that the movement was by plastic flow rather than as a melt. Similar deformed, aplitic rocks occur along the southeast edge of the mapped area, and may be marginal to a larger mass of formerly mobile rocks. Relations in that area are so poorly understood that the following discussion will deal largely with the area in the northwest part of the district.

Structural setting — Local mobilization took place only within large bodies of quartz monzonite gneiss. The new structures developed during mobilization are locally transgressive, particularly along the strike of original foliation, but more commonly the once-mobile rocks grade into rocks of the surrounding gneiss complex.

The funnel-shaped mass in the northwest corner of the district is a prominent topographic feature that stands out strongly in the field and on aerial photographs. Discontinuous layers of quartz monzonite gneiss and minor amounts of hornblende gneiss close completely around the structure and give it a distinct annular appearance. Layers dip 60° to 70° N. on the south flank, 80° to 85° W. on the east nose, 80° N. through vertical to 85° S. on the north flank, and the northwest nose plunges 50° to 60° SE. (see Pl. 2). Where annular layers are parallel or nearly parallel to the foliation or banding in the surrounding gneiss complex, margins of the funnel-shaped mass are completely gradational. They grade into normal rocks of the gneiss complex to the south and into highly deformed rocks to the west and southwest; the northern margin is outside the area mapped and was not observed. The highly deformed layering in the surrounding rocks splits and bends around the northwestern nose of the "funnel," and rocks in the vicinity of the nose are massive, nearly structureless quartz monzonite gneiss. The eastern nose of the flow structure is sharply transgressive against adjacent hornblende gneiss and pegmatite, and the annular layers cut almost at right angles across the more normal trend of the country rocks. Massive quartz monzonite gneiss marks the transition between the funnel-shaped mass and the surrounding rocks in the areas where the annular layers swing from nearly normal to parallel to the adjacent banding and foliation. New textures are most prominent along the flanks of the funnel-shaped mass where most movement apparently was concentrated; some relict textures can be recognized in the core and toward the outside edges of the "funnel."

The area of highly deformed rocks to the west and southwest of the funnel-shaped mass contains hornblende gneiss and quartz monzonite gneiss that range from nearly normal rocks of the gneiss complex to massive, recrystallized rocks with no relict textures. In the absence of distinctive horizon markers, it is difficult to determine the details of structure in this area, but the relations of the deformed hornblende gneiss inclusions indicate the general course of plastic deformation. The northward-plunging fold adjacent to the funnel-shaped mass trends almost at right angles to the trends of folds in regionally metamorphosed rocks away from the area of rheomorphism. Original small-scale layering in the quartz monzonite gneiss was highly crumpled during this deformation, indicating that mobilization and deformation followed metasomatic transformation. Some bands in the original quartz monzonite gneiss were milled out into spindle-shaped boudins an inch or two in diameter and a foot or two long. Lineation shown by these boudins and by the contorted bands conforms to the same pattern of lineation in regionally metamorphosed hornblende gneiss and in the later, dynamically metamorphosed mylonite gneiss (see Fig. 5B). Apparently the same stress field persisted through regional metamorphism, metasomatic and dynamic metamorphism, and mobilization.

Deformation of the rock west of the annular flow structure apparently was accompanied by plastic flow, particularly of the quartz monzonite gneiss. The larger folds show thickening on limbs and crests, and new textures are best displayed in areas of greatest apparent thickening. The southern margin of the large mass of quartz monzonite gneiss that encloses the formerly mobile rock follows the normal regional trend of the gneiss complex. Fixing attention on the part of the large, north-trending cross fold within the outermost discontinuous arc of hornblende gneiss inclusions, one can see that the fold starts on the west from an interlayered series of quartz monzonite gneiss and hornblende gneiss about 1,500 feet thick. The hornblende gneiss inclusions in the fold show a progressively wider spacing outward from the core of the fold, and the interlayered series of rocks where the fold loses its identity to the east is nearly twice as thick as at the western end. Much of the apparently thickened quartz monzonite gneiss in the core and eastern limb of the fold is massive and only minor relict texture survived deformation. If the outer, discontinuous band of hornblende gneiss inclusions were straightened out, it would extend nearly to the east end of the mass showing annular flow structure. Thus the intrusion of the funnel-shaped mass of mobile quartz monzonite gneiss apparently forced the displaced rocks relatively westward by plastic flow, which is recorded by the folding. Quartz monzonite gneiss shows the greatest thickening, but local bulging of hornblende gneiss inclusions suggests that this rock also underwent plastic flow. No surfaces of discontinuity other than the layering were discovered in this area, and apparently the deformation was wholly plastic and without faulting.

The area between the north-trending cross fold and the North Platte River underwent deformation as intense as that in the area to the east. The hornblende gneiss inclusions are highly contorted and irregular, and the larger bodies of quartz monzonite gneiss are rather massive, as though they too were thickened through flow. The relations undoubtedly record the movement of plastic quartz monzonite gneiss, but geologic data on adjacent areas are insufficient to permit an evaluation of the structures.

The markedly different behavior of the rocks east and west of the funnel-shaped mass is probably due to differences in the plasticity of the surrounding rocks. The large mass of quartz monzonite gneiss feathers out into hornblende gneiss a short distance east of the "funnel"; the rocks here probably were somewhat cooler and more brittle, and the flow structure cuts sharply across them. Quartz monzonite gneiss is abundant west of the funnel-shaped mass, and reconnaissance west of the North Platte River disclosed that it is the dominant rock there as well. Apparently toward the interior of this large mass of quartz monzonite gneiss, the rock was so plastic that it deformed readily with the local movement of more mobile rock.

Lithology — Rocks in the area where the quartz monzonite gneiss was widely mobilized show all gradations in the destruction of the layered texture of normal quartz monzonite gneiss and the development of a new, aplitic texture. Although still medium-grained, most of the rocks are somewhat coarser than the original quartz monzonite gneiss; some feldspar grains are 3 mm or more in diameter. Quartz and feldspar form an even-grained pink aggregate with a little biotite. The biotite tends to be oriented roughly parallel to the larger-scale layering, but in most rocks it is so sparse and widely scattered that foliation is poor or absent. Locally biotite is more abundant and tends to form thin, discontinuous bands, rendering the rock distinctly gneissose.

Although most rocks show little banding or foliation in a hand specimen, they are distinctly layered on a larger scale. The layers recognized in outcrops range from a few feet to a few tens of feet in thickness. Many adjacent layers are similar and differ only slightly or not at all in texture and composition; elsewhere the rocks of the several layers differ markedly. Hornblende gneiss is abundant in the area of deformed rocks west and southwest of the funnel-shaped mass, and is subordinate but widespread within the mass showing annular flow structure as well. Inclusions of hornblende gneiss are oriented parallel to the layering in rheomorphic quartz monzonite gneiss, and the contacts of the inclusions are sharp.

Quartz monzonite gneiss with highly contorted but still recognizable original layering occurs throughout the area of apparently folded rocks, and in the core of the funnel-shaped mass as well. In most such places a new foliation cuts the deformed layers, and all stages in the disruption of the original texture can be seen. The original banding is still readily recognizable where it parallels the new foliation, but it is very hazy and indistinct where it is cut by the new foliation. Relict textures are best displayed in the smaller bodies or near the margins of the larger masses of quartz monzonite gneiss; they were largely destroyed in areas where significant thickening took place.

Irregular pegmatitic masses occur throughout the rheomorphic quartz monzonite gneiss. These masses have gradational margins and apparently formed by local recrystallization that obliterated all previous textures, including the crumpled original layering and the later, indistinct foliation and layering related to plastic movements.

Though generally sparse, biotite is the most common ferromagnesian mineral in these rocks. Hornblende, or hornblende and biotite, occurs in some layers, and the rock, although still leucocratic and aplitic, commonly has a slightly different aspect than biotite-bearing quartz monzonite gneiss. In outcrop, hornblende-bearing rocks appear somewhat more closely knit and blocky, the color generally is lighter, and where hornblende makes up more than a few percent of the rock it gives the rock a distinctive foliation. Most of these differences are so minor that they are difficult to describe, but the rocks can be recognized readily in the field.

Hornblende gneiss inclusions appear much the same as normal hornblende gneiss in the rest of the gneiss complex. Some rocks show a tendency for plagioclase and hornblende to occur in light- and dark-colored clusters, but more commonly the rocks are relatively even grained salt-and-pepper aggregates.

Petrography — Minerals in rheomorphic quartz monzonite gneiss largely recrystallized during movement and deformation. The textures range from typically crystalloblastic with mutually interfering grain boundaries to various mixtures of crystalloblastic and replacement textures. In the latter, microcline and quartz, which embay and replace plagioclase and biotite, apparently were nearly contemporaneous. Most rocks show some replacement textures. Except for the minor biotite, minerals in these rocks show little or no dimensional orientation but occur in aggregates of equidimensional, xenoblastic grains. Although most rocks appear equigranular in hand specimen, they show a wide range of grain size in thin section.

Plagioclase in the formerly mobile quartz monzonite gneiss for the most part is clear or only slightly saussuritized. In the more common, biotite-bearing or alaskitic varieties of quartz monzonite gneiss, the plagioclase composition is generally between An_5 and An_{15}; in hornblende-bearing quartz monzonite gneiss it is generally somewhat more calcic. Plagioclase forms roughly equidimensional grains up to 2.5 mm in diameter in rocks with good crystalloblastic texture, but generally it is corroded by microcline and quartz and shows all stages of replacement. Many plagioclase grains show the effects of minor deformation that was not shared by the adjacent, recrystallized microcline and quartz. Twin lamellae are distorted, grains show wavy extinction, and some crystals were broken into mosaics of smaller grains with slightly different orientations. Only a small percentage of the plagioclase grains are deformed, but the minor cataclasis took place throughout the area where rocks were mobile. The grains evidently were bent and broken while the rocks were being deformed; apparently some plagioclase survived plastic movement without significant recrystallization.

Myrmekite is widespread in the rheomorphic quartz monzonite gneiss and generally occurs along the margins of plagioclase adjacent to corrosive microcline. The myrmekite developed subsequent to the brecciation and deformation shown by some of the plagioclase grains.

Microcline crystals range from mere intergranular wisps to relatively coarse, poikiloblastic grains 3 mm or more in diameter that enclose relict inclusions of plagioclase. Although locally they have mutually interfering, crystalloblastic relations with the adjacent minerals, they are generally corrosive toward the plagioclase and biotite. Twinning is slightly distorted in a few grains, but adjacent grains show no related cataclastic texture. In many places, microcline tongues with replacement relations project into broken plagioclase grains along fractures or strained zones. Although microcline shows a wide range in grain size, most crystals are medium-grained and either of about the same size as the associated plagioclase crystals or a little coarser.

Quartz evidently recrystallized during a relatively long period. It occurs with plagioclase and microcline in the crystalloblastic aggregates, as grains about contemporaneous with strongly corrosive microcline, and as lobate to irregular grains that cut microcline as well as plagioclase and biotite. When observed under low magnification and with crossed nicols, quartz in many rocks appears as an overprint of lobate to irregular grains impressed on the microcline and plagioclase aggregate. Grain size is highly uneven; the older grains are nearly as large as the associated feldspar grains and tend to be coarser and more irregular than the younger, lobate to rounded grains that cut microcline. Quartz also did not share the deformation shown by some plagioclase and in many places preferentially replaced the strained parts of plagioclase crystals.

The irregular masses of pegmatitic rock that cut the crumpled layers of rheomorphic quartz monzonite gneiss formed through the more complete replacement and recrystallization by microcline and quartz. The relations are similar to those observed in most thin sections where microcline and quartz are corrosive toward plagioclase and biotite. Evidently the recrystallization of most microcline and quartz was later than the deformation.

Biotite rarely makes up more than a few percent of the rheomorphic quartz monzonite gneiss, and much of the rock carries only a trace as small, corroded shreds and grains with abundant associated magnetite. In general, magnetite is most abundant where biotite is most highly corroded. A few layers of the rock, however, contain as much as 10 percent of biotite, and here it either forms a crystalloblastic aggregate with plagioclase, microcline, and quartz or has mutually interfering contacts toward plagioclase and is corroded by microcline and quartz. Where it is most abundant, the biotite flakes are as much as 1 1/2 mm long, but most of the corroded shreds are less than 1 mm.

Magnetite is considerably more abundant in rheomorphic quartz monzonite gneiss than in normal quartz monzonite gneiss, and in places makes up to a percent or two of the rock. It occurs as small, equant crystals 1 mm or more in diameter scattered through the rock and as dusty grains associated with the corroded biotite. Most of the magnetite recrystallized during mobilization, and many grains tend to be idiomorphic. The relative increase in magnetite along with a decrease in biotite content and the close association of magnetite with corroded biotite crystals suggest that much of the disseminated magnetite developed by recrystallization of material left from the destruction of biotite during mobilization.

Small, rounded to idiomorphic red garnet crystals up to 2 mm in diameter occur here and there through the rheomorphic quartz monzonite gneiss. They are completely recrystallized and show no evidence of their origin, but it is likely that they are recrystallized relicts that survived mobilization and deformation.

Hornblende occurs in some of the discontinuous layers of quartz monzonite gneiss in the funnel-shaped mass and in the deformed rocks to the west and southwest. It ranges from mere traces up to 10 percent of some rocks and generally is most abundant where microcline makes up 25 percent or less of the rock. Irregular grains of hornblende generally have mutually interfering contacts with plagioclase grains, and, in those rocks that have minor replacement relations, with microcline and quartz grains as well. In most rocks, however, microcline corrodes the hornblende, and where microcline is abundant the hornblende tends to be in small, ragged grains.

Sillimanite, with associated muscovite, was found in two specimens from the once-mobile quartz monzonite gneiss; it makes up nearly 15 percent of a resistant, spindle-shaped boudin about 2 inches thick and 1 1/2 feet long from the area of deformed rocks, and a little was seen in a specimen from the north flank of the funnel-shaped mass. In this the sillimanite and muscovite occur along several closely spaced fractures that cut the crystalloblastic texture of the rheomorphic rock. The minor shear zones were largely healed by later recrystallization, and the muscovite and sillimanite are both younger than the shearing. Sillimanite forms single needles and sheaves; also bundles enclosed in muscovite, microcline, or quartz. Much of the muscovite has a peculiar, myrmekitic texture with irregular, wormy quartz inclusions, and in part is closely associated with biotite and apparently developed from it. Petrographic relations suggest that biotite along the shear zone altered to muscovite and minor magnetite, and that muscovite in turn broke down into sillimanite and perhaps microcline. The materials migrated considerably during recrystallization, and details of the alteration are obscure. Sillimanite and muscovite, however, are confined to the shear zones, and muscovite is associated with biotite on one hand and sillimanite on the other. This distribution suggests a progressive alteration. A similar sequence is suggested by relations in the boudin, but greater migration of recrystallizing materials makes interpretation difficult.

The dominant biotite-bearing or alaskitic varieties of rheomorphic quartz monzonite gneiss carry significantly more microcline than the average quartz monzonite gneiss elsewhere. Seventeen specimens from the funnel-shaped mass and the deformed rocks to the west averaged 41 percent microcline. The average microcline content of 22 specimens of typical quartz monzonite gneiss from all parts of the district was only 32 percent, a significant difference. The plagioclase content (An_{5-15}) averages only 25 percent in the 17 specimens of rheomorphic gneiss; of these only 7 can be classed as quartz monzonitic or granodioritic, whereas the remaining 10 are truly granitic in composition.

Only traces of biotite are present in 9 of the 17 specimens of rheomorphic rock; 5 specimens have 1 to 5 percent, and 3 have 5 to 10 percent biotite. Magnetite is an abundant accessory mineral in all the specimens and makes up 1 or 2 percent of at least 10 of them. The quartz content ranges between 25 and 50 percent and averages 35 percent in the 17 specimens.

Hornblende-bearing rheomorphic quartz monzonite gneiss varies much more in composition than the more common varieties of quartz monzonite gneiss. Microcline ranges from mere traces up to 50 percent of the rock and generally is very irregularly distributed. Of eight specimens studied it averages almost 30 percent. Mutual crystalloblastic relations are more common in these rocks than in the biotite-bearing rocks, but even here most microcline tends to embay the plagioclase and hornblende. Plagioclase ranges between 20 and 60 percent of the eight specimens studied and averages around 35 percent. The composition ranges between An_{10-26} and averages An_{20}. In general, plagioclase is most calcic where it is most abundant; but in one specimen with only traces of microcline sodic oligoclase (An_{12}) makes up nearly 60 percent of the rock, while in another, calcic oligoclase (An_{26}) makes up only 20 percent and is subordinate to microcline. Deformed plagioclase grains occur in four of the eight specimens studied. The hornblende content also varies considerably; two of the eight specimens studied contain only traces, four contain 1 to 5 percent, and the other two 5 to 10 percent. Where it is most abundant the hornblende occurs in a crystalloblastic aggregate with plagioclase, and locally with microcline and quartz. Generally it is somewhat corroded, and where small in amount, it forms small ragged wisps and grains. Magnetite constitutes up to 2 percent of these rocks and is even more abundant here than in the biotite-bearing varieties. Traces of biotite occur in all of these rocks. The quartz content is rather uniform and ranges between 30 and 35 percent in all specimens studied.

The inclusions of hornblende gneiss in rheomorphic quartz monzonite gneiss resemble normal hornblende gneiss in hand specimen, but in thin section they display a completely recrystallized texture. The hornblende tends to be idioblastic and the plagioclase grains are more equant and much less irregular than in regionally metamorphosed hornblende gneiss. In all specimens studied the plagioclase is highly saussuritized and sericitized and ranges in composition between An_{30} and An_{35}. A little quartz is widespread as an overprint of small, rounded blebs. Some specimens show a tendency toward mineral segregation and have irregular clusters of somewhat coarser hornblende and plagioclase set in the more typical hornblende-plagioclase aggregate.

Origin — Crumpled original banding and the gradual destruction of normal quartz monzonite gneiss textures and the development of new textures with an increase in degree of deformation indicate that the mobilization followed the metasomatic transformation. As the lineation shown by boudins and axes of small crenulations in contorted gneiss is parallel to that in regionally and dynamically metamorphosed rocks, the mobilisation presumably took place under the same stress field. Corrosion relations of microcline and quartz grains and the irregular pegmatitic masses that obliterate earlier textures suggest that silica- and alkali-bearing solutions similar to those active in metasomatic transformation persisted through rheomorphism. Thus it seems probable that the change from regional metamorphism to dynamic and metasomatic metamorphism and to rheomorphism reflected a progressive change in conditions during a single orogenic episode.

Condition of rocks — The crumpling, destruction of texture, and apparent thickening and thinning of the deformed rocks rather conclusively indicate that they were considerably more plastic than those elsewhere in the gneiss complex, but relations within the area of formerly mobile rocks are not so clear cut. The funnel-shaped mass is the only mapped structure within the area of rheomorphic rocks that cannot be explained by deformation of rocks that previously occupied nearly the same position they now fill. This feature has the appearance of a foreign body that forced aside the rocks already there; most of the displaced rocks were shoved westward, where they were further deformed by movement of other mobile masses of rock.

A knowledge of the relative plasticity of the funnel-shaped mass and the surrounding rocks at the time of origin is critical for the interpretation of the flow features. Considering only the pattern of deformation shown on the map (Pl. 2) it is conceivable that the annular structure either could have acted as a more resistant mass that rotated and controlled deformation in the adjacent, more plastic rocks, or it could have been a more mobile mass that attained its present position by invading and shoving aside the adjacent rocks. The axis of the funnel-shaped mass roughly parallels the tectonic axis elsewhere shown by fold axes in regionally and dynamically metamorphosed rocks and by lineation in adjacent, contorted rheomorphic gneiss. From geometrical considerations, the funnel-shaped body is properly oriented to have originated through rotation. However, several lines of evidence suggest that the funnel-shaped mass was more plastic than the surrounding rocks and that rotation was unimportant.

Under the rotation hypothesis, the annular layers should have originated through differential rotation of the various layers. It is significant that these layers are neither most prominent nor most closely spaced near the periphery, as might be expected if the rocks composing the "funnel" were resistant; instead the layers, though well-formed throughout the structure, are somewhat more prominent near the middle of the limbs, suggesting that the differential movement was rather evenly distributed. The amount of differential movement between the layers appears to have been great. For example, inclusions of hornblende gneiss near the northwestern and southeastern ends of the mass were so dragged that their foliation strikes at right angles to the regional trend. The amount of rotation suggested by the map pattern is so small however, that the distributive movement between any two layers would be almost unmeasurable and certainly inadequate to account for so great a drag.

If the deformed rocks west and southwest of the funnel-shaped mass were straightened out and corrected for thickening, they would occupy much of the area now filled by the rocks in the funnel-shaped mass. Thus the funnel-shaped mass appears to be a foreign body, and simple rotation does not explain how it came to occupy the space it now fills.

Evidence from the rocks themselves is even more telling against the hypothesis of a rotating resistant mass. The rocks in the funnel-shaped mass are indistinguishable from many of the more deformed and thickened rocks in the adjacent areas. These grade into normal rocks of the gneiss complex with a decrease in the intensity of deformation. The destruction of old textures and development of new provides a crude measure of the extent of plastic deformation. As relict textures are almost completely absent on the flanks of the "funnel," it appears that the rocks here were more mobile as a whole than the most plastic rocks in the adjacent, highly deformed masses where relict textures are still widespread.

Method of movement -- The evidence for progressive softening and mobilization of quartz monzonite gneiss suggests the method by which the rock moved. The hornblende gneiss inclusions and the quartz monzonite gneiss, which still show such relict features as crumpled original layering, apparently retained structural continuity during deformation and acted as plastic solids. To what extent the rocks with entirely new textures behaved as plastic solids and to what extent as viscous fluids are considerably more difficult to answer. Many of the aplitic rocks are structureless or only slightly gneissose in hand specimen, but they occur in discontinuous layers that close around the funnel-shaped mass. Within each layer the rocks are relatively uniform and may be either very similar to or markedly different from rocks in adjacent layers. Layering is fully as distinct where rocks in adjacent layers are almost indistinguishable from each other as where they contrast sharply; evidently the layering is an original feature of the rocks. Thus the method of movement was such as to give relatively homogeneous layers with similar or contrasting composition, separated by sharp discontinuities.

Leucocratic, hornblende-bearing quartz monzonite gneiss is a minor but widespread rock in the funnel-shaped mass and in the more deformed parts of the adjacent rocks. This rock shows the recrystallized texture of rheomorphic rokks, but is extremely variable in composition. In general the plagioclase is more calcic, and the microcline is less abundant and more irregularly distributed than in the more common varieties of rheomorphic quartz monzonite gneiss. Hence the hornblende-bearing rheomorphic rock is more closely related mineralogically to hornblende gneiss than to quartz monzonite gneiss and probably originated by shearing out of hornblende gneiss while the rocks were mobile.

Rocks that show contorted original layers have the same microtextures as the layered rocks without relict textures, and are cut by similar irregular pegmatitic masses; and deformed plagioclase grains are found in rocks from all occurrences. Apparently complete fluidity was not attained by any large segment of rocks. The significantly larger percentage of microcline in rheomorphic quartz monzonite gneiss and the post-deformation crystallization of microcline and quartz, however, suggest that the mobile rocks were at least lubricated by alkalic solutions, and the material surrounding the plagioclase grains may have closely approached a melt.

Penetrative intergranular movement in the presence of alkalic solutions, followed by recrystallization, converted the originally banded quartz monzonite gneiss into a more uniform, aplitic rock with more abundant microcline and minor amounts of biotite. Where hornblende gneiss was subjected to penetrative movemant, much of the hornblende was destroyed, the plagioclase was converted to a more sodic feldspar, and the rock was irregularly penetrated by alkalic and silicic solutions. The hornblende gneiss that was not sheared out but was dragged along more or less passively recrystallized somewhat but did not change composition greatly. The sharp discontinuities between relatively even textured layers, which range from very similar compositions to markedly different compositions, suggest that much of the movement in the mobile rock took place by shear between the layers. Apparently movement was that of a very plastic solid or an extremely viscous fluid in which the various layers retained their compositional identities.

Direction of movement -- In a determination of the direction of flow, much hinges on the question of how the orientation of structures at the present time compares with that at the time of origin. This question is very difficult to answer as it is impossible even to determine the extent or direction of Laramide deformation within the pre-Cambrian rocks, without considering the long periods for which we have no record. There is no petrographic evidence, however, for a period of metamorphism later than that during which the rocks in the gneiss complex were formed, and the regional trend of foliation and lineation in the gneiss complex are rather uniform. Most local deviations in the attitude of foliation occur in the vicinity of crests and troughs of folds. Evidence for local deformation was seen only along large Laramide faults, and involved cataclasis rather than flexure. That large-scale tilting, folding, or inversion took place seems unlikely from a consideration of the zonal distribution of the various rock types. Large masses of quartz monzonite gneiss occur in the northern and southern parts of the district, and each of these masses shows evidence that some of the rock became mobile subsequent to transformation. These two masses reached about the same stage in development at the time of origin, and presumably were at comparable depths. Pegmatite and biotite-garnet gneiss bodies are abundant through the central part of the district in a zone peripheral to the large bodies of quartz monzonite gneiss, and this zone may have been downwarped. This suggestion is not borne out by any systematic variation in attitude of foliation through the district. Although pegmatite and biotite-garnet gneiss are not uniformly distributed, they both occur throughout the zone, so presumably there has been no strong east-west tilting. Although not conclusive, these considerations suggest that the present vertical coodinate through the rheomorphic rock was not far from vertical at the time of metamorphism and mobilization.

The annular layers of the funnel-shaped mass could arise most easily by differential movement either around, or in the direction of the axis of the funnel. In view of the evidence that the rocks in the annular structure were more plastic than the surrounding rocks at the time of deformation, (see previous section on Conditions of Rocks), it is difficult to understand how rotational movement could account for the features shown. If the funnel-shaped structure had been a mass of mobile rock that intruded and shoved aside the adjacent rocks by movement in the direction of the axis, the differential movement due to frictional drag on the walls would have been distributed through much more of the mass than if the structure had been a rotating resistant body. In a mobile map the greatest differential movement would have taken place along the flanks where the most prominent layering and best-developed new textures now occur , and movement of the mobile rock would be limited only by the physical condition of the intruded rocks. It seems necessary to postulate movement in terms of at least several thousands of feet, to account for the discordant relations of the annular structure and the orientation of hornblende gneiss inclusions parallel to the layering and locally athwart the regional trends. The funnel shape and the general appearance of the mass, suggestive of a foreign body that shoved aside the pre-existent rocks, implies a rootless mass of mobile rock with the greater part of the body above the levels now exposed.

Cause of movement — Movement in the direction of the axis of the annular structure would be subparallel to the tectonic axis as shown by the lineation of fold axes in regionally and dynamically metamorphosed rocks and thus about at right angles to the direction commonly inferred for regional tectonic transport. The regional stress field that persisted through the complex sequence of metamorphism in the district could hardly account for movement of this type. It seems more plausible that the movement was governed largely by gravity. Quartz monzonite gneiss is considerably less dense than hornblende gneiss, and if large enough masses of the lighter rock became mobile under the influence of high temperature and abundant pore solutions, the buoyant force would exceed the strength of the surrounding rocks and the mobile rock would rise.

The specific gravity of typical specimens of most pre-Cambrian rock types in the district was determined (see Table 1), and the average specific gravity of the rocks in different parts of the district was approximated. The specific gravity of biotite-bearing rheomorphic quartz monzonite is about 2.64, the average specific gravity for the rocks cropping out in a strip of gneiss complex a mile wide along the south margin of the large mass of quartz monzonite gneiss that includes the once mobile rocks is about 2.76, and the average specific gravity of rocks in a large block of gneiss complex south of this strip is about 2.80. The average specific gravity of rocks in that part of the gneiss complex lying between the large mass of quartz monzonite gneiss in the northwest part of the district and the stock of Sherman granite is near 2.78.

These comparative figures represent only the order of magnitude of the differences during mobilization. They do not take into account variations due to elevated temperature and pressure; and more importantly they do not show the effect of pore solutions. If, as seems likely, intergranular alkalic solutions were abundant in the mobile rock, they would have lowered the specific gravity of that rock significantly. A comparison of the specific gravity of adjacent blocks of rocks now exposed considers only part of the environment at the time of rheomorphism; the buoyant force of the mobile rocks depended as well on the specific gravity of the overlying rocks. Metasomatism was zonal, and transformation probably decreased upward. The hydrostatic pressure of the cooler and presumably more dense overlying rocks would provide a powerful mechanism to force the lighter, mobile rocks upward.

Table 2 Approximate specific gravities of pre-Cambrian rocks from the Northgate district, Colorado

ROCK	SPECIFIC GRAVITY
Hornblende gneiss	2.95-3.00
Quartz monzonite gneiss	2.61-2.63
Biotite-garnet gneiss	2.80-2.85
Pegmatite	2.58-2.59
Hornblende-biotite gneiss	2.80-2.82
Mylonite gneiss	2.68-2.78
Rheomorphic quartz monzonite gneiss	2.64
Sherman granite	2.61-2.63

Intrusive rocks in the Northgate district comprise some very fine grained andesite porphyry dikes, and a stock and associated dikes of quartz monzonite. These bodies cut across the structures in the gneiss complex and are believed to be much younger. The andesite porphyry dikes are definitely older than the quartz monzonite stock and may be unrelated to it.

Andesite porphyry

General features and distribution -- A very fine grained, medium- to dark-gray porphyritic rock occurs in several north-trending dikes near the lower end of Camp Creek. The rock is extremely hard and resistant to weathering, and its outcrops are numerous. The dikes are up to 5 feet thick and 3,200 feet long; they are nearly vertical, and all have the same general trend. No offset of the walls was detected across any of the dikes, which were apparently injected into tension fissures. Most dikes end in hornblende gneiss, and no fracture or group of fractures continue along the strike.

The dikes trend roughly at right angles to the strike of foliation of the gneiss complex and in the same general direction as the plunge of fold axes in the metamorphic rocks. Evidently the tension fissures along which the dikes were injected were not related to the original deformation plan of the gneiss complex. Similar small dikes are found in xenoliths in the Sherman granite stock south of lower Camp Creek;

these are definitely older than the enclosing granitic rock. The dikes are intermediate in age between the rocks in the earlier pre-Cambrian gneiss complex and the later Sherman granite and may be unrelated to either.

Petrography — The andesite porphyry typically is composed of 40 to 50 percent sodic andesine, 15 to 20 percent green biotite, 10 to 15 percent orthoclase, and 5 percent epidote. Apatite and magnetite are relatively abundant minor accessory minerals. Andesine occurs as idiomorphic phenocrysts up to 1.5 mm long and as small, lathlike crystals in the fine groundmass. Biotite occurs in irregular plates and generally is evenly distributed throughout the rock. A few ragged poikilitic hornblende phenocrysts up to 1 mm in diameter are found in some dikes. Quartz and orthoclase form a fine mosaic interstitial to the other major constituents. Epidote is secondary. The crystals in the groundmass generally are 0.5 mm or less in diameter.

Sherman granite (quartz monzonite)

General features and distribution — Intrusive quartz monzonite forms a stock and associated dikes in the central part of the Northgate district and several related dikes near the eastern edge of the district. Although the relief is not great, the area of the stock is extremely rough. Weathering and erosion of the relatively coarse grained, jointed rock has reduced the surface to a rugged mass of rounded pinnacles and boulders, abrupt cliffs, and benchlike flat areas. Very little soil or talus is present. The main body of the stock passes eastward into a complex of dikes that cuts the older gneisses on Pinkham Mountain. The broad summit of Pinkham Mountain is relatively flat and is covered by a heavy pine forest and a thick mantle of weathered rock. The dikes are more resistant to weathering than the surrounding gneisses, however, and tend to stand out as low outcrops. Exposures of granite on the slopes of Pinkham Mountain are good.

Although the composition of most of the rock is near quartz monzonite, it is similar to the Sherman granite first described by Blackwelder (1908, pp. 778-788; Darton et al., 1910) from the widespread exposures in the Laramie and Sherman quadrangles, Wyoming. The Sherman granite, as described by Blackwelder, is very coarse-grained and is composed chiefly of pink feldspar, glassy quartz, hornblende, and biotite; it varies considerably in texture and composition and commonly is coarsely porphyritic. At some points its contacts are sharp, but elsewhere they are marked by broad zones of breccia containing fragments of older rocks cemented by granite. Nowhere does the country rock show notable evidences of metamorphism. With certain exceptions, the above describes the stock in the Northgate district very well.

The nearest exposure of the Sherman granite in the Laramie quadrangle (Darton et al., 1910) is on Sheep Mountain, about 16 miles northeast of the Northgate district. Reconnaissance near the Colorado-Wyoming state line showed that a large mass of similar granitic rock extends from a point about a mile east of the Northgate district for approximately 6 miles eastward to a point where it is covered by younger sedimentary rocks near the Laramie River. The western margin of this body is cross-cutting and sharp and shows little evidence of contact metamorphism. A similar large granitic mass occurs in the central part of the Park Range, 20 to 25 miles southwest of the Northgate district. Thin sections of specimens collected near Rainbow Lake in the Park Range and along Boswell Creek, about 2 miles east of the Northgate district, were studied for comparison. The rock from both of these areas strongly resembles that in the Northgate district, and the stock in the Northgate district appears to be but one of many related granitic masses that occur in the pre-Cambrian of northern Colorado and southern Wyoming.

The variation in texture and composition of the quartz monzonite in the Northgate district is related in large part to deuteric or hydrothermal alteration. Plagioclase, biotite, and perhaps some quartz were the earliest minerals to crystallize from the magma, and they formed a rock of dioritic composition. The rock was deformed after it was consolidated or nearly consolidated, and the biotite and plagioclase crystals were bent and broken.

Silica- and alkali-bearing solutions permeated the broken rock; and the early minerals were corroded and in part replaced by abundant microcline, quartz, and more sodic plagioclase. The intensity of the hydrothermal alteration varied from place to place through the stock and associated dikes; the mineral transformations tend to show a rough zoning. In general the plagioclase is more sodic and the biotite is largely altered to chlorite and sericite in the peripheral zones.

Emplacement — The magma from which the rock in the stock originally formed was emplaced at the levels now exposed chiefly by means of magmatic stoping. The hydrostatic pressure of the rising magma column undoubtedly caused some initial fracturing and dilation of the roof of the magma chamber and permitted the earliest dikes to penetrate the surrounding rocks. These fractures, filled with tongues of magma, served as locally favorable zones of accelerated stoping. Many examples of fractures irregularly enlarged by local stoping can be seen on the geologic map (Pl. 1). The maximum spreading of such a fracture that can reasonably be credited to the hydrostatic pressure of the magma is limited to the narrowest width across the fissure, and in most places this appears to have been relatively small. It is difficult to determine which of the dikes or irregular masses of granite were emplaced along fractures opened by actual spreading of the roof of the magma chamber. Once stoping enlarged a single fracture or zone of fractures to any extent above the general top of the magma body, other fissures could open by the movement of blocks of country rock toward the already active zone of stoping, and no further dilation of the roof or walls of the magma chamber would be required.

The striking straightness of the stoping dikes and the margin of the stock shows that the emplacement of the magma was controlled in general by two different groups of fractures. Many of the blocks pried from the roof and walls of the magma chamber broke along two sets of fractures, one roughly parallel to the foliation and the other at right angles. Small blocks in particular show this control, although several large masses also are bounded by these fractures. Most of the fissures developed along these directions of weakness are rather irregular and generally do not persist far. Thus the small-scale fracturing of the country rock and the piecemeal stoping by the magma appear to have been controlled largely by directions of weakness inherent in the wall rocks.

Another group of fractures trends east to southeast more or less parallel to the elongation of the stock. These fractures control parts of the northern margin of the stock and are followed by most of the dikes that extend eastward from the main body of the stock toward the Baker Pit and the Camp Creek mine (see Pl. 1). They trend obliquely to the foliation in the gneiss complex, and most have relatively smooth and regular walls. The fissures followed by these dikes are not related to known directions of weakness in the wall rocks, are much more regular and persistent than those following the foliation or related fractures, and are parallel to the general trend of the stock. They might well have originated in the fracturing and spreading of the roof of the magma chamber by the hydrostatic pressure of the rising column of magma. The more abundant but smaller-scale fissuring along foliation thus may have resulted from the detailed brecciation of a roof already stretched and broken along east-to southeast-trending master fissures.

The details of magmatic stoping are exceptionally well shown in many places in the stock. The northern margin of the stock has many angular, steplike irregularities; and in one place a narrow dike projects out from the main body of the stock parallel to a nearby section of the angular contact. In this place the dike most certainly was frozen while prying off a block from the wall of the stock. The extremely complex group of dikes and stoped blocks on Pinkham Mountain displays all stages in the disruption of the roof over a stock. The magma apparently penetrated fairly wide-spaced fractures in advance of most active stoping. These fissures opened under the pressure of the injected magma and were irregularly enlarged by local stoping. As stoping proceeded, certain chambers were particularly enlarged and irregular masses of magma projected well up into the fractured and veined roof rock; continued stoping gradually engulfed the pendants and septa between these areas of more rapid stoping. Effects of this process are shown along the southern flank of Pinkham Mountain, where exposures are good and relations are clear. Narrow dikes with regular walls, perhaps representing fissures formed by local spreading, connect angular masses of granite which are fringed in part by a lace-work of small dikes. Many of these small dikes completely surround blocks of country rock, and obviously were actively breaking up the wall rocks when cooling of the stock put an end to the process. The highly brecciated mass of metamorphic rocks between the Gero and Penber workings and the Fluorspar mine and in the area to the east is particularly significant. This block, approximately a half mile in diameter, is separated from the rest of the metamorphic rocks in the stoping area by an irregular dike that ranges roughly from 400 to 1,000 feet in thickness. Although the walls of the dike are different in detail, in general they appear to be matching; and superficially this block of metamorphic rock appears to have broken from the wall and roof of the magma chamber and to have drifted several hundred feet out into the magma. Near the northern margin of sec. 16 T. 11 N., R. 79 W., however, a projection of metamorphic rock comes within about 50 feet of bridging across the dike; so any drifting or forceful separation must have been small, and the broad dike more probably resulted from piecemeal stoping along an originally irregular fracture. The western end of this large mass of metamorphic rocks displays the most extreme example of wall-rock fragmentation found near the stock, and this area has the aspect of a large-scale breccia cemented by quartz monzonite.

Despite the highly broken character of the roof and walls of the stock and the abundant evidence for magmatic stoping, the main body of the stock is surprisingly free of xenoliths. As wall-rock alteration is slight and the xenoliths that are found are very little altered, this lack of xenoliths cannot be due to assimilation. Rather it must have resulted from the sinking of the blocks to levels below those now exposed. To accomplish this removal of xenoliths below a very active zone of stoping, either the sinking must have been rapid or the cooling of the stock must have been slow enough to permit sinking of most of the xenoliths after the periphery of the stock had congealed. If this were so, the stoped blocks might be expected to be concentrated near the contacts, and to decrease in number toward the center of the stock. In general this is not true. Along the northern margin of the stock, the quartz monzonite is rather free of xenoliths up to the contact, and even the irregular, larger bodies of quartz monzonite in the stoping area enclose relatively few blocks of country rock. Many blocks of country rock do occur in quartz monzonite in the vicinity of the breccialike aggregate of metamorphic blocks and granitic dikes near the Fluorspar mine, and the mine workings show abundant xenoliths in quartz monzonite. This whole area of breccia and stoping dikes may show that elsewhere the blocks were larger and sank rapidly, but that here they were smaller and the quartz monzonite crystallized before the blocks had time to sink.

Rapid sinking of the blocks implies relatively low vicinity for the magma, a large average size of the blocks, or perhaps a significant difference in density between the xenoliths and the melt. The rocks in the gneiss complex include such varied types as quartz monzonite gneiss, pegmatite, hornblende gneiss, hornblende-biotite gneiss, and mylonite gneiss. Of these, the hornblende-bearing metamorphic rocks have relatively high specific gravities, but other rocks, such as quartz monzonite gneiss and pegmatite, are not significantly different from the quartz monzonite now found in the stock (see Table 1). The specific gravity of the original melt undoubtedly was lower than that of the rock now found in the stock, but the difference probably was not as great as might be expected; petrographic evidence (see following sections) suggests that the rock that first crystallized was dioritic in composition. Even so, the few xenoliths that are found show no selective accumulation of the lighter rocks, suggesting a relatively low viscosity for the melt. Further evidence for the low viscosity is the ease with which stoping was accomplished along relatively narrow fissures. It is difficult to imagine a viscous melt penetrating the wall rocks in as intricate a manner and in as small dikes as it did on Pinkham Mountain, let alone permitting the blocks so loosened to sink easily to great depths.

Lithology — The texture and grain size of the Sherman granite (quartz monzonite) vary widely, not only between the stock and the associated dikes but also within each body. The main body of the stock is made up largely of a medium- to coarse-grained, somewhat porphyritic rock, but significant quantities of relatively fine grained, distinctly porphyritic quartz monzonite also occur. Rectangular pink microcline phenocrysts half an inch or more long are set in a variable groundmass of pink microcline, white plagioclase, and glassy quartz. Biotite varies widely in abundance; in places it makes up nearly 10 percent of the rock and elsewhere is entirely absent. On weathered surfaces the rock appears dull gray to brown, but its fresh exposures appear mottled pink and gray.

The rock in some of the larger dikes and irregular masses on Pinkham Mountain resembles that in the central part of the stock, but most of the rock in the stoping dikes, and some near the margin of the main body is fine- to medium-grained and appears distinctly aplitic. Biotite is a minor constituent in most of the rock in the peripheral zones, and the quartz and feldspar form an aggregate of anhedral grains with scattered larger crystals of microcline and quartz. The rock contains few well-formed microcline phenocrysts, and most of the larger grains are irregular in shape. Small masses of fine-grained pegmatite are common in some dikes, and all gradations exist between these and the surrounding aplitic rock.

Fine-grained, porphyritic quartz monzonite occurs in several dikes and small masses northeast of the stock and near the eastern edge of the district. The dikes range from less than a foot thick and several tens of feet long to nearly 75 feet thick and more than 3,000 feet long. In general the larger bodies are slightly coarser grained than the small bodies. Many of these dikes are too small to be shown on the geologic map (Pl. 1). The phenocrysts in these dikes are plagioclase, whereas those in the stock are microcline; and they are set in a very fine grained, pinkish gray groundmass of quartz, feldspar, and biotite.

Petrography

Main body of the stock -- Although locally variable, typical rock in the main body of the stock is medium- to coarse-grained and is composed of about 5 percent biotite, 30 to 35 percent plagioclase, 30 to 35 percent microcline perthite, and 30 percent quartz. Zircon, apatite, and fluorite comprise the minor accessory minerals. Depending on the quantity of introduced microcline, the stock ranges in composition from the more common quartz monzonite to granodiorite on one hand and to granite on the other. Local rocks vary even more, and in these either quartz, microcline, or plagioclase may greatly predominate.

Small, ragged crystals of green biotite scattered throughout the rock form as much as 10 percent of the rock, but locally they are entirely lacking. Many of the grains are deformed and broken and most are embayed and corroded by microcline and quartz. Biotite commonly contains inclusions of magnetite, and in many places has been altered in part to a mixture of sericite, chlorite, and magnetite. Secondary epidote also is common.

The plagioclase ranges between An_5 and An_{17}, but in most of the rock it is sodic oligoclase. It occurs in corroded laths up to 4 mm long and in irregular, untwinned grains that in part replace the older plagioclase crystals. Many of the lath-shaped plagioclase crystals, like the biotite, were broken. Much of the polysynthetic twinning was partly or completely destroyed during the deformation and the later hydrothermal alteration, but in many crystals a hazy or "ghost" twinning still can be recognized. The cores of some of the laths are crowded with fine sericite and very fine grained saussuritic inclusions. The arrangement of these inclusions in some crystals suggests that the plagioclase originally was zoned and was appreciably more calcic in composition. The irregular and untwined plagioclase grains are not deformed; they evidently formed by recrystallization after cataclasis. These grains have nearly the same composition as the earlier, deformed crystals adjoining them. The sericite and saussuritic inclusions in the recrystallized plagioclase are in patches rather than zones. Clear borders are common in plagioclase crystals, and the cores of many grains have in part been cleared of the inclusions.

Microcline perthite forms irregular to roughly rectangular phenocrysts and smaller, irregular grains in the ground mass. It generally embays the deformed plagioclase and biotite and commonly contains abundant inclusions of them. Microcline is not deformed and definitely crystallized after the brecciation of the early plagioclase and biotite. The age relations between microcline and recrystallized plagioclase are not so definite, and the two minerals commonly appear about contemporaneous.

Myrmekite is widespread along the contacts between plagioclase and microcline grains. It occurs as rounded growths embaying microcline, as border zones on both relict and recrystallized plagioclase crystals, and as irregular growths within some deformed plagioclase crystals. The plagioclase in myrmekite commonly is slightly more sodic than the associated oligoclase or albite.

Irregular grains and aggregates of quartz embay the relict plagioclase and biotite crystals and appear to have been introduced both contemporaneously with and slightly later than the microcline. Some of the quartz aggregates are comparable in size to the microcline phenocrysts, but generally they are smaller. In places abundant irregular to rounded grains of quartz embay all other constituents of the rock. This relatively late quartz is common in the stoping dikes or near the margin of the stock, but is not restricted to these occurrences. All the quartz shows wavy extinction, but this could have been produced much later than the time of introduction.

One small area near the center of the stock is particularly significant as no microcline was introduced here. Hydrothermal action was sufficiently intense to convert the plagioclase to sodic albite (An_{3-5}), to introduce considerable quartz, and to cause the crystallization of idiomorphic epidote. Albite makes up nearly 70 percent of the rock, and over half of this quantity has recrystallized as undeformed grains that range from small, irregular crytals to rectangular phenocrysts more than half an inch long. The remainder of the albite occurs in pseudomorphic laths, most of which show marked effects of deformation. These latter grains are abundant and preserve some of the pre-deuteric texture of the rock. The rest of the rock consists of 20 to 25 percent quartz with replacement relations, and 5 to 10 percent idiomorphic epidote. The relict texture shows that plagioclase was one of the major constituents of the original rock and that quartz and microcline either were lacking or were present in very subordinate amounts. The original ferromagnesian minerals were completely destroyed by the deuteric alteration.

Stoping area of the stock — The composition of the rocks in the stoping area of the stock differs significantly from that in the interior of the stock. In general, quartz, microcline, and plagioclase are present in nearly the same proportions as in the main body of the stock, However, biotite is decidedly less abundant here, and the average plagioclase is significantly more sodic.

Biotite generally forms only minor wisps and shreds generally associated with varied amounts of chlorite, sericite, and magnetite. In places these minerals form rough pseudomorphs after biotite, but elsewhere they are disseminated through the rock. A trace of muscovite occurs in some of these dikes, but it is generally rare. Here and there several percent of biotite has survived the alteration; and in one specimen studied biotite made up about 8 percent of the rock.

The composition of the plagioclase varies considerably, in 10 specimens ranging from An_3 to An_{14}. Generally the range is between An_5 and An_{10}. Plagioclase forms corroded and deformed pseudomorphic laths, as well as undeformed irregular grains partly replacing the earlier crystals. These broken grains originally had abundant polysynthetic twinning, but much of this was destroyed during deformation and subsequent deuteric alteration. The surviving twinning commonly is patchy or in hazy "ghosts" like that in the interior of the stock. The recrystallized plagioclase is untwinned and definitely replaces the earlier plagioclase; in a given area the composition of the plagioclase in both habits is essentially the same. The saussuritic and sericitic inclusions in both the relict and recrystallized grains of plagioclase in the stoping area of the stock tend to cluster into irregular patches separated by abundant relatively clear plagioclase. Clear rims are common, and some crystals are almost free of inclusions. In general the more sodic the plagioclase, the fewer the inclusions; some almost clear crystals of albite contain evenly distributed, sparse saussuritic inclusions.

As in the central part of the stock, microcline perthite does not have a cataclastic texture, and it corrodes and replaces the deformed plagioclase laths. The larger grains contain abundant relicts of the earlier minerals, many of which show common optical orientation. The phenocrysts are more irregular than those in the main body of the stock, though still roughly rectangular. The smaller grains are very irregular. In the pegmatitic parts of the dikes the microcline shows the same replacement relations as in the finer-grained portions, and the pegmatite texture apparently was formed at the time microcline was introduced.

Quartz was the last important constituent to be introduced. Some appears to have formed more or less contemporaneously with the microcline, but other grains definitely corrode the microcline. Some quartz occurs as irregular masses and rounded blebs and rods that replace all the other minerals. In places a pseudographic texture developed, and one specimen from the core of Sentinal Mountain shows that the quartz rods in adjacent microcline and albite grains have a common optical orientation.

In places where replacement by microcline was less complete, some relict texture of the original rock can be seen. Bent and broken plagioclase laths of random orientation, now pseudomorphed by albite, have contact relations characteristic of a normal granitic texture. Commonly considerable recrystallized albite is present, but not enough to mask the original textural relations.

Satellitic dikes -- The composition of the rock in the satellitic dikes near the eastern edge of the district is variable. As in the stock and associated dikes, plagioclase and biotite appear to have been the original minerals of the rock. These were replaced in varying degree by potash feldspar, more sodic plagioclase, and quartz. In general, plagioclase, potash feldspar, and quartz each make up about 25 to 35 percent and biotite 5 to 10 percent of the rock. The groundmass of these rocks is very fine grained; the phenocrysts are up to 2 mm long. In contrast with the rock in the stock, the phenocrysts are plagioclase rather than microcline, and were an original constituent of the rock.

Plagioclase is highly corroded both in phenocrysts and in groundmass, and much of the original twinning was destroyed. Commonly the crystals are crowded with saussuritic and sericitic inclusions and the composition is difficult to determine. The original plagioclase crystals were irregularly albitized, an in thin sections compositions range from near mid-oligoclase (An_{15})to calcic albite (An_7). Irregular, recrystallized plagioclase crystals which replace the early plagioclase laths are common, but they are generally not as abundant as in the stock or stoping dikes.

Plagioclase and biotite are corroded and replaced by a very fine grained aggregate of potash feldspar and quartz. Some quartz clearly embays microcline, but in much of the rock no age sequence could be discerned for these two minerals. Many corroded plagioclase laths are surrounded by micrographic intergrowths of potash feldspar and quartz, with the quartz rods arranged more or less radially around the plagioclase cores. The thickness of the micrographic rims is related to the degree of replacement of the plagioclase. Where plagioclase laths still retain their form, the rims are thin; where the laths are highly corroded, the rims are thicker and considerably more irregular. In some places plagioclase is almost completely replaced by irregular, radial masses of micrographic quartz and potash feldspar.

The relatively large dike in the eastern part of sec. 36, T. 12 N., R. 79 W., is unusual in containing no potash feldspar. Relatively clear albite (An_{3-5}) makes up about 60 percent of the rock. Sericite inclusions are fairly abundant, but zoisite or clinozoisite inclusions are very minor. The albite is in laths with relict granitic texture and in irregular replacement grains of the same composition. Some irregular to roughly rectangular albite crystals 2 to 3 mm long replace both the early laths and the smaller replacement grains of albite and enclose many residual inclusions. Biotite apparently once made up about 10 percent of the rock, but almost all of it has been altered to ragged aggregates of chlorite and magnetite. Irregular quartz grains comprise up to 30 percent of the rock; they corrode and replace all the minerals except some late epidote. Epidote is very abundant in places but generally comprises only about 5 percent of the rock. It occurs in veinlets, random crystals, and granular aggregates. Although the plagioclase has been thoroughly albitized and in part recrystallized, much of the original texture of the rock can be seen. Apparently the original rock was a biotite diorite or quartz diorite.

Wall rock alteration -- Contact alteration along the walls of the stock and the dikes has been slight, and rarely affected more than a few feet of the country rock. Hornblende gneiss was most readily altered, and it commonly is somewhat silicified and epidotized adjacent to the granite.

Along many contacts, particularly where the wall rock is quartz monzonite gneiss or quartz- and biotite-bearing gneisses, no evidence of alteration was recognized in the field.

Thin sections from a suite of specimens collected across a contact of granite- and hornblende gneiss were studied. The hornblende gneiss away from the contact consists of about equal amounts of andesine and hornblende, with as much as 5 percent biotite. Minor amounts of epidote occur as scattered granules. Next to the contact with granite the rock has a cataclastic texture, and the original minerals have been altered somewhat. Hornblende was transformed in part to chlorite and epidote, biotite was altered to chlorite, and plagioclase was saussuritized and changed in composition to near An_{20}. Minor amounts of quartz and potash feldspar were introduced along fractures and cataclastic zones, and abundant epidote occurs in veinlets and scattered grains as well as with chlorite in pseudomorphs after hornblende.

Origin

Original rock — Deformation and cataclasis of the early minerals could have taken place only after complete or nearly complete consolidation of the magma. No unaltered remnant of the original rock has been found, but several lines of evidence indicate that it probably was a diorite or quartz diorite.

Biotite and lath-shaped plagioclase crystals are the only minerals that clearly show brecciation. Microcline, where not broken by later, unrelated movements, is not deformed and everywhere is corrosive toward deformed biotite and plagioclase. Irregular, recrystallized plagioclase grains of about the same age as the microcline also are not deformed and clearly replace the earlier crystals. Most of the quartz was introduced at about the same time or even a little later than microcline. Under the microscope, almost all quartz shows the wavy extinction generally attributed to strain; so evidence of deformation cannot be used to establish the presence or absence of an earlier generation of quartz. A former interstitial habit of early quartz could easily have been masked by quartz introduced later.

In the central part of the stock where albitization was least intense, many of the relict plagioclase laths contain zonally arranged saussuritic inclusions of zoisite or clinozoisite and sericite. These probably were inherited from an original zoned and more calcic feldspar. As the inclusions commonly are somewhat disrupted and clear rims of plagioclase grains are common, it is probable that even here albitization involved some introduced material and was not merely saussuritic alteration. This is further suggested by the progressive disruption and decrease in abundance of saussuritic inclusions with an increase in albite content of plagioclase. Thus the original plagioclase probably was significantly more calcic than the sodic oligoclase or calcic albite now found.

Relict granitic texture still persists in the various stoping and satellitic dikes and in local areas in the stock where less microcline was introduced. Although considerable albitization and recrystallization of plagioclase and alteration of biotite took place during deuteric alteration, enough relict texture is preserved to indicate that biotite probably made up 10 percent or more of the original rock and that plagioclase comprised much of the remainder.

Hydrothermal alteration — Hydrothermal alteration of the original igneous rock produced a crude zoning of transformation products, which is shown best by the degree of albitization of plagioclase and alteration of biotite. In the main body of the stock, most of the plagioclase is sodic oligoclase which in general contains abundant saussuritic inclusions. Biotite, although considerably corroded, is still fairly well preserved and has only a minor amount of associated chlorite, sericite, and magnetite. Large, rectangular phenocrysts of microcline are common. In the stoping area the plagioclase generally is more thoroughly albitized and in places is highly sodic albite; the abundance of saussuritic inclusions decreases with an increase in degree of albitization. Very little biotite persists, as most of it was replaced by microcline and quartz or was converted to various mixtures of sericite (and muscovite), chlorite, and magnetite. Microcline phenocrysts are not nearly as abundant here as in the main body of the stock. Although more variable, the rocks in the satellitic dikes to the east belong in general to the same zone as the stoping area of the stock.

The zoning does not appear to be due to incomplete reaction between the through-travelling hydrothermal solutions and the fractured rock. The plagioclase in both the pseudomorphed original grains and in the recrystallized grains with replacement relations has essentially the same composition in any given specimen, so at least the plagioclase appears to have approached equilibrium with the hydrothermal solutions. Biotite in the main body of the stock and in the mixture of sericite, chlorite, and magnetite in the peripheral zones also probably approached equilibrium with the hydrothermal solutions, as the assemblages biotite-oligoclase-quartz and chlorite-sericite-albite-quartz are common associations in regionally metamorphosed rocks where approximate equilibrium generally was reached.

More probably the zoning resulted from differences in temperature and concentration of the solutions in the different parts of the stock and associated dikes. The successive mineral assemblages developed in progressive regional metamorphism indicate that oligoclase and biotite are formed at higher temperatures than are the albite, chlorite, and sericite, so the zonal arrangement of these minerals, with the lower temperature assemblages in the peripheral zone, is just what would be expected from a progressive lowering of the temperature of the through-travelling hydrothermal solutions.

Little is known of what happened to the lime, magnesia, and iron removed from the replaced minerals. Some of the lime was fixed in the minor amounts of epidote which is relatively common in the dikes and near the walls of the stock, but certainly most was removed in solution.

Little could be held in saussuritic inclusions in plagioclase, as these inclusions decrease in abundance with an increase in degree of albitization. The chlorite and secondary magnetite occur chiefly in minor aggregates left from the disassociation of biotite, and they represent only a small percentage of the magnesia and iron in the original rock. No concentrations of calcic or ferromagnesian secondary minerals were noted in the vicinity of the stock, but the wall rocks carry abundant hornblende and intermediate plagioclase; it is impossible to trace the origin of the widely distributed secondary epidote and chlorite.

It is difficult to explain the relatively minor alteration of the wall rock around a body as intensely endomorphosed as the quartz monzonite stock in the Northgate district. Perhaps the drop in temperature of the hydrothermal solutions as they passed from the relatively hot mass of the stock into the cooler wall rock inhibited further hydrothermal alteration, but this hypothesis encounters difficulties when it is applied to the complex of stoping dikes on Pinkham Mountain, where the dikes could hardly have been at significantly higher temperatures than the surrounding rocks. Whatever the reason, the trivial alteration of the wall rock noted here seems also to characterize other bodies of Sherman granite in southern Wyoming (Blackwelder, 1908).

Hydrothermal solutions — The hydrothermal solutions probably originated at depth within the igneous body. An external source is extremely unlikely as the wall rocks show only minor alteration adjacent to the intrusive contact, and in the stock the endomorphic alteration products are arranged in rough zones, with the higher-temperature minerals toward the center. Residual magmatic solutions of local origin conceivably might account for some of the alteration, but the volume of residual magma remaining after crystallization of the plagioclase could hardly account for the microcline which averages 35 percent of the rock and quartz which averages 30 percent of the rock. The zonal arrangement of the alteration products is consistent with the thesis that the deuteric solutions moved upward and outward through the brecciated rock of the stock.

The composition of the deuteric solutions can be approximated roughly from the various minerals introduced or transformed by them. Judging from the quantity of microcline and quartz that corrodes and replaces the deformed plagioclase and biotite, potash and silica were important constituents of the solutions. Some quartz may have been original, but certainly much was introduced during deuteric alteration.

The progressive albitization of plagioclase proves that soda was present in the solutions. Some albitization was undoubtedly merely saussuritic, but zoisite and sericite inclusions are most abundant in the main body of the stock, where the plagioclase is most calcic, and they are almost entirely absent in some sodic albite. In any specimen, however, the composition of plagioclase generally is independent of its content of saussuritic inclusions, and both relatively clear and heavily clouded grains have about the same composition. The broad zonal decrease in saussurite with increasing albite content is accompanied by a progressive disruption of the original zonal arrangement of the inclusions within individual crystals. Plagioclase crystals with zonally arranged inclusions are restricted to the main part of the stock, and even here they are not abundant.

Potash apparently was more abundant than soda in the hydrothermal solutions that invaded the stock and related dikes. O'Neill (1948, pp. 167-180), in a series of experiments on the hydrothermal alteration of feldspars, showed that the substitution of potash for soda in albite is a reversible reaction controlled by the law of mass action. Thus about a third of the rock could have been replaced by microcline only if the concentration of potassium ions in the solution was significantly higher than that of sodium ions. Replacement of plagioclase by microcline would impoverish the solution in potassium ions; at the same time the sodium ion concentration would increase from the replaced plagioclase. This may account in part for the increased albitization toward the peripheral parts of the stock. The presence of abundant microcline in the dikes and near the margins of the stock, however, indicates that even here the potassium ion concentration was high relative to sodium ion concentration. It has long been recognized that the residual liquid from the crystallization of a normal subalkaline magma is rich in alkalies, silica, and water; and Bowen (1928, p. 100) has shown that potash commonly increases relative to soda in the late differentiates.

Experiments by Gruner (1944, pp. 578-589) and O'Neill (1948, pp. 167-180) indicate that the transformation of albite to potash feldspar and the albitization of plagioclase take place most readily in basic solutions and that alkali leaching takes place in acid solutions. No evidence of alkali leaching was observed in the specimens from the quartz monzonite stock in the Northgate district; the hydrothermal solutions responsible for the endomorphic transformations probably were basic.

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