Resin, a great field dog who made the otherwise lonely days in the wilderness much more fun, atop a highly sheared outcrop of porphyritic metabasalt of the Mullen Creek mafic complex cut by Big Creek granite within the Big Creek shear zone in the SW/4 of section 33.

THESIS

PETROLOGY AND CONTACT RELATIONSHIPS, SW PORTION PC MULLEN CREEK MAFIC COMPLEX, MEDICINE BOW MTS., WY

Submitted by

Jeffrey Scott Edwards

Earth Resources Department

In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring, 1983

COLORADO STATE UNIVERSITY

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION

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ENTITLED PETROLOGY AND CONTACT RELATIONSHIPS, SW PORTION P€ MULLEN CREEK MAFIC COMPLEX, MEDICINE BOW MTS., WY

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ABSTRACT OF THESIS

PETROLOGY AND CONTACT RELATIONSHIPS,
SW PORTION ~~PC~~ MULLEN CREEK MAFIC COMPLEX,
MEDICINE BOW MTS., WY

Geologic mapping and thin section petrography of rock units in and adjacent to the southwestern portion of the Mullen Creek mafic complex reveals the presence of a roof zone of a Precambrian layered basic intrusion that invaded a metavolcanic sequence (predominantly hornblende gneiss). This portion of the mafic complex consists of variably metamorphosed interlayered rocks that originally ranged from pyroxenite to anorthosite but were dominantly gabbro and leucogabbro. Most of these rocks underwent regional medium-grade metamorphism to form amphibolite facies assemblages in which hornblende has replaced pyroxene, labradorite has remained stable and relict igneous textures are preserved. A later episode of retrogressive low-grade metamorphism has produced locally abundant fractures, veinlets and minerals typical of the greenschist facies such as chlorite, epidote, talc, serpentine and saussurite.

Contacts between the mafic complex and host hornblende gneiss are gradational and generally parallel the layering in both the gneiss and the complex. One or more pulses of tholeiitic basaltic magma apparently intruded the hornblende gneiss and layering in the complex developed by the process of crystal settling under the influence of gravity and convection currents. Based on geochemistry and structure, Donnelly (1979) suggests that the mafic complex is overturned and therefore its southern most portion is the upper part, or roof zone, of the layered body.

The gradational nature of the mafic complex-hornblende gneiss contact suggests emplacement during regional metamorphism, and the concordance of layering suggests that the roof of the complex and the layers of the adjacent gneiss were relatively horizontal at the time of emplacement. The form of the intrusion was most likely a large sill or funnel-shaped body with a relatively flat roof. Wedge-shaped apophyses of the mafic complex locally cross-cut hornblende gneiss and apparently formed where mafic magma forced the overlying gneiss apart along favorable layers.

The Mullen Creek-Nash Fork shear zone truncates the mafic complex to the northwest, and the sub-parallel Big Creek shear zone cuts the complex in the northwestern portion of the study area. Several less extensive shear zones also are present. Cataclastic rocks in the shear zones are gradational from mafic (hornblende, plagioclase and minor quartz) to felsic (quartz, plagioclase, microcline and biotite) and range from relatively undeformed plutonic rocks to well foliated gneiss (± augen) to very fine-grained mylonite. Mineral assemblages and textures indicate that deformation in these zones most likely accompanied regional medium-grade metamorphism, but locally abundant fractures, veinlets and minerals typical of the greenschist facies indicate reactivation of shearing in these zones under low-grade metamorphic conditions.

Igneous layering in the block of the mafic complex between the Mullen Creek-Nash Fork and Big Creek shear zones generally trends northwest, and left-lateral movement along the Big Creek shear zone apparently moved this block southwest relative to the rest of the complex. Southeast of the Big Creek shear zone in the western portion of the mafic com-complex, igneous layers form an overturned anticline that plunges steeply to the northest.

Two older felsic intrusives, the Big Creek and Prospect Mountain granites, intrude both the mafic complex and hornblende gneiss. Big Creek granite-mafic complex contacts are sharp and cross-cutting where undeformed and gradational and conformable where highly sheared. Emplacement of this granite apparently was dominantly controlled by areas of weakness along the Big Creek shear zone. Hybridization of adjacent mafic rocks by this granite is exhibited by the presence of biotite in the metagabbroic rocks of the complex, and this infers the complex was not completely cooled and(or) under stress at the time of granite emplacement. The Prospect Mountain granite occurs as a stock and as extensive sills in the hornblende gneiss. Mafic complex-Prospect Mountain granite contacts are sharp and cross-cutting, and the granite was probably forcefully injected along the hornblende gneiss-mafic complex contact and along favorable layers in the gneiss. The granite stock has caused recrystallization but no hybridization of adjacent mafic complex rocks. Most of the Prospect Mountain granite is strongly fractured with locally abundant hematite and epidote, suggesting the granite failed brittley under low-grade metamorphic conditions during deformation.

Younger felsic intrusions of granite, tonalite, pegmatite and bull quartz intrude all other Precambrian rock units in the study area. They are of multiple ages and some may be as old as the hornblende gneiss. Contacts with host rocks are generally sharp (except locally with older felsic intrusives) and the younger felsic intrusions range in form from conformable sills to cross-cutting dikes and irregular stocks.

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Dedicated to my father, the late Arnold L. Edwards,
who always encouraged educational endeavors.
He encouraged the beginning and would have been
proud to see the completion of this thesis.

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CHAPTER I

INTRODUCTION

Purpose

The southwestern portion of the Mullen Creek mafic complex and adjacent country rocks were studied in detail in an effort to better understand the relationship between the complex and (1) the Mullen Creek-Nash Fork shear zone, (2) the host hornblende gneiss, and (3) two large felsic intrusions along the mafic complex-hornblende gneiss contact. Additional objectives include evaluation of the internal structures (particularly the layering) and metamorphism of the mafic complex and location and evaluation of mineralized zones in the study area.

Location and Description of Study Area

The Mullen Creek mafic complex is located on the western flank of the Medicine Bow Mountains in Albany and Carbon Counties, southeastern Wyoming (Fig. 1). The southwestern portion of the complex and adjacent terrain comprise the study area, which covers approximately 10 square miles (25 km^2) in T.13N. R.80W., T.14N. R.80W. and T.13N. R.81W. in the northwestern part of the Elkhorn Point, the southwestern part of the Overlook Hill, the southeastern part of the Barcus Peak and the northeastern part of the Trent Creek, Wyoming 7½ minute quadrangles. Most of the area is situated west of the North Platte River.

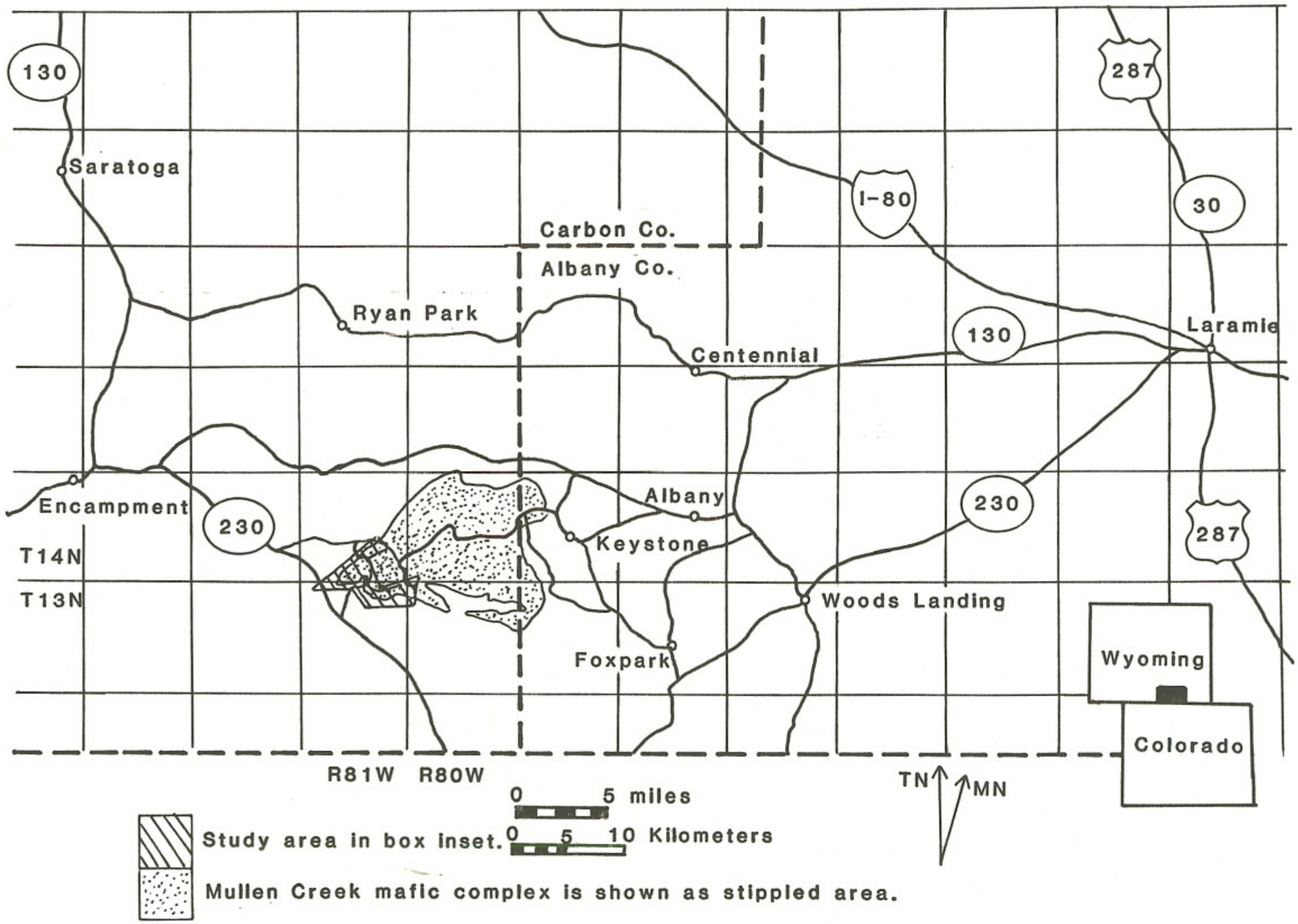


Fig. 1. Index map of study area (after Donnelly, 1979, Fig. 1).

A well-graded gravel road leading from Wyoming State Highway 230 into the A-Bar-A ranch provides access to the northern part of the study area. Three miles (5 km) south of the A-Bar-A turnoff on Highway 230, a jeep trail on the Platt Ranch leads to the extreme western part of the study area (west of Big Creek). The southern part of the study area is on National Forest and Bureau of Land Management land and can be reached by a poorly graded access road that crosses part of the Big Creek Ranch from Highway 230.

A northwest trending ridge divides the area into two drainages. West of the ridge, water flows into Big Creek, and east of the ridge, water flows into the North Platte River. Relief is greatest adjacent to the North Platte River: the 8430 feet (2570 m) peak of Prospect Mountain is only 0.4 mile (0.6 km) from the river at 7400 feet (2255 m). Relief also is high adjacent to Big Creek, and is moderate between this area and the northwest trending ridge that separates drainages. Outcrop is excellent where relief is high except on north-facing slopes in the Prospect Mountain area that have dense forest cover. The rest of the area generally is covered with sagebrush and grass. Areas of moderate relief have poor to good outcrop that typically is more abundant where local relief is high. Float can be used to delineate felsic units within mafic units where outcrop is poor.

Previous Investigations

The study area is included on a reconnaissance geologic map (scale 1:63,360) that is a product of regional studies of the Precambrian rocks of the Medicine Bow Mountains in Wyoming by Houston and others (1968), and it also is included on a regional geological map (scale

1:125,000) of the Sierra Madre and western Medicine Bow Mountains (Houston and Ebbett, 1977).

Detailed geologic investigations of portions of the Mullen Creek mafic complex and adjacent areas have previously been done and are presently continuing. Houston (1961) included the southern portion of the study area in a report of pegmatites in the Big Creek area. Ruehr (1961) studied the south central part of the mafic complex in his study of the Devils Gate area and McCallum (1964a) mapped the extreme northern part of the complex and a large area north and east of the complex. Ramirez (1971) worked in the north central part of the complex and the adjacent Mullen Creek-Nash Fork shear zone. Donnelly and McCallum (1977) and Donnelly (1979) studied the central portion of the mafic complex. Petrography and geochemistry of felsic intrusions in the mafic complex have been evaluated by Mussard and McCallum (1977), Mussard (1982) and McCallum and Mussard (1983). Preliminary results of this thesis were presented by Edwards (1981). Extensive stream sediment and rock chip geochemistry is included in a mineral resource potential report of the Savage Run Wilderness (McCallum and Kluender, 1983) and similar data are available for the general study area (McCallum et al., 1983a and b). In addition, most of the previously unmapped portions of the mafic complex have been mapped by McCallum, and geologic maps of the 7½ minute Keystone and Overlook Hill, Wyoming Quadrangles are in preparation (M. E. McCallum, pers. commun., 1983).

Methods of Investigation

Geologic mapping along with stream sediment and rock sampling was conducted during the summers and falls of 1979 and 1980. Initial work was done using the U. S. Geological Survey 7½ minute topographic Overlook Hill, Barcus Peak and Elkhorn Point, Wyoming Quadrangles (scale 1:24,000). Portions of these quadrangles were enlarged to a scale of 1:16,000, providing a base on which most mapping was done. Geology was transferred to an enlarged air photo (scale 1:10,226) and field checked. The remainder of the study area was mapped directly on this air photo, and a geologic map (Plate 1) was prepared from this base.

Attitudes of foliations, joints, and lineations were recorded to the nearest interval of 5 degrees for simplicity. These attitudes were grouped according to rock unit and fabric type and pole plot diagrams were prepared using the contouring methods described by Billings (1972, p. 95-110).

Thin sections for petrographic study were made of 127 rock samples. Polished slabs of approximately half the samples were treated with hydrofluoric acid, barium chloride and sodium cobaltinitrate to stain potash feldspar yellow and etch plagioclase white as described by Bailey and Stevens (1960). Modal analyses were conducted on 17 slabs and 87 thin sections: between 300 and 500 point counts were made for each sample on a 9 bank Lab Count Denominator. Plagioclase compositions were determined using the Michel-Levy twin method or the combined Carlsbad-Albite twin method described by Kerr (1977, p. 293-298).

Alteration products of some extensively altered plagioclase samples were determined using a GE XRD-6 X-Ray Diffractometer. Samples were crushed, and the size fraction between 80M (0.007 in., 0.018 cm) and 100M (0.006 in., 0.015 cm) was run through a Frantz Isodynamic Separator to remove magnetic minerals. The remaining minerals were then crushed to a fine powder and mixed with water; droplets of this mixure were put onto a glass slide and dried. These dried slurry samples were then X-rayed and their diffraction patterns were evaluated.

Stream sediment samples were taken at 28 locations in and adjacent to the study area. Two samples were collected at each site: one sample was obtained of material that passed through a screen with openings of approximately 1.5 mm. A heavy mineral concentrate sample was obtained by sieving sediment through a screen with approximately 3.0 mm openings and panning the sediment that passed through. Relative stream activity, the ratio of felsic to mafic minerals and the amount of organic materials in the sample was noted at each location. An attempt was made to avoid organic materials and to sample natural concentrations of heavy minerals whenever possible. Where no running water was present, sediment taken from a dry stream bed was brought to running water and processed.

CHAPTER II

REGIONAL GEOLOGY

Medicine Bow Mountains

The Medicine Bow Mountains occupy the core of a large asymmetrical anticline that is bordered on the east by thrust faults that trend north to northwest in both southeastern Wyoming and north central Colorado. Sedimentary rocks of Paleozoic to Recent age border the range. The range is flanked on the east by the Laramie Basin and Laramie River Valley, and on the west by Saratoga Valley and North Park Basin. The following discussion has been derived in large part from the excellent compilation by Houston and others (1968) of the Precambrian geology of the Medicine Bow Mountains in Wyoming.

Rocks of Precambrian age predominate and they are divided into two distinct geologic provinces by the Mullen Creek-Nash Fork shear zone (Fig. 2). The shear zone trends northeast through the central part of the mountains, is approximately 0.5 mile (0.8 km) wide at its southwest extension and splits into a three-pronged system in the central and northeastern part (Houston and McCallum, 1961; McCallum, 1964a, 1974).

Northwest of the shear zone, the basement rock consists of a complex sequence of Archean quartzo-feldspathic gneisses of almandine-amphibolite faces, that are cut by numerous basaltic dikes. Large and small bodies of granite, quartz diorite and gabbro occur within the

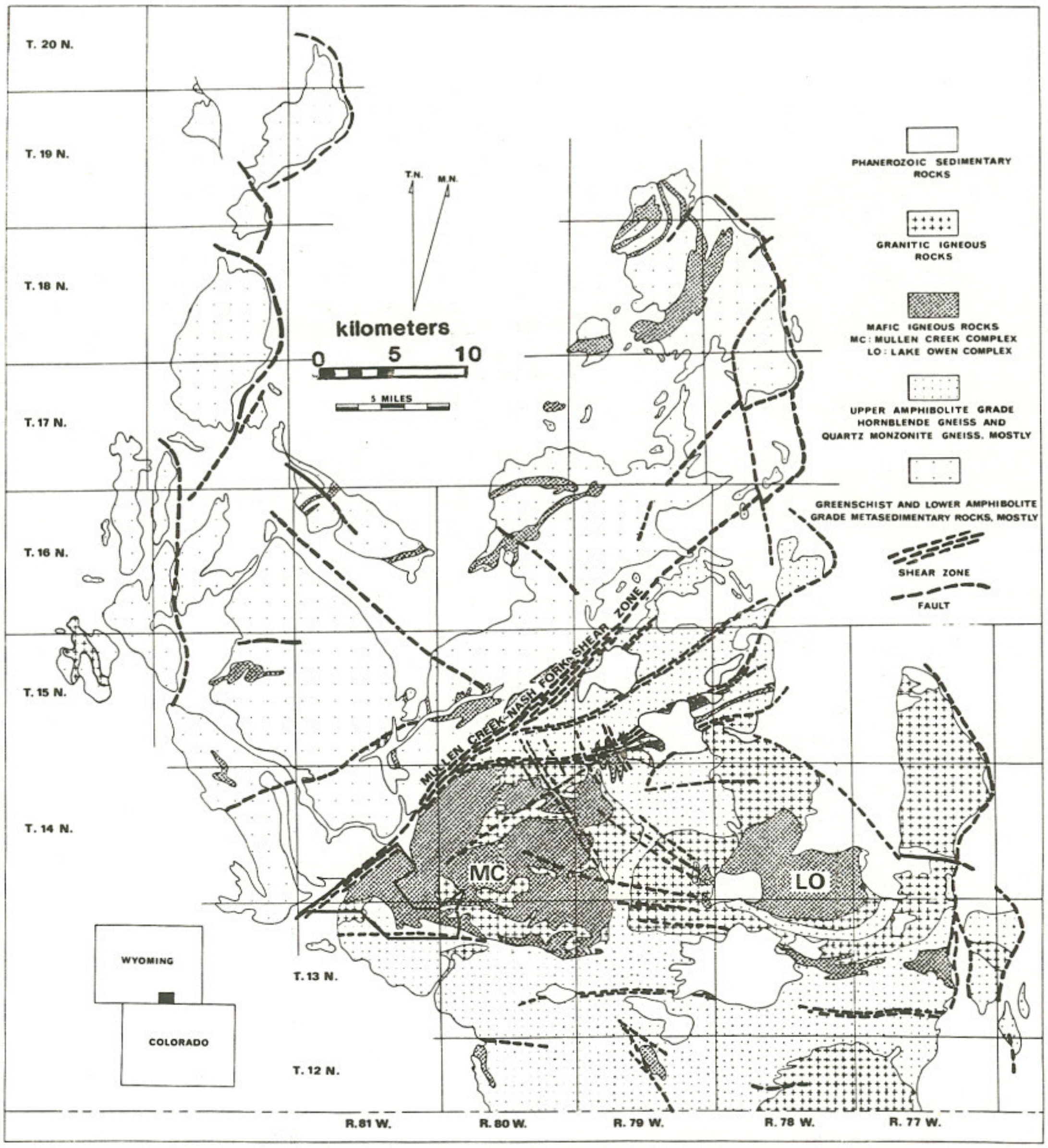


Fig. 2. Generalized Precambrian geologic map of the Medicine Bow Mountains, Wyoming (after McCallum et al., 1976, Fig. 1). Study area in box inset.

gneiss. Age determinations of the gneiss and granite respectively yield 2500 ± 50 m.y. and 2425 ± 50 m.y. to 2365 ± 50 m.y. (Hills and Houston, 1979). The gneiss has been overprinted by at least two metamorphic events of Proterozoic age that occurred at approximately 1700 m.y. and 1400 m.y. (Hills and Houston, 1979). Metasedimentary rocks that overlie the gneiss have a minimum age of 1700-1750 m.y. (Hills and Houston, 1979). Gabbroic sills are common within the metasedimentary rocks.

Interlayered gneisses that grade into each other along and across strike comprise the basement assemblage southeast of the shear zone. These rocks are considered to have been a series of volcanics and graywacke with interbedded limestone, sandstone, and shale. Mafic sills within these gneisses are equally as common as they are northwest of the shear zone. Quartz diorite, numerous gabbroic bodies and at least two ages of granite intrude the gneisses.

Precambrian Basement Metamorphic Rocks Southeast of the Mullen Creek-Nash Fork Shear Zone

Hornblende gneiss makes up approximately 40% of the basement rocks southeast of the shear zone. Included in the hornblende gneiss sequence are interlayered and gradational, finely layered hornblende gneiss, coarsely layered hornblende gneiss, amphibolite, biotite gneiss, sillimanite biotite gneiss, calc-biotite gneiss, diopside gneiss, and marble.

A typical hornblende gneiss is comprised primarily of hornblende and andesine with quartz as the major accessory mineral. It may be finely laminated or have layers up to 50 feet (15 m) thick, and may be passively folded. Light-colored quartz-plagioclase layers grade into quartzo-feldspathic gneiss layers with accessory biotite and(or) microcline and(or) sillimanite: massive hornblende-rich layers grade into amphibolite. Layers of quartzo-feldspathic gneiss grade into a massive gneiss with a granitic appearance that has more sodic plagioclase and is richer in microcline and quartz. This gradational relationship suggests a metasomatic origin for the massive gneiss. Contacts and foliation of this hornblende gneiss sequence are generally comformable; contacts may be gradational across as well as along strike. Marble and calc-silicate gneisses are interlayered with each other and hornblende gneiss on both a large and small scale (McCallum, 1964b).

Mafic Igneous Rocks Southeast of the Mullen Creek-Nash Fork Shear Zone

Three large mafic bodies, the Keystone Quartz Diorite and the Lake Owen and Mullen Creek mafic complexes, and numerous generally comformable smaller bodies of amphibolite, metagabbro, meta-olivine gabbro, metadiorite and metapyroxenite, occur southeast of the Mullen Creek-Nash Fork shear zone. Amphibolites are completely recrystallized and may be gradational with hornblende gneiss, but field evidence suggests that most are of igneous origin. Hornblende gneiss has less amphibole and better developed layering and foliation than amphibolite. Amphibolite is also gradational with the mafic intrusions that are variably metamorphosed but generally retain some relict igneous texture and mineralogy. Plagioclase is saussuritized and pyroxene is variably altered to amphibole. The sequence of intrusions of these bodies is not known.

The Keystone Quartz Diorite is a dark gray medium-grained rock that is faintly to strongly foliated. It generally has comformable contacts with hornblende gneiss and quartz-andesine gneiss, but has gradational contacts with hornblende gneiss in the southwest and locally cross hornblende gneiss in the east.

The Lake Owens mafic complex is a large circular layered intrusion that is cut by the Keystone Quartz Diorite (McCallum and Houston, 1983). The mafic complex is comprised of cyclic units, each of which ranges from troctolite at its base to magnetite gabbro in its upper part, and has abundant primary structures such as graded bedding, channeling and alignment of plagioclase (Houston and Ridgely, 1976). These rocks show the least metamorphism of any mafic rocks in the Medicine Bow Mountains; the rock is relatively unaltered, except along its borders where metamorphic foliation and alteration to amphibolite occur.

The Mullen Creek mafic complex, like the Lake Owens mafic complex, is a layered intrusion, but regional amphibolite-grade metamorphism has masked most of the primary mineral assemblages. Textures most commonly are primary, but a late-stage kinetic metamorphic event at lower amphibolite-upper greenschist facies conditions locally has imparted a cataclastic and accompanying retrograde overprint (Donnelly, 1979). Rocks of the complex generally consist of primary plagioclase and secondary hornblende after pyroxene and range from anorthosite to metapyroxenite, and have both gradational and sharp contacts (Donnelly, 1979). Gravitational differentiation and convective motion are thought to be responsible for the cross-bedding, scour channeling, igneous lamination and rhythmic layering found in the complex (Donnelly, 1979). Diabase, late stage gabbro, two periods of basalt dikes, and at least two felsic phases that hybridized adjacent mafic rocks, intrude the complex (Donnelly, 1979). Geochemistry and spatial relationships have led Mussard and

McCallum (1978) and Mussard (1982) to conclude that some of the older felsic phases are late stage differentiates from the same parent magma as the mafic complex. Contacts along the southern border of the complex are gradational with hornblende gneiss, but hornblende gneiss and quartz-biotite-andesine gneiss are cut by the complex along its eastern border. To the northwest, the complex is truncated by the Mullen Creek-Nash Fork shear zone, and its extreme western portion is covered by Tertiary sediments.

Felsic Igneous Rocks Southeast of the Mullen Creek-Nash Fork Shear Zone

McCallum (1964a) and Houston and others (1968) mapped a group of "older granite" southeast of the shear zone which ranges from large felsic intrusives that clearly cut the Mullen Creek mafic complex to smaller conformable felsic bodies found within the older metamorphic rocks. Some smaller felsic bodies have gradational contacts and indicate extensive hybridization. A few of the felsic bodies both cut the mafic complex and are gradational with the hornblende gneiss. Generally, the older granites are medium grained, foliated and cataclasized to varying degrees. Two of the bodies, the Rambler Granite and granite of Horse Creek, were dated at approximately 1730 m.y., but age relationships between the different bodies of older granite are uncertain (Hills and Houston, 1979).

Felsic pegmatites are common southeast of the shear zone, especially within the hornblende gneiss. Houston and others (1968) believe that the majority of these pegmatites were introduced at approximately the same time as the older granite. Fine-grained, relatively fresh dikes of granitic composition cut all other Precambrian rocks with the exception of the 1350 m.y. old Sherman Granite, which is the last major igneous rock unit emplaced in the area. The Sherman Granite is a pink, coarse-grained massive rock that is exposed in the southeastern Medicine Bow Mountains, near the town of Albany, Wyoming.

Cataclastic Rocks Southeast of and in the Mullen Creek-Nash Fork Shear Zone

Cataclastic rocks occur throughout the area south of as well as in the Mullen Creek-Nash Fork shear zone. Rocks in the shear zone vary considerably in texture and composition as a function of intensity of deformation, nature of host rock, and metamorphic grade (McCallum, 1974). Different rock types of the shear zone are gradational with each other, and include mylonitic, phyllonitic and coarser grained cataclastic igneous rocks. Quartz-feldspar-rich mylonitic rocks include mylonite and blastomylonite that are light colored, resistant, and have very pronounced fluxion structures; and mylonite gneisses that typically have porphyroclasts of quartz and feldspar, lensatic quartz, and mortar or weak to moderate fluxion structures (McCallum, 1974). Mylonitic metagabbro, metadiorite and amphibolite are generally rich in biotite, chlorite and epidote, indicating retrogressive metamorphic reactions; however, some of these rocks that contain abundant hornblende and calcic plagioclase apparently formed under amphibolite-grade conditions (McCallum, 1974). Felsic phyllonites are dominantly light colored, finely laminated and consist mostly of quartz and muscovite, whereas phyllonites associated with mafic rock are comprised mainly of quartz, chlorite, biotite, plagioclase and muscovite (McCallum, 1974). Most of the intrusive bodies within the shear zone have been sheared along their margins and some show complete penetrative deformation (McCallum, 1974).

Almost all rock types southeast of the shear zone have undergone some degree of cataclastic deformation. Localized zones of intense shearing are common in this area and rocks of these zones are gradational with adjacent unsheared units. Rocks in these zones are similar to those found in the Mullen Creek-Nash Fork shear zone.

CHAPTER III

PRECAMBRIAN ROCKS

Introduction

Precambrian rocks in the study area have been divided into five units. The oldest unit is a hornblende gneiss sequence which is intruded by the Mullen Creek mafic complex. The complex comprises the bulk of the rocks in the area and is primarily composed of rocks of gabbroic composition which exhibit the effects of differential metamorphism. Felsic rocks of two distinct ages intrude the mafic complex and hornblende gneiss: two bodies of older granite are relatively widespread and compositionally homogeneous, and numerous bodies of younger felsic intrusives are relatively small and have variable compositions. All of the above rock types are cataclasized locally to varying degrees and limited zones of shearing are common. The Mullen Creek-Nash Fork shear zone is a major shear zone that truncates the mafic complex and includes a variety of cataclastic rocks of diverse parentage.

Rocks of the study area exhibit a variety of grain sizes. For clarity of discussions the following dimensional ranges have been utilized for grain size terms: very fine-grained is less than 0.5 mm, fine-grained is between 0.5 mm and 1.0 mm, medium-grained is between 1.0 mm and 5.0 mm, coarse-grained is between 5.0 mm and 10.0 mm, and very coarse-grained is greater than 10.0 mm.

Hornblende Gneiss

General statement and field characteristics

Hornblende gneiss occurs in the southern portion of the study area (Plate 1) and is part of the hornblende gneiss sequence described by Houston and others (1968). Mineral layering is the most distinctive characteristic of the hornblende gneiss: dark green to dark gray to black hornblende-rich layers predominate over light gray quartzo-feldspathic layers that weather pink and locally pinch and swell to form pods and lenses. The scale of layering is quite variable. Quartzo-feldspathic layers range from a few millimeters to a few meters in thickness and up to 0.5 km in length. Most of the thickest quartzo-feldspathic layers were mapped and are represented by lines on Plate 1. Younger felsic intrusive units also occur as layers in the hornblende gneiss sequence and distinguishing them from quartzo-feldspathic layers is difficult. Hornblende-rich layers range up to a few meters thick and commonly are relatively massive. Mafic sills metamorphosed to amphibolite occur within the gneiss and are very difficult to distinguish from massive hornblende-rich layers.

Contacts between layers are usually sharp and parallel metamorphic foliation. Foliation generally is well-developed in the hornblende gneiss and nematoblastic alignment of hornblende is ubiquitous. Conformable and cross-cutting quartz veins, quartzo-feldspathic veins, felsic pegmatites and bull quartz are abundant locally.

Petrography of mafic layers

The mafic mineral components of the hornblende gneiss are confined primarily to the hornblende-rich layers that dominate the rock. Modal and petrographic data are summarized in Tables 1 and 2, respectively. Internal layering within these mafic layers is variably developed and ranges from clusters of lensatic mineral aggregates less than a millimeter wide to thin laminae a few millimeters wide that consist of different percentages of minerals than the adjacent rock.

Generally prismatic, subhedral hornblende is the dominant mineral (average 50%) in the mafic layers along with major amounts of usually equant to tabular anhedral plagioclase (An_{39-52}) (average 31%) and minor amounts of rounded quartz (average 11%). Grain size varies from very fine- to medium-grained; very fine-grained mosaic aggregates of hornblende, quartz and(or) plagioclase are common.

Primary accessory phases include apatite, sphene, ilmenite and magnetite. They are very fine-grained and occur in amounts up to 2.5%. Apatite occurs as individual euhedral crystals and as rod-shaped microlites in plagioclase. Sphene is generally anhedral but exhibits a strong tendency to form rhombic cross-sections. It is conspicuously more abundant than in rocks of the Mullen Creek mafic complex. Magnetite and ilmenite are anhedral to euhedral and are generally rare.

Secondary accessory minerals include epidote, chlorite and biotite that replace mafic minerals, white mica that replaces plagioclase, and epidote and potash feldspar in veinlets. They are generally anhedral and very fine-grained.

Petrography of felsic layers

The felsic mineral components of the hornblende gneiss are most abundant in the quartzo-feldspathic layers. Modal and petrographic data are summarized in Tables 3 and 4, respectively. These layers average 38%

Table 1. Modal analyses of mafic layers in hornblende gneiss.

Sample	23-2	23-3	23-4	23-51	23-59	23-63	23-72
hornblende	47	45	76	42	47	39	53
plagioclase	24	13	14	12	43	18	27
An content	(48)	(52)	(42)	(44)	(44)	(39)	(42)
white mica (composition undetermined)	21	22	--	26	--	5	3
quartz	2	19	9	4	8	31	5
apatite	1	tr	1	tr	1	tr	1
sphene	3	1	tr	1	tr	tr	2
opaque minerals (undivided)	tr	tr	tr	1	tr	tr	2
epidote	2	tr	--	6	tr	3	6
chlorite	tr	tr	tr	5	--	--	1
biotite	--	--	tr	--	1	tr	tr
potash feldspar	tr	--	--	3	--	4	--

Table 2. Thin section characteristics of minerals in mafic layers of hornblende gneiss.

Plagioclase	clear, An_{39-52}, average An_{44}, composition determinations imprecise because of generally poor Albite twinning, oscillatory or normal zoning is common, crystals in mosaic aggregates are relatively poorly twinned and unaltered compared to larger crystals, inclusions of apatite microlites is common, alteration to white mica is common (especially in cores), bent and broken albite twins occur locally.
Hornblende	moderately to strongly pleochroic (color scheme X=light brown to brown green, Y=light green to green, Z=pale blue green to blue green).
Quartz	clear, generally has undulatory extinction.
Apatite	clear.
Sphene	light gray to brown.
Magnetite	opaque, black in reflected light.
Ilmenite	opaque, black in reflected light.
Epidote	clear to light gray.
Chlorite	moderately pleochroic (color scheme X=very light brown, Y=Z=light green), generally well-developed basal cleavage, anomalous blue birefringence.
Biotite	moderately pleochroic (color scheme X=light brown, Y=Z=brown), well developed cleavage.
Potash feldspar	clear, microcline grid twinning observed in only one thin section.

Table 3. Modal analyses of felsic layers in hornblende gneiss.

Sample	23-1	23-6	23-14	23-17B	23-40	23-58
plagioclase	28	44	29	51	34	39
An content	(46)	(32)	(?)	(37)	(?)	(?)
quartz	40	30	33	33	21	21
microcline	31	16	27	--	11	21
biotite	1	7	8	10	25	13
apatite	tr	tr	tr	1	tr	tr
sphene	--	1	tr	tr	1	tr
opaque minerals (undivided)	tr	1	2	2	tr	tr
ferrohastingsite	--	--	--	--	1	5
epidote	tr	1	1	3	7	1
muscovite	tr	tr	tr	--	--	--
chlorite	--	--	--	tr	--	--

Table 4. Thin section characteristics of minerals in felsic layers of hornblende gneiss.

Plagioclase	clear, An_{32-46}, average An_{38}, compositions imprecise because of generally poor Albite twinning, normal zoning is common, apatite microlite inclusions locally common, slight alteration to white mica is common.
Quartz	clear, ubiquitous undulatory extinction.
Microcline	clear, generally fairly well developed grid twinning, zoning is rare, minor string microperthite, rare plagioclase and quartz bleb inclusions along with locally abundant apatite microlites.
Biotite	strongly pleochroic (color schemes X=light brown, Y=Z=brown, and X=brown green, Y=Z=dark brown).
Apatite, sphene, ilmenite and magnetite	characteristics generally the same as in the mafic layers of the hornblende gneiss (Table 2).
Ferrohastingsite	moderately pleochroic (color scheme X=green with a yellow tint, Y=green with blue tint, Z=dark green), similar to hornblende except 2V angle is approximately 10°.
Epidote	generally clear but may be slightly green with anomalous greenish birefringince.
Muscovite	clear.
Chlorite	light green.

plagioclase (An_{32-46}), 30% quartz, 18% microcline and 11% biotite, are generally very fine- to fine-grained, and have a xenoblastic texture. In general, plagioclase is equant to tabular, quartz grains are irregular and microcline is equant. Biotite generally occurs between grains and is platey with length-width ratios of 4:1. Grain boundaries tend to be sharp and smooth. Foliation is fairly well developed: biotite is lepidoblastically aligned and may be concentrated adjacent to shear planes; major minerals are segregated into lenses and layers, and most minerals exhibit a parallel to subparallel planar orientation. Well defined lineations are expressed by biotite trains and, to a lesser extent, quartz rods.

Primary accessory minerals include apatite, sphene, ilmenite and magnetite, and they occur in a similar fashion as comparable phases in the mafic layers of the hornblende gneiss. Ferrohastingsite is the amphibole present locally and it is generally very fine-grained and subhedral.

Secondary accessory minerals include epidote replacing mafic minerals and very minor amounts of muscovite and chlorite replacing biotite. They are very fine-grained and anhedral to subhedral.

Mullen Creek Mafic Complex

General statement

The Mullen Creek mafic complex is a layered basic intrusion that consists of numerous gabbroic phases that have been variably metamorphosed. Gabbro, leucogabbro, microgabbro, diabase, and their metamorphosed equivalents are the dominant rock types in the southwestern portion of the mafic complex. Phases that are included on the geologic map (Plate 1) are listed with their diagnostic characterics in the appendix (Table 1). Rock types' symbols on Plate 1 reflect the predominant units present in any given area, although several phases invariably are present. Contacts between units of the complex are commonly gradational, erratic, or unexposed, and therefore, only exposed or strongly inferred contacts within the complex have been included on Plate 1.

Phases of the mafic complex in the study area have been divided into four groups on the basis of metamorphic overprint: (1) gabbroic and related rocks, (2) metagabbroic and related rocks, (3) retrograde metagabbroic and related rocks, and (4) hybrid metagabbroic and related rocks. Those rocks that have more pyroxene than amphibole are classified as gabbroic rocks, those with more amphibole than pyroxene as metagabbroic rocks, and those with appreciable amounts of minerals typical of greenschist facies metamorphism as retrograde metagabbroic rocks. Felsic intrusives have locally hybridized rock of the mafic complex and these are classified as hybrid metagabbroic rocks. Rocks of one group commonly have a gradational relationship with and occur locally within rocks of another group.

Gabbroic and related rocks

General statements and field characteristics. Rocks of the complex that have more pyroxene than amphibole have been classified as gabbroic in character. They occur principally in the southeastern portion of the study area in and near Prospect Mountain (Plate 1). This area has the best developed primary igneous layering, both large and small scale, and this planar fabric commonly controls the orientation of ridges.

The most distinctive field characteristic of the gabbroic rocks is the typical brown colorization of outcrops which is caused by weathering of pyroxene and olivine. Pyroxene grains commonly are rimmed by dark green amphibole, a feature that is very apparent in the coarser, more leucocratic phases. Phases comprising the gabbroic rock group include gabbro, leucogabbro, olivine gabbro, microgabbro, pegmatitic gabbro, granular gabbro, porphyritic gabbro (with pyroxene phenocrysts), diabase, and anorthosite (Table 1, Appendix).

Petrography. All gabbroic rocks are composed predominantly of primary clinopyroxene and plagioclase with lesser amounts of primary orthopyroxene, olivine, ilmenite, pyrite and magnetite. Most of the rocks are medium-grained and have sub-ophitic and(or) poikilitic textures, although fine-grained granular and pegmatitic phases also occur. Plagioclase (An_{54-76}) occurs as subhedral to euhedral lath shaped crystals with an average length of 0.9 to 1.3 mm. They commonly impart a prominent, primary foliation. Olivine and orthopyroxene, where present, are subhedral or show relict subhedral shapes. Clinopyroxene and primary magnetite are generally interstitial and may form oikocrysts (Fig. 3). Modal and petrographic data are summerized in Tables 5 and 6 respectively.

Amphibole, especially tremolite-actinolite, progressively replaces clinopyroxene, initially along grain boundaries and cleavage planes, then in patches until the replacement process is complete. Orthopyroxene also may be rimmed or replaced by amphibole. A thin zone of magnetite surrounded by talc occurs along fractures in orthopyroxene crystals (Fig. 4), and progressive replacement by talc may result in pseudomorphs that retain pyroxene cleavage. Olivine typically is rounded and is altered to magnetite and serpentine plus trace amounts of iddingsite along fractures. Where adjacent to plagioclase, olivine has an inner reaction rim of fibrous orthopyroxene aligned perpendicular to

Fig. 3. Photomicrograph of gabbro with hypidiomorphic texture. Composed of subhedral plagioclase (light gray) and orthopyroxene (gray-brown to yellow-brown) and interstitial anhedral clinopyroxene (purple to blue to green) and magnetite (black). Sample 23-66, crossed nicols, field of view is 18 mm.

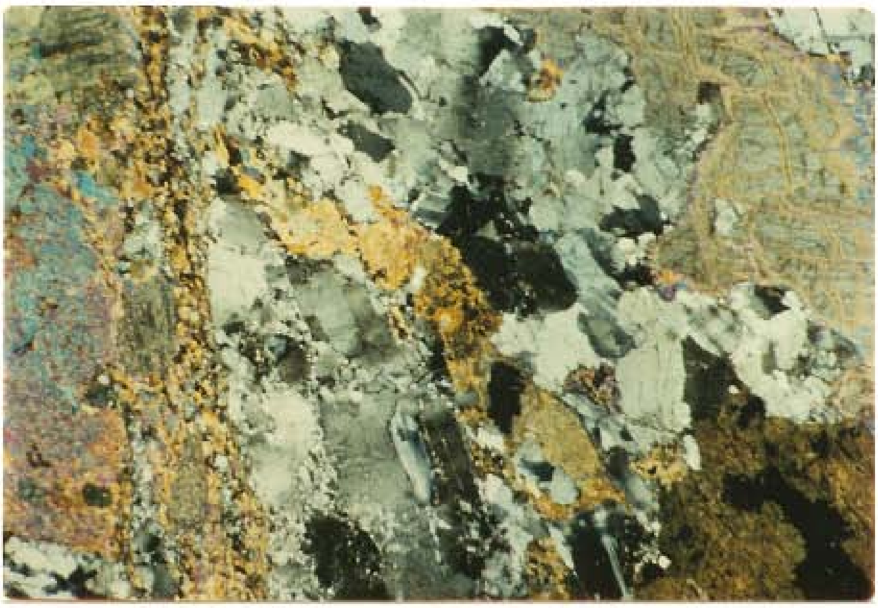


Fig. 4. Photomicrograph of metamorphosed pegmatitic gabbro. Note magnetite surrounded by talc replacing orthopyroxene (upper right), hornblende (yellow-brown) along shear plane (left), and granoblastic plagioclase along grain boundaries of larger primary plagioclase crystals (left center). Sample 23-67, crossed nicols, field of view is 18 mm.

Table 5. Modal analyses of gabbroic and related rocks of Mullen Creek mafic complex.

Sample	gabbro					diabase	
	23-66	23-67	23-68	23-77	23-79	23-28	23-91
plagioclase	45	40	63	50	42	28	44
An content	(54)	(58)	(70)	(76)	(75)	(50)	(64)
white mica (composition undetermined)	tr	--	--	--	tr	--	--
clinopyroxene	19	32	24	9	29	27	18
orthopyroxene	14	5	10	2	tr	--	2
olivine	--	--	--	13	tr	2	--
amphibole	2	18	tr	2	15	--	15
opaque minerals (undivided)	8	1	tr	1	tr	5	5
talc	--	4	tr	tr	4	--	tr
chrysotile	10	--	tr	--	--	--	--
secondary orthopyroxene (reaction rims)	--	--	--	7	--	6	--
amphibole + green spinel (reaction rims)	--	--	--	16	10	32	--
epidote	tr	--	tr	--	tr	tr	--
chlorite	--	tr	--	tr	tr	--	--
iddingsite	tr	--	--	tr	--	tr	--
hematite	--	tr	tr	tr	tr	tr	--
limonite	--	tr	3	tr	tr	tr	--
biotite	tr	--	tr	--	--	--	15
apatite	--	--	--	--	--	--	1

Table 6. Thin section characteristics of minerals of gabbroic and related rocks of the Mullen Creek mafic complex.

Plagioclase	clear, range An_{54-76}, average An_{65}, Albite and Carlsbad twins well developed, normal zoning very common, inclusions of schiller needle-like rutile present locally, minor alteration to undetermined white mica.
Clinopyroxene	cloudy (due to alteration) pale brown to brown green, probably augite, commonly has primary schiller inclusions of opaque minerals.
Orthopyroxene	may be moderately pleochroic (color scheme X=light pink, Y-Z=clear), usually cloudy due to alteration, optically negative with a high 2V angle therefore is hypersthene or bronzite, very fine exsolution lamellae of clinopyroxene present locally.
Olivine	clear, optically negative in olivine gabbro ($<Fo_{87}$) and optically positive in olivine diabase ($>Fo_{87}$).
Tremolite-actinolite	faintly pleochroic (color scheme X=very light green, Y=light brown, Z=brown green).
Hornblende	strongly pleochroic (color scheme X=green, Y=dark green, Z=green with a blue tint).
Magnetite	opaque, black in reflected light.
Ilmenite	opaque, black in reflected light.
Pyrite	opaque, yellow in reflected light.
Talc	clear to very cloudy.
Chrysotile	light green.
Amphibole and spinel reaction rim aggregate	cloudy, dark green, cryptocrystalline.

Table 6. (continued)

Secondary orthopyroxene (after olivine)	light green.
Epidote	clear to dusty light gray.
Chlorite	light green.
Iddingsite	red brown.
Hematite	dark red to opaque.
Limonite	dark brown to opaque.

the olivine grain boundary and an outer reaction rim aggregate of cloudy dark green amphibole or spinel (Fig. 5).

Shear planes are locally common and usually have amphibole, especially hornblende, developed adjacent to them (Fig. 4). Chrysotile is conspicuous and abundant (10%) in one sample (23-66) where it occurs in veinlets and rims magnetite, orthopyroxene and clinopyroxene. Trace amounts of other secondary minerals are locally common: chlorite may occur in veinlets, epidote in veinlets and replacing plagioclase, iddingsite replacing olivine, orthopyroxene and clinopyroxene, and hematite and limonite replacing mafic minerals.

Diabase. Diabase is similar to the gabbroic rocks but is distinguished by its fine-grained ophitic texture. Two samples of diabase were found that are distinctly different from their host metagabbroic rocks. Olvine diabase (sample 23-28, Fig. 5) is finer grained than its metagabbroic host rocks and occurs in a dike-like fashion although no contacts were exposed. It is comprised predominantly of plagioclase (An_{60}), clinopyroxene and a mixture of amphibole and spinel, and has minor amounts of olivine, magnetite, and secondary orthopyroxene (after olivine).

Biotite diabase (sample 23-91) contains 15% biotite and is characterized by abundant inclusions of apatite in plagioclase. It has major amounts of plagioclase (An_{64}), clinopyroxene and amphibole and minor amounts of magnetite and orthopyroxene. Biotite is generally anhedral, lacks well developed cleavage, and shows some evidence of replacing pyroxene. It is strongly pleochroic with the color scheme X=light brown, Y=Z=dark brown. Apatite crystals commonly are elongate (up to 0.2 mm long) and oriented along twin planes within the plagioclase.

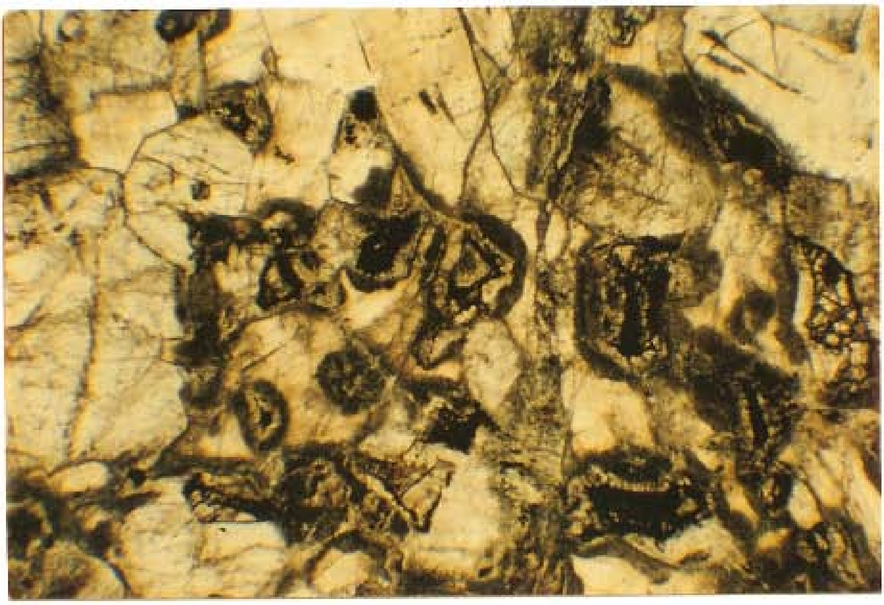


Fig. 5. Photomicrograph of olivine diabase exhibiting olivine reaction rims. Where olivine (cloudy light green, high relief) is in contact with plagioclase (very light brown), olivine has an inner rim of orthopyroxene (light green, fibrous alignment radial to olivine core) and an outer rim of amphibole and spinel (dark green brown, amorphous). Note replacement of olivine by magnetite (black) along fractures and completely. Sample 23-28, plane polarized light, field of view is 3.0 mm.

Metagabbroic and related rocks

General statement and field characteristics. Metagabbroic rocks consist predominantly of hornblende and plagioclase and are classified in this report as those rocks of the complex that have more amphibole than pyroxene and lack appreciable amounts of minerals typical of greenschist facies metamorphism. They comprise most of the complex in the study area between the older felsic intrusives and are also common north of the Big Creek felsic intrusive body.

Metagabbroic rocks generally have relict igneous textures and are massive but may exhibit foliation expressed by alignment of lath-shaped plagioclase crystals, primary igneous layers, or prismatic hornblende. Outcrops are typically dark green to dark gray except for leucocratic phases that are buff to light gray with dark green clots of hornblende. The metagabbroic rocks include metagabbro, metaleucogabbro, meta-porphyritic (spotted) gabbro, late stage metagabbro, migmatitic metagabbro, metamicrogabbro, meta-pegmatitic gabbro, metadiabase, metabasalt and transitional metagabbro (Table 1, Appendix).

Petrography. Most metagabbroic rocks are fine- to medium-grained and consist of plagioclase with interstitial hornblende. Coarse- to very coarse-grained hornblende (up to 5 cm) commonly form oikocrysts with plagioclase inclusions. Modal and petrographic data for all phases except metabasalt and transitional metagabbro are summarized in Tables 7 and 8, respectively.

Plagioclase (An_{44-73}) generally occurs as subhedral to euhedral lath-shaped crystals with lengths averaging 3.0-5.0 mm (3 to 5 times their width). It also occurs as aggregates with mosaic texture, typified by very fine-grained equigranular crystals with smooth grain boundaries

Table 7. Modal analyses of metagabbroic and related rocks of the Mullen Creek mafic complex.

	metaleucogabbro		metagabbro							
Sample	23-16	23-18	23-29	23-31	23-33	23-34	23-35	23-73	23-89	23-95
plagioclase	66	21	61	32	35	19	26	28	22	32
An content	(72)	(54)	(73)	(70)	(68)	(68)	(44)	(51)	(65)	(52)
white mica (composition undetermined)	--	53	--	--	1	2	9	8	14	6
hornblende	31	21	26	57	64	75	55	54	47	54
quartz	1	1	1	2	--	3	3	7	1	1
apatite	1	--	1	1	tr	--	tr	tr	--	tr
rutile	tr	--	--	tr	--	tr	--	tr	--	--
opaque minerals (undivided)	tr	1	tr	tr	tr	tr	2	1	1	1
sphene	tr	tr	tr	2	tr	tr	tr	1	2	1
scapolite	tr	--	6	1	--	--	--	--	--	--
epidote	1	3	5	5	tr	1	tr	1	13	5
biotite	--	--	--	--	--	--	5	tr	--	--
chlorite	--	--	--	--	--	--	--	tr	tr	tr
hematite	--	--	--	--	--	tr	--	--	--	--
limonite	--	--	--	--	tr	--	--	tr	tr	tr

Table 8. Thin section characteristics of minerals of metagabbroic and related rocks of the Mullen Creek mafic complex.

Plagioclase	clear, An_{44-73}, average An_{57}, Albite twinning very well developed, zoning generally normal but may be reverse or oscillatory, elongate microlites of opaque rutile, apatite and(or) light green amphibole common, commonly altered to white mica, saussurite and(or) clay, granoblastic plagioclase generally is unaltered with only poorly developed twinning and zoning.
Hornblende	moderately to strongly pleochroic (color scheme X=light brown, Y=light green to green, Z=green with a blue tint).
Quartz	clear.
Apatite	clear.
Rutile	deep red brown, birefringence masked by its strong color.
Magnetite	opaque, black in reflected light.
Ilmenite	opaque, black in reflected light.
Pyrite	opaque, yellow in reflected light.
Sphene	dusty brown.
Scapolite	clear, resembles muscovite but is uniaxial and does not show basal cleavage.
Epidote	clear to light green, typically dusty.
Biotite	strongly pleochroic (color scheme X=light brown, Y=Z=brown), prominent basal cleavage.
Chlorite	light green, dark gray or anomalous blue birefringence.
Hematite	dark red to opaque.
Limonite	dark brown to opaque.

and abundant 120° triple junctions. This granoblastic plagioclase is very common between larger plagioclase crystals, and locally becomes fine-grained and more pervasive (Fig. 6). In two samples, plagioclase is pervasively granoblastic except where laths are enclosed in hornblende oikocrysts.

Hornblende is generally anhedral but rarely has the blocky shape of relict pyroxene. It usually has very fine-grained, rounded quartz bleb inclusions that may make up 10% of the grains. Quartz inclusions are generally concentrated away from hornblende rims and may define schiller structure. With increasing quartz content the quartz becomes coarser grained and may occur as fine-grained crystals between hornblende crystals and(or) cluster together to form lensatic aggregates (Fig. 7). Inclusions of opaque minerals (magnetite?) are common in hornblende where quartz is lacking; these opaque minerals may define schiller structure. Hornblende very commonly occurs as very fine- to fine-grained aggregates of subhedral and euhedral prismatic crystals that have elongate or diamond shaped cross-sections, and are generally nematoblastically aligned. Hornblende also occurs within and between plagioclase and within and adjacent to veinlets of epidote.

Original primary igneous accessory minerals are apatite, rutile, ilmenite, magnetite, and pyrite. Apatite and rutile occur as tiny inclusions in plagioclase. Apatite also occurs as very fine- to fine-grained interstitial grains. Rutile may occur as very fine-grained crystals rimmed by sphene. Primary opaque minerals may reach medium-grained size and are either ilmenite rimmed by sphene, anhedral magnetite, or cubic crystals of pyrite (minor).

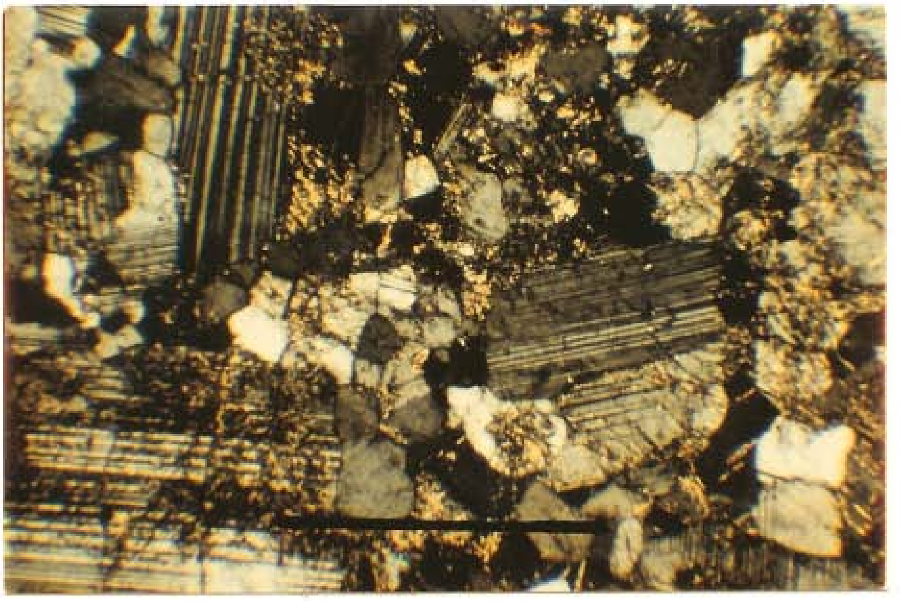


Fig. 6. Photomicrograph of anorthosite exhibiting granoblastic plagioclase grains between larger crystals of primary subhedral plagioclase. Note the alteration of plagioclase to white mica along grain boundaries and cleavage planes. Sample 23-83, crossed nicols, field of view is 2.7 mm.

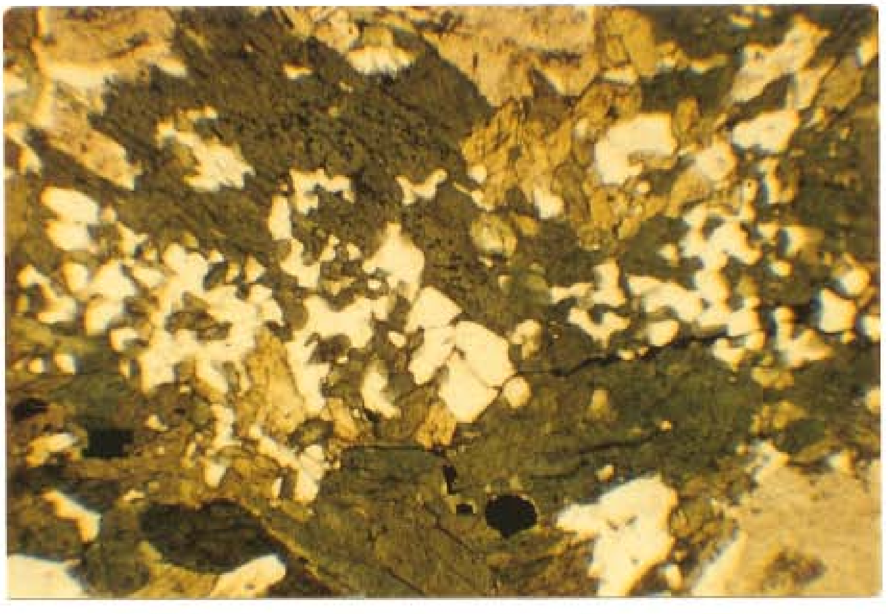


Fig. 7. Photomicrograph of metagabbro exhibiting an incipient quartz lens. The rock is comprised chiefly of hornblende (green and brown), plagioclase (light gray brown) and quartz (white). Sample 23-35, plane polarized light, field of view is 2.7 mm.

Accessory prograde metamorphic minerals include sphene and scapolite. Scapolite occurs ubiquitously between plagioclase and hornblende and locally forms oikocrysts that average 4.0 mm and are up to 8.0 mm long. Sphene, in addition to rimming rutile and ilmenite, also occurs as disseminated rounded blebs, usually associated with hornblende and(or) epidote, or in veinlets.

Secondary minerals include epidote, biotite, chlorite, hematite and limonite. Epidote occurs in all metagabbroic rocks and is the dominant secondary mineral. It forms euhedral crystals between plagioclase and hornblende and may be associated with scapolite. Epidote's most common occurrence is in or associated with veinlets and shear planes (average width 0.1 mm). It also occurs as an alteration product of plagioclase where it is very fine-grained and intergrown with white mica. Plagioclase alteration is commonly spatially related to epidote veinlets. Biotite occurs as generally dispersed subhedral grains but may replace mafic minerals. Chlorite occurs in veinlets, replaces hornblende and is interlayered with biotite which it replaces. It is generally anhedral and fine-grained. Limonite and hematite are common and replace mafic minerals.

Metabasalt. Metabasalt typically is comprised of very fine-grained hornblende and plagioclase with fine- to medium-grained plagioclase phenocrysts. It is very dark green with light gray rectangular plagioclase phenocrysts. Metabasalt is found throughout the complex but is concentrated in the SE/4 of section 3, the S/2 of section 33, and the NW/4 of section 4. Modal data are summarized in Table 9 and petrographic data are similar to those for other metagabbroic rocks (Table 8).

Table 9. Modal analyses of metabasalt of the Mullen Creek mafic complex.

Sample	23-30	23-71	23-94	23-110
plagioclase	26	27	29	33
phenocryst An content	(70)	(--)	(--)	(65)
groundmass An content	(43)	(46)	(42)	(60)
white mica (composition undetermined)	6	1	9	4
hornblende	60	66	44	57
quartz	1	2	3	--
apatite	tr	tr	--	tr
opaque minerals (undivided)	4	2	7	2
sphene	--	tr	tr	--
epidote	2	1	7	4
biotite	tr	1	tr	--
chlorite	1	tr	1	--

Groundmass is generally ophitic to sub-ophitic with the plagioclase (An_{43-60}) immersed in a hornblende matrix. Phenocrysts are common to rare and are generally euhedral tabular plagioclase crystals (An_{65-70}), with well developed albite twins, normal zoning, and variable alteration. Groundmass plagioclase is less altered and exhibits more poorly developed twinning and zoning. Granoblastic plagioclase in a massive array is common, especially within the groundmass, and aggregates generally reflect outlines of relict tabular plagioclase crystals.

Hornblende generally occurs as very fine-grained idioblastic prismatic crystals but may occur as fine-grained anhedral crystals with rare quartz inclusions. Quartz also occurs as individual grains or may be associated with granoblastic plagioclase in segregations or crude layers.

The primary accessory phases apatite, rutile, ilmenite, magnetite and pyrite and the secondary minerals sphene, epidote, chlorite, biotite and limonite occur in similar fashion as in other metagabbroic rocks.

Transitional metagabbroic and related rocks. Transitional metagabbroic and related rocks are considered to be part of the complex even though they greatly resemble hornblende gneiss. Criteria for recognizing the genetic associations of transitional metagabbro with the complex include: (1) proximity to rocks that are clearly part of the complex, (2) absence of abundant interlayered felsic rock, (3) coarse grain size which is more typical of intrusive rock than metamorphic rock in the area, (4) general absence of quartz except as inclusions in amphibole, (5) massive rather than layered structure, and (6) presence of euhedral, zoned and(or) calcic plagioclase (greater than An_{60}). They are typically comprised of dark green amphibole and light gray plagioclase and are cut by felsic veins. Modal data are summarized in Table 10 and petrographic data are similar to those of other metagabbroic rocks (Table 8).

Nematoblastic alignment of hornblende is the dominant textural feature. Hornblende and(or) plagioclase commonly form thin (average 0.1 mm) mineral trains adjacent to foliation planes. Hornblende is usually idioblastic and plagioclase generally forms aggregates with mosaic texture. Accessory and secondary minerals are the same as in other metagabbroic rocks and they occur in similar fashion, except for sphene, which tends to have crystal faces in transitional metagabbroic rocks.

Retrograde metagabbroic and related rocks

General statement and field characteristics. Retrograde metagabbroic and related rocks are those rocks of the complex that are enriched in minerals indicative of retrograde greenschist facies metamorphism. These minerals include chlorite, epidote, tremolite-actinolite and the products of plagioclase saussuritization. They occur throughout the study area but are concentrated in section 27 near the Mullen Creek-Nash Fork shear zone. They appear to be similar to other metagabbroic rocks but are distinguished by their chloritic sheen and commonly cataclastic texture. Light gray or greenish plagioclase and green to dark green amphibole, chlorite and epidote are the dominant minerals of these rocks. All of the gabbroic, metagabbroic and related rock types show at least local effects of retrograde metamorphism.

Petrography. Texture and mineralogy are basically the same as for other metagabbroic rocks except for the textural and mineralogical overprint of retrograde metamorphism. The most notable textural feature of

Table 10. Modal analyses of transitional metagabbroic and related rocks of the Mullen Creek mafic complex.

Sample	23-9	23-22	23-53	23-54A	23-54B
plagioclase	50	11	47	15	79
An content	(44)	(46)	(68)	(?)	(?)
white mica (composition undetermined)	1	31	6	19	1
hornblende	38	49	39	63	18
quartz	10	--	--	--	--
apatite	tr	--	tr	tr	tr
opaque minerals (undivided)	tr	1	tr	1	tr
sphene	1	--	tr	tr	1
epidote	tr	2	7	2	1
biotite	--	--	1	--	tr
chlorite	tr	2	--	--	--
tremolite-actinolite	--	4	--	--	--
potash feldspar	tr	--	--	tr	--
serpentine	--	--	--	--	--

these rocks is the abundance of veins and veinlets of epidote and(or) chlorite. Relict igneous texture may be lost where retrograde metamorphism has been intense and the resulting rock consists of fine-grained crystals with indistinct grain boundaries and random orientation. Intergranular relationships may become difficult to decipher because of fine-grained mineral clusters. Modal and petrographic data are summarized in Tables 11 and 12, respectively.

Plagioclase usually occurs as medium-grained, subhedral to euhedral, lath-shaped crystals. Saussuritization to epidote, albite and white mica are very common and most samples studied had at least twice as much altered as unaltered plagioclase. Alteration usually occurs in cores and along fractures and cleavage planes but entire crystals may be replaced where alteration was intense. A clear spatial relationship is commonly seen between epidote veinlets and plagioclase alteration. An X-ray diffraction study was performed on 13 samples of retrograde metagabbroic and related rocks to identify the type of mica and clay that occur as alteration products of plagioclase. The products are dominantly sericite (muscovite) with minor kaolinite and locally minor paragonite.

Two amphiboles, hornblende and tremolite-actinolite, occur in the retrograde metagabbroic rocks. Hornblende occurs in a fashion comparable to that in other metagabbroic rocks, and contains opaque minerals and quartz inclusions that locally define schiller structure. Tremolite-actinolite occurs interstitially, is commonly fibrous, and has fewer opaque minerals and quartz inclusions than hornblende. Hornblende may rim tremolite-actinolite and both amphiboles may occur together in very fine-grained subhedral aggregates. The primary accessory phases apatite,

Table 11. Modal analyses of retrograde metagabbroic rocks of the Mullen Creek mafic complex.

Sample	23-8	23-19A	23-36	23-48	23-49	23-80A	23-92	23-93	23-97	23-105	23-108	23-112
plagioclase	8	4	24	12	15	29	27	3	3	12	tr	11
An content	(51)	(39)	(58)	(44)	(53)	(60)	(54)	(43)	(44)	(49)	(?)	(?)
white mica (composition undetermined)	40	30	18	29	36	--	1	28	42	20	24	27
hornblende	--		--	48	31	--	--	33	45			--
tremolite-actinolite	41		44	--	--	66	70	--	--			52
amphibole (undivided)		43								45	62	
quartz	3	9	1	tr	--	tr	1	1	2	4	--	tr
apatite	--	tr	tr	tr	tr	--	--	tr	tr	--	tr	--
rutile	--	--	--	--	--	--	--	--	tr	--	tr	--
opaque minerals (undivided)	tr	1	10	1	1	tr	tr	tr	1	2	2	tr
sphene	1	2	1	1	tr	--	1	1	1	1	--	2
epidote	7	--	2	6	11	--	tr	9	2	4	2	4
clinozoisite	--	4	--	--	--	5	--	--	--	--	--	--
chlorite	tr	7	--	3	3	--	--	2	4	8	10	3
prehnite	--	--	--	--	--	--	--	--	--	2	--	--
calcite	--	--	--	--	3	--	--	13	--	--	--	1
zeolite (composition undetetmined)	tr	--	--	--	--	--	--	--	--	--	--	tr
biotite	--	--	--	--	--	--	--	--	tr	2	--	--

Table 12. Thin section characteristics of minerals of retrograde metagabbroic and related rocks in the Mullen Creek mafic complex.

Plagioclase	clear, An_{28-75}, average An_{50}, composition variable but generally has the lowest An content of all rocks of the complex (composition determinations imprecise in many samples due to highly altered state of plagioclase), other characteristics similar to metagabbroic rocks (Table 8).
Hornblende	strongly pleochroic (color scheme X=light green brown, Y=light green, Z=green with a blue tint).
Tremolite-actinolite	faintly pleochroic (color scheme X=very light green, Y=light green, Z=green with a blue tint).
Ilmenite, magnetite, pyrite, apatite, rutile, sphene	same as in metagabbroic rocks (Table 8).
Quartz	clear, undulatory extinction.
Epidote	clear to very light green.
Clinozoisite	very light green, anomalous blue birefringence.
Chlorite	faintly pleochroic (color scheme X=very light green, Y=Z=light green), well developed basal cleavage, locally has anomalous gray-yellow birefringence.
Prehnite	clear, platey cleavage, anomalous blue birefringence.
Calcite	clear to light gray.
Undetermined zeolite	clear, dark gray birefringence, optically negative, 2V=30.
Biotite	strongly pleochroic (color scheme X=light brown, Y=Z=brown to brown with a green tint), well developed basal cleavage.
Muscovite	clear, well developed basal cleavage.
Cummingtonite	moderately pleochroic (color scheme X=light green brown, Y=light green, Z=green with a blue tint).

Table 12. (continued)

Talc	light green.
Olivine	clear; optically positive with 2V angle equal to approximately 85° (Fo_{95}).
Pleonaste	deep green, isotropic.
Antigorite	light yellow to yellow brown to dark yellow brown, optically uniaxal negative with a low 2V.

rutile, ilmenite, magnetite and pyrite are similar in occurrence to those in other metagabbroic rocks.

A wide variety of generally very fine- to fine-grained secondary minerals occurring in these rocks includes quartz, epidote, clinozoisite, chlorite, sphene, magnetite, zeolite, calcite, biotite, muscovite, and prehnite. Quartz occurs in veins, veinlets and interstitially in some samples. Epidote is very common and occurs in veinlets, rims opaque minerals (magnetite?), and is disseminated in amphibole and plagioclase. Clinozoisite occurs replacing plagioclase in a few samples (generally th se that lack epidote). Chlorite is most commonly in or associated with veinlets, but also replaces mafic minerals and occurs between grains and along plagioclase cleavage planes. Sphene and(or) opaque minerals (magnetite?) commonly occur along basal cleavage planes of chlorite. An undetermined zeolite mineral is associated with chlorite veinlets. Calcite occurs in veinlets and may be present as an alteration product of plagioclase, especially in cores that have white mica rims. Ilmenite may be rimmed by sphene. Biotite and muscovite locally replace amphibole and plagioclase, respectively. Some unknown opaque mineral (magnetite?) is locally replaced by interlayered to patchy mixtures of biotite and(or) chlorite and(or) prehnite.

Retrograde gabbroic and related rocks. These units are essentially the same as retrograde metagabbroic rocks except that clinopyroxene is present in amounts up to 5%. Modal data are summarized in Table 13 and petrographic data are similar to those for other retrograde metagabbroic rocks (Table 12).

Clinopyroxene is generally anhedral, medium- to coarse-grained and is pale green to "dirty" brown in thin section. It occurs as cores of

Table 13. Modal analyses of retrograde gabbroic rocks of the Mullen Creek mafic complex.

Sample	23-23	23-26	23-78	23-84	23-111
plagioclase	11	15	34	56	32
An content	(59)	(60)	(75)	(54)	(64)
white mica (composition undetermined)	39	41	5	2	26
clinopyroxene	2	1	5	2	tr
hornblende (undivided)	22	23	33	30	30
tremolite-actinolite	15	5	20	2	8
quartz	--	--	--	1	--
rutile	--	--	tr	--	--
opaque minerals (undivided)	1	1	tr	4	tr
sphene	--	--	tr	1	--
epidote	1	3	2	1	2
chlorite	7	10	1	--	--
prehnite	2	1	--	--	1
biotite	--	tr	--	1	1

oikocrysts that have hornblende rims. Tremolite-actinolite commonly replaces clinopyroxene in patches and may completely replace the pyroxene so that tremolite-actinolite is rimmed by hornblende, a relationship that also occurs in retrograde metagabbroic rocks (Fig. 8). Hornblende also replaces clinopyroxene cores (in patches or completely) but it is dissimilar in color (and therefore composition) to the hornblende rims.

Metapyroxenite and related rocks. Metapyroxenites are considered related to retrograde metagabbroic rocks because they contain considerable amounts of minerals typical of greenschist facies metamorphism. They are easily recognizable in the field because of their characteristic green to dark green color, lack of plagioclase, abundance of tremolite-actinolite and(or)chlorite that imparts a schistose appearance, and a typical lumpy and pitted weathered surface. Modal data are summarized in Table 14 and petrographic data are similar to those for other retrograde metagabbroic rocks (Table 12).

Chlorite, talc, antigorite, cummingtonite and tremolite-actinolite occur as secondary minerals that completely replace primary phases. Lepidoblastic and(or)nematoblastic foliation is common and cataclastic layering, flaser structure and lensatic mineral aggregates may be present.

Chlorite occurs in all samples and is generally fine-grained. It replaces and is locally interlayered with biotite, replaces plagioclase, is related to veinlets, and occurs in medium-grained clusters. Amphibole is very fine- to medium-grained. Cummingtonite may have quartz bleb inclusions or form aggregates of prismatic crystals with prominent (110) cleavage. Locally cummingtonite is partially or completely replaced by longate prisms of talc that are aligned parallel to relict amphibole cleavage. Tremolite-actinolite is distinctly lighter colored in thin

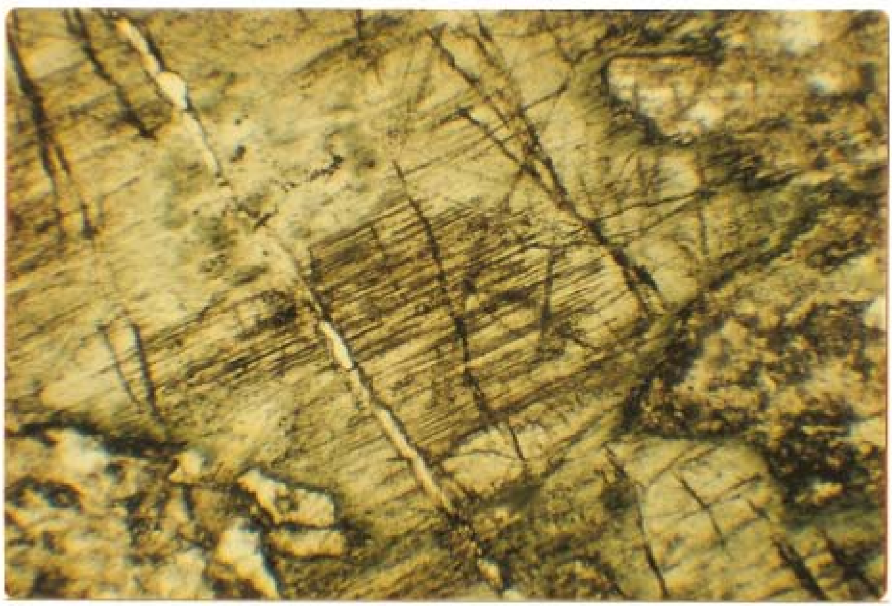


Fig. 8. Photomicrograph of retrograde gabbro. Note hornblende (dark green) rimming a core of clinopyroxene (light brown) which is being replaced by tremolite-actinolite (light green). Sample 23-23, plane polarized light, field of view is 2.8 mm.

Table 14. Modal analyses of samples of metapyroxenite and related rocks of the Mullen Creek mafic complex.

	metapyroxenite			ultramafic rock
Sample	23-82A	23-82B	23-86	23-87
cummingtonite	55	--	--	--
tremolite-actinolite	--	92	57	32
opaque minerals (undivided)	tr	tr	1	19
chlorite	29	8	40	1
talc	16	--	2	--
olivine	--	--	--	9
hercynite	--	--	--	5
antigorite	--	--	--	34

section and forms long prismatic crystals. Opaque minerals occur as inclusions in amphibole and as very fine-grained disseminated anhedral to euhedral crystals.

Sample 23-87 is an ultramafic rock that contains primary olivine and pleonaste and secondary tremolite-actinolite, antigorite, and magnetite. Olivine and pleonaste are now anhedral to subhedral but their distribution and alteration products reflect that they were once medium-grained euhedral crystals. Antigorite is flakey to fibrous with inclusions of concentric magnetite rings generated from the gradual replacement of olivine. Very fine-grained tremolite-actinolite has replaced pleonaste. Shearing has produced flaser structure defined by augen of amphibole with minor spinel in a matrix of antigorite, minor olivine, and streaks of magnetite bending around the augen.

Hybrid metagabbroic and related rocks

General statement and field characteristics. Many mafic rocks of the complex have been hybridized by contamination by felsic intrusives. Ramirez (1971) and Donnelly (1979) used this term to describe similar rocks in other parts of the mafic complex. In the study area, these rocks occur mostly in the vicinity of the Big Creek granite in sections 4, 33 and 34. Hybrid rocks were most easily recognized by the presence of biotite in otherwise metagabbroic rocks.

Petrography. Hybrid metagabbroic rocks commonly are recrystallized to very fine-grained mosaic aggregates of plagioclase, hornblende and biotite. Modal and petrographic data are summarized in Tables 15 and 16, respectively. Relict igneous texture is preserved by plagioclase and mafic mineral aggregates retaining the shape of relict primary crystals. Plagioclase generally is untwinned and has a low calcium component (An_{30-41}).

Table 15. Modal analyses of hybrid metagabbroic and related rocks of the Mullen Creek mafic complex.

	hybrid metamelanogabbro			hybrid metagabbro	
Sample	23-25A	23-25B	23-25C	23-43	23-44
plagioclase	15	7	17	46	33
An content	(40)	(?)	(30)	(?)	(?)
sericite	8	--	11	5	10
hornblende	45	67	--	13	10
ferrohastingsite	--	--	58	--	--
quartz	--	--	--	1	13
potash feldspar	--	--	--	tr	--
apatite	tr	tr	tr	1	1
opaque minerals (undivided)	8	1	3	2	2
sphene	1	tr	--	2	2
calcite	tr	--	tr	--	--
epidote	tr	tr	tr	10	8
biotite	18	17	7	20	11
chlorite	5	8	4	--	8
chrysotile	--	--	--	--	2

Table 16. Thin section characteristics of minerals of hybrid metagabbroic and related rocks of the Mullen Creek mafic complex.

Plagioclase	clear, An_{30-40}, average An_{35}, determinations very questionable due to extensive alteration or untwinned granoblastic crystals, normally zoned.
Hornblende	strongly pleochroic (color scheme X=light brown to light green brown, Y=green to green brown, Z=blue green to green with a blue tint).
Ferrohastingsite	same pleochroism as hornblende, distinguished from hornblende by a 2V angle of approximately 10°.
Ilmenite, magnetite, pyrite, apatite, sphene	same as in metagabbroic rocks (Table 8).
Epidote	bright yellow, anomalous yellow birefringence.
Biotite	strongly pleochroic (color scheme X=light brown, Y=Z=brown to dark brown to brown with a green tint), may have well developed basal cleavage.
Chlorite	weakly pleochroic (color scheme X=very light green, Y=Z=light green), anomalous gray-yellow birefringence.
Chrysotile	light green, anomalous green birefringence.
Calcite	clear to light gray.

Hornblende commonly has abundant schiller inclusions of opaque minerals. Biotite replaces hornblende and opaque minerals (magnetite?) or occurs as individual platey crystals. Minor and accessory minerals include primary apatite, rutile, ilmenite, magnetite and pyrite, prograde metamorphic sphene, and secondary sericite, epidote, calcite, quartz, chlorite and magnetite. These minerals are similar in occurrence to those in other metagabbroic rocks. Sericite and epidote replace plagioclase; epidote, calcite and quartz occur in veinlets; and epidote and chlorite replace mafic minerals or occur disseminated as interstitial grains.

Older Felsic Intrusives

Big Creek Granite

General statement and field characteristics. The Big Creek granite occurs primarily in the southwestern part of the study area with an extension to the northeast in sections 3, 4, 33 and 34. Outcrops tend to be prominent, are typically pink and rounded, have well developed foliation defined by aligned biotite, and quartz rod lineations are locally abundant. Where relatively undeformed the unit generally is uniform and massive. Cataclasized phases are characterized by rounded porphyroclasts of K-feldspar in a dark gray mylonitized groundmass.

Petrography. In the relatively undeformed phases of the Big Creek granite, crystals are generally fine-grained, equigranular and xenobalstic with slightly sutured grain boundaries. Medium-grained microcline phenocrysts occur locally. Directional fabric is imparted by platey mica, quartz rods, lensatic aggregates of minerals and crudely layered mineral segregations. Thin laminae of sheared rocks are common and contain very fine-grained quartz with minor potash feldspar, plagioclase, biotite and epidote. Modal and petrographic data are summarized in Tables 17 and 18, respectively.

Relatively undeformed granite is reasonably consistent compositionally and averages 38% quartz, 34% microcline and 26% plagioclase (An_{32-40}) (Fig. 9). Microcline tends to be equant and blocky, quartz is generally interstitial but also may be blocky, and plagioclase, the finest grained major component, is generally interstitial.

Accessory minerals are rare and consist of trace amounts of very fine- to medium-grained anhedral to euhedral ilmenite, magnetite and muscovite. Secondary minerals also are uncommon; muscovite may occur with sericitized plagioclase, sphene replaces ilmenite, biotite replaces muscovite and opaque minerals, and epidote replaces biotite and opaque minerals.

Prospect Mountain granite

General statement and field characteristics. The Prospect Mountain granite occurs in the southeastern part of the study area in sections 1, 2, 6, 7, 11 and 12. Outcrops are generally pink to light gray brown and typically exhibit a cataclastic to porphyroclastic fabric (Fig. 10). The main body of granite is to the west, where it forms a stock which is characterized by a relatively high, flat terrain. To the east of the main body, granite is interlayered with hornblende gneiss and forms prominent ridges. Hematite is relatively abundant, especially adjacent to shear planes and in small (up to 1.0 cm) cavities.

Petrography. The Prospect Mountain granite is similar to the Big Creek granite in its generally xenoblastic nature, slightly sutured grain boundaries, and variable grain size caused by differential

Table 17. Modal analyses of Big Creek granite.

Sample	23-7	23-11A	23-37*	23-39	23-96*
microcline	34	36	40	32	68
quartz	35	44	23	35	19
plagioclase	29	18	34	32	13
An content	(32)	(40)	(?)	(30)	(38)
opaque minerals (undivided)	tr	tr	tr	tr	tr
muscovite	1	1	tr	tr	--
biotite	1	tr	--	1	--
epidote	tr	1	1	tr	tr
sphene	tr	--	--	tr	--
chlorite	--	--	2	--	tr

*strongly cataclasized

Table 18. Thin section characteristics of minerals of older felsic intrusives (Big Creek and Prospect Mountain granites).

Microcline	clear, well developed grid twinning except in granoblastic crystals in groundmass, rarely zoned, string or bead microperthite, quartz inclusions occur as blebs or granophyric intergrowths, rare plagioclase fracture filling, minor alteration products.
Quartz	clear, undulatory extinction, least altered major mineral.
Plagioclase	clear, An_{26-39}, average An_{33}, poorly twinned, poorly zoned locally, antiperthitic locally.
Apatite	clear.
Zircon	clear.
Spinel (pleonaste?)	clear to brown.
Rutile	dark red with anomalous yellow brown birefringence, zoned.
Magnetite	opaque, black in reflected light.
Ilmenite	opaque, black in reflected light.
Muscovite	clear, well developed basal cleavage.
Biotite	strongly pleochroic (color scheme X=brown, Y=Z=dark brown), locally becomes dark brown to black with anomalous brown birefringence, well developed basal cleavage.
Epidote	clear, light gray, light green or bright yellow green with anomalous yellow birefringence.
Sphene	brown.
Chlorite	moderately pleochroic (color scheme X=light green, Y=Z=green), anomalous yellow gray birefringence.
Hematite	dark red to opaque.

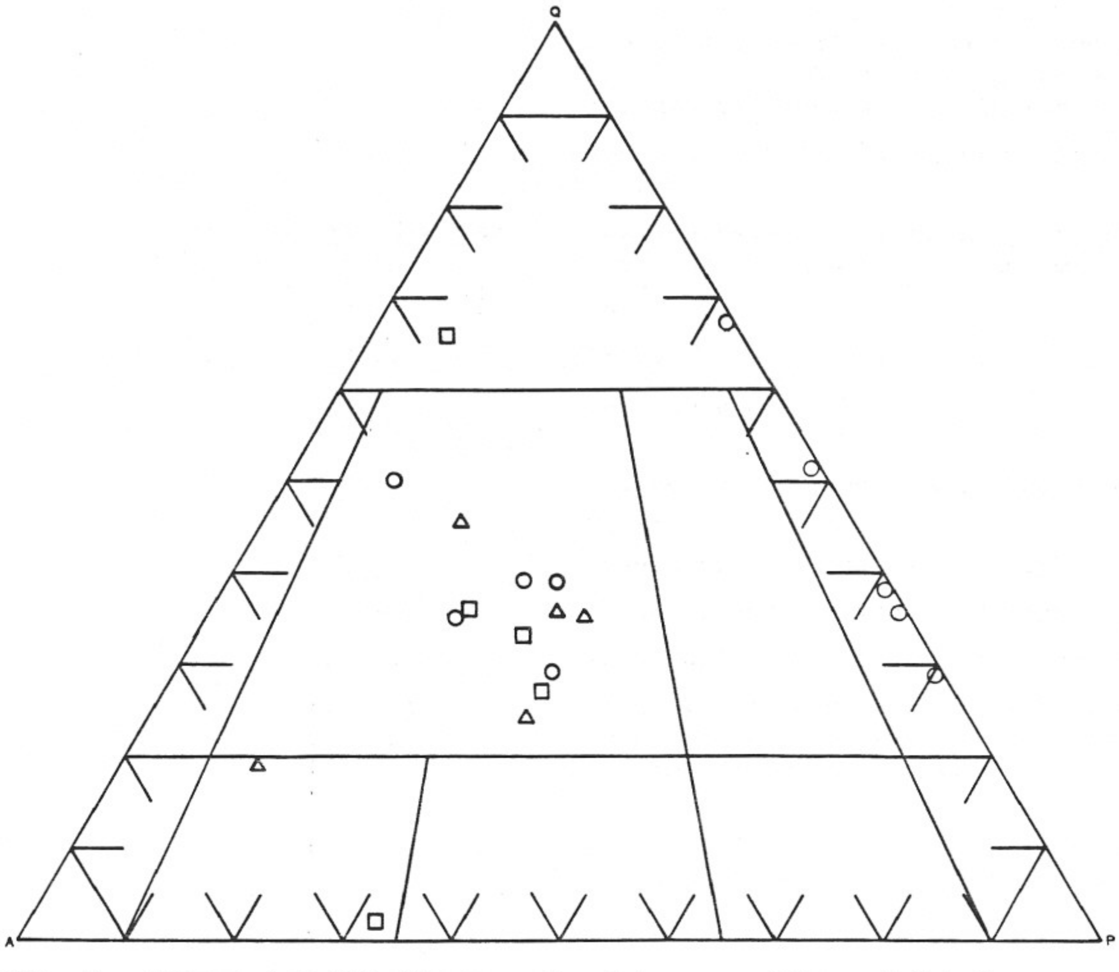


Fig. 9. Triangular QAP diagram of modal composition of felsic intrusive rocks in the study area. Triangles represent Big Creek granite, squares represent Prospect Mountain granite and circles represent younger felsic intrusives.

Fig. 10. Outcrop of porphyroclastic Prospect Mountain granite in NW/4 of section 12. Note fractured and rotated porphyroclasts of very coarse-grained microcline in a fine-grained matrix of quartz, microcline, plagioclase, epidote and chlorite. Pencil is 5 inches (13 cm) long.

shearing. Cataclastic effects are best expressed where the granite contains medium- to very coarse-grained microcline porphyroclasts that locally have been broken and rotated to form augen. Foliation is expressed by mineralogical and(or) grain size layering, alignment of lensatic minerals and mineral aggregates, alignment of porphyroclasts, flaser structure, lepidoblastic alignment of biotite, and the subparallel alignment of microfractures. Petrographic and modal data are summarized in Tables 18 and 19, respectively.

The granite averages 35% microcline, 31% quartz and 22% plagioclase (An_{26-34}) (Fig. 9). Quartz content is quite variable: sample 23-57 contains 62% quartz, some of which occurs in cavity fillings in which subhedral crystals are coated with hematite. Quartz is generally fine- to medium-grained, irregular in shape and may occur as stringers. Plagioclase is very fine- to medium-grained and occurs interstitially or as equant grains. Microcline occurs as porphyroclasts and in the groundmass. Porphyroclasts are medium- to very coarse-grained and may be recrystallized to granoblastic aggregates. Groundmass microcline generally is fine-grained and crystals may be equant or irregular in shape.

Primary accessory minerals are apatite, zircon, rutile, spinel (pleonaste?), muscovite, ilmenite and magnetite. Apatite, zircon, spinel and some ilmenite and magnetite occur as very fine-grained subhedral crystals. Rutile shows a relict medium-grained prismatic shape. Muscovite and some ilmenite and magnetite are anhedral.

Secondary minerals are biotite, epidote, chlorite, sphene and hematite. Biotite and epidote occur as very fine- to fine-grained disseminated grains. Epidote also occurs in veinlets and in the matrix

Table 19. Modal analyses of Prospect Mountain granite.

Sample	23-52	23-55	23-57	23-61	23-62
microcline	35	35	26	41	38
quartz	32	32	62	2	26
plagioclase	22	28	7	20	35
An content	(35)	(39)	(?)	(32)	(26)
apatite	--	tr	tr	tr	tr
zircon	--	--	tr	--	--
spinel	--	--	--	--	tr
rutile	--	--	--	1	--
opaque minerals (undivided)	tr	tr	2	1	tr
muscovite	--	tr	1	--	--
biotite	--	1	1	3	1
epidote	11	1	tr	16	tr
sphene	--	--	--	3	--
chlorite	--	--	--	13	--
hematite	tr	3	1	--	--

of porphyroclastic rocks (e.g. sample 23-61) where it forms fine- to medium-grained, long prismatic crystals with well developed crystal faces. Chlorite occurs with epidote in the matrix and has a radiating habit. Sphene occurs as disseminated grains and as rims on ilmenite. Hematite commonly has replaced mafic mineral psuedomorphically and occurs in fractures.

Cataclastic Rocks

General statement and field characteristics. Rocks in which the most prominent textural feature was produced by intense shearing have been classified as cataclastic rocks. These rocks occur locally throughout the study area but are concentrated in the Mullen Creek-Nash Fork shear zone which traverses the northwestern margin of the study area in sections 5, 6, 22, 27, 28 and 32. Locally well laminated mylonites, augen gneiss and moderately sheared igneous rocks are the dominant rock types of the shear zone. They range gradationally from light colored quartzo-feldspathic phases to dark gray mafic rocks, and extreme interlayering down to the scale of millimeters is common. The shear zone is mapped primarily simply as sheared rocks although thicker, prominent layers of felsic- or mafic-rich rocks have been mapped locally. Younger felsic intrusives are common in the shear zones and generally are conformable to layering.

Local shear zones occur in other portions of the study area and a relatively large zone of shearing that sub-parallels the Mullen Creek-Nash Fork shear zone in sections 4, 5, 33 and 34 is informally referred to as the Big Creek shear zone in this report. This shear zone includes cataclasized Big Creek granite and rocks of the mafic complex.

Cataclastic deformation has affected most rocks in the study area to some degree and zones of cataclasis are in part characterized by epidote filled fractures, broken and bent crystals, and parallelism of fractures accentuated by secondary minerals such as biotite. Poor exposure and the gradational nature of cataclastically deformed rocks both along and across strike made the mapping of local shear zones difficult.

Cataclastic rocks have been divided into three groups: (1) mylonites, (2) augen gneiss, and (3) sheared granitic rocks. Textural features rather than mineralogy are stressed in descriptions; petrographic data are not presented in table form because of the great diversity of mineral species that comprise these rocks. Modal data are summarized in Table 20.

Petrography. Mylonites are extremely fine- to very fine-grained with average grain size down to less than 0.1 mm. Foliation is generally defined by alignment of elongate, lensatic minerals and mineral aggregates. Mafic layers are dark gray and consist predominantly of mosaics of prismatic hornblende with lesser amounts of plagioclase, quartz and locally abundant epidote. Felsic layers consist of fine-grained porphyroclastic microcline or plagioclase in a matrix of quartz, plagioclase and locally microcline. Chlorite and biotite may occur in either mafic or felsic layers and commonly are lepidoblastically aligned. Accessory minerals include sphene, ilmenite and magnetite.

Augen gneiss is characterized by augen of fine- to medium-grained plagioclase or microcline with minor quartz and(or) plagioclase or microcline, and shows well developed flaser structure (Fig. 11). Augen may be mosaic aggregates or single rotated crystals. They comprise up to approximately 40% of the rock. Flaser structure is common and expressed

Table 20. Modal analyses of samples of cataclastic rocks, including sheared granite, augen gneiss, quartzo-feldspathic gneiss and sheared mafic rocks.

	sheared granite		augen gneiss			quartzo-feldspathic gneiss				sheared mafic rocks	
Sample	23-23A	23-24	23-70	23-98	23-99	23-100	23-101	23-103	23-109	23-96	23-104D
microcline	45	7	tr	13	36	4	tr	--	47	--	--
quartz	51	32	10	28	36	35	9	37	9	6	2
plagioclase	3	11	44	45	10	35	30	41	18	17	6
An content	(?)	(30)	(39)	(?)	(?)	(?)	(?)	(36)	(32)	(48)	(?)
white mica (composition undetermined)	--	35	3	?	?	?	13	3	?	?	5
amphibole (undivided)	--	--	37	tr	--	--	39	--	18	75	55
apatite	--	--	tr	tr	--	--	1	--	tr	tr	1
opaque minerals (undivided)	1	1	--	tr	tr	tr	tr	tr	1	1	7
muscovite	--	1	--	1	5	7	--	--	--	--	--
biotite	--	1	--	8	9	12	2	16	3	--	2
epidote	--	5	tr	5	4	7	3	3	3	tr	17
sphene	tr	tr	1	--	tr	tr	tr	tr	1	1	tr
chlorite	--	7	5	--	--	--	3	--	--	--	5
hematite	tr	--	--	--	--	--	--	--	--	--	tr

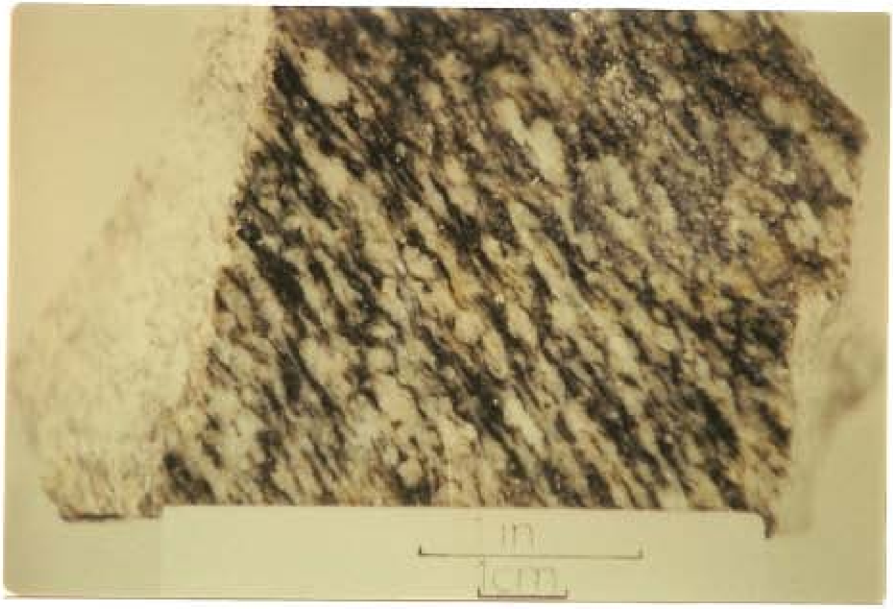


Fig. 11. Photograph of slabbed augen gneiss of the Mullen Creek-Nash Fork shear zone. Note medium-grained augen of microcline surrounded by quartz stringers and minor plagioclase in a groundmass of very fine-grained biotite, epidote, muscovite, sphene, magnetite, quartz, plagioclase and microcline. Sample 23-99.

Fig. 12. Photograph of slabbed, highly sheared, Big Creek granite. Note abundant fractures, epidote veinlets, granulation along shear planes and rounded porphyroclasts of microcline. Sample 23-90.

by alignment of amphibole in mafic rocks and biotite in felsic rocks. Groundmass is comprised of very fine- to fine-grained quartz, plagioclase ± microcline, amphibole, and biotite with minor amounts of epidote, sphene, muscovite, ilmenite and magnetite.

Sheared granites consist primarily of quartz, plagioclase and microcline. All of the major minerals occur as porphyroclasts locally and as medium- to coarse-grained lensatic mosaic aggregates, especially quartz. Foliation is expressed by alignment of these aggregates and porphyroclasts along with prismatic amphibole or platey biotite. Thin zones (up to 5.0 mm) of mylonite containing finely granulated major minerals along with epidote, biotite, ilmenite and(or) magnetite are very common (Fig. 12).

Younger Felsic Intrusives

General statements and field characteristics

Younger felsic intrusives include a diverse group of quartzofeldspathic dikes and sills that occur throughout the study area. They generally are fine-grained and have a pink to reddish color. They form low lying ridges and are easily mapped by float where hosted by mafic rocks.

Petrography

Younger felsic intrusives consist of two mineralogically distinct rock-types, granite and tonalite, which have similar textures. They generally are xenoblastic and are characterized by sutured grain boundaries (most developed of any rock in the study area). Foliation is prominent and is expressed by alignment of lensatic mineral aggregates, prismatic amphibole, and platey biotite and chlorite. Sub-parallel and thin en echelon zones of shearing (0.1 mm to 1.0 mm) are common and contain granulated quartz, potash feldspar and plagioclase along with introduced epidote, biotite and(or) chlorite. Porphyroclasts occur locally and may be rounded, rotated, and broken and(or) recrystallized to form mosaic aggregates. Modal and optical data are summarized in Tables 21 and 22, respectively.

The younger felsic intrusives consist primarily of quartz and plagioclase (An_{26-36}) plus microcline in the granites. Microcline is generally equant and medium-grained, and is the coarsest mineral phase in the granites. Quartz commonly forms rods or lenses and generally has highly irregular and sutured contacts, although secondary quartz may be euhedral. Plagioclase is generally equant to tabular but may be irregularly shaped.

Primary accessory minerals include apatite, ilmenite, magnetite, spinel (pleonaste?), and ferrohastingsite. Apatite is common in trace amounts as euhedral, extremely fine-grained crystals. Opaque minerals occur in amounts up to 3%, are very fine-grained and both anhedral and euhedral. Rare spinel occurs as medium-grained subhedral crystals with abundant poikilitic quartz inclusions. Ferrohastingsite occurs as very fine- to fine-grained elongate prisms.

Secondary minerals include sphene, epidote, biotite, muscovite and chlorite. They are generally very fine- to fine-grained and occur in veinlets, along fractures and shear planes, between grains and replacing plagioclase and opaque minerals.

Pegmatites

Felsic pegmatites are common in the study area, especially within the hornblende gneiss. Although some may have formed concurrently with

Table 21. Modal analyses of younger felsic intrusives.

Sample	tonalite				granite				
	23-5	23-11B	23-20	23-38	23-13	23-32A	23-32B	23-47	23-56
microcline	1	1	--	--	35	42	32	29	36
quartz	60	51	35	32	45	35	38	37	27
plagioclase	29	48	57	58	9	23	27	29	35
An content	(34)	(26)	(32)	(36)	(34)	(35)	(36)	(29)	(31)
apatite	tr	tr	tr	tr	--	--	--	tr	--
opaque minerals (undivided)	--	tr	tr	5	tr	tr	tr	2	tr
spinel	--	--	tr	--	--	--	--	--	tr
ferrohastingsite	9	--	--	--	--	--	--	--	--
epidote	1	tr	1	5	11	tr	tr	--	tr
biotite	--	--	5	--	--	--	tr	2	1
muscovite	tr	tr	2	--	--	tr	--	1	1
sphene	tr	tr	tr	--	--	tr	--	tr	--
chlorite	--	--	--	--	--	tr	3	tr	--
hematite	--	--	--	--	--	tr	--	--	--

Table 22. Thin section characteristics of minerals in the younger felsic intrusives.

Microcline	clear, well developed grid twinning, commonly microperthitic, relatively commonly zoned, locally contains quartz bleb inclusions, rarely micrographophyric.
Quartz	clear, undulatory extinction.
Plagioclase	clear, An_{26-36}, average An_{33}, poor to well developed Albite twinning, generally normally zoned, quartz inclusions common, sericitization and alteration to brown clay (kaolinite) fairly common (especially in cores).
Apatite	clear.
Magnetite	opaque, black in reflected light.
Ilmenite	opaque, black in reflected light.
Spinel (pleonaste?)	light brown, isotropic.
Ferrohastingsite	moderately pleochroic (color scheme X=brown green, Y=dark green, Z=green with a blue tint).
Epidote	generally clear but may be pale green or yellow green.
Biotite	strongly pleochroic with the color scheme X= light brown to green brown, Y=Z=brown to red brown.
Muscovite	clear, well developed basal cleavage.
Sphene	light brown.
Chlorite	weakly pleochroic (color scheme X=very light green, Y=Z=light green), anomalous Berlin Blue birefringence.
Hematite	dark red to opaque.

the gneiss, they are discussed with younger felsic intrusives because some clearly cut the older felsic intrusives, some have locally gradational contacts with younger felsic intrusives and they generally have similar relationships with country rock as the younger felsic intrusives. Within the hornblende gneiss and Mullen Creek-Nash Fork shear zone, pegmatites grade from thin (3-10 ft, 1-3 m) conformable layers to elliptical somewhat conformable pods to cross-cutting bodies.

Pegmatites primarily consist of very coarse-grained (up to 3.3 ft, 1.0 m) crystals of pink potash feldspar, white plagioclase and smokey gray quartz. Light gray muscovite and black biotite commonly form very coarse-grained subhedral to euhedral "books", and other less common accessory minerals include red garnet and black tourmaline. Monazite, euxenite and columbite occur at the Platt Mine in section 3, and these are discussed further in the chapter on mineralization.

Bull quartz

Bull quartz occurs in a similar fashion to pegmatites but is less common and the individual bodies are generally smaller. It is comprised of massive milky white quartz that locally has a yellow (limonitic?) stain, especially along fractures.

CHAPTER IV

CONTACT RELATIONSHIPS

Introduction

A better understanding of the contact relationships of the Mullen Creek mafic complex is essential to unraveling the geologic history of the complex and surrounding area. The southwestern portion of the complex is well suited to study these relationships because in this relatively small area the complex is in contact with hornblende gneiss, the Big Creek and Prospect Mountain granites, the Mullen Creek-Nash Fork shear zone and younger felsic intrusives. Also within the study area, hornblende gneiss is in contact with Big Creek and Prospect Mountain granites, and younger felsic intrusives occur within all other Precambrian rock units. Contacts are not simply cross-cutting and sharp as the terms intrusive and shear zone may imply, but commonly are interfingered, gradational and(or) conformable.

Hornblende Gneiss and Mullen Creek Mafic Complex

Hornblende gneiss and rocks of the Mullen Creek mafic complex are adjacent to one another in the southern portion of the study area in sections 2, 3, 4, 10 and 11. Precise relationships of contacts are uncertain in that no outcrop was found where the contact actually can be seen. Where the contact appears to be essentially comformable to the gneissic foliation, a gradational change from metagabbroic rocks to transitional metagabbroic rocks to hornblende gneiss occurs across strike. In the metagabbroic rocks this change is reflected initially by the destruction of relict igneous texture and the accompanying development of nematoblastically aligned hornblende and granoblastic plagioclase and quartz. In transitional metagabbroic rocks, quartz and plagioclase are segregated from amphibole into lensatic aggregates a few grains (less than 5.0 mm) thick. These rocks resemble the massive mafic layers of hornblende gneiss. The following criteria are used to distinguish rocks that are probably part of the mafic complex from hornblende gneiss: (1) the presence of subhedral to euhedral plagioclase, (2) a massive rather than laminated fabric, (3) lack of abundant quartz, (4) high An content of plagioclase (greater than An_{60}), (5) proximity to rocks that have reasonably undisputed origin as part of the complex, (6) lack of abundant interlayered felsic units which are typical of hornblende gneiss, and (7) a coarse- to very coarse-grain size (not observed in hornblende gneiss in the study area). These gradational relationships are best observed in section 3 northeast of the Platt Mine. The distance across strike from outcrops of typical metagabbroic rocks through various types of transitional metagabbroic rocks to typical hornblende gneiss is approximately 300 feet (90 m).

Where the apparent contact between the mafic complex and the hornblende gneiss is generally discordant to metamorphic foliation, a somewhat interfingering relationship is present. Apophyses of the complex form wedge-shaped bodies in the gneiss and gradually pinch out. The best example of this type of interfingering contact occurs in SW/4 of section 3 where metagabbroic rocks form a wedge 2000 feet (610 m) thick which pinches out into the gneiss over a stike-lenth of 2000 feet (610 m).

Another type of interfingered mafic complex-hornblende gneiss contact has apparently been produced by shearing and occurs in the NW/4 of section 11. Cataclastic metagabbroic rocks pinch out over a distance of 110 feet (33 m) into hornblende gneiss, and rocks of the complex and gneiss appear to be interlayered as one goes across the strike of the cataclastic fabric.

Hornblende Gneiss and Older Felsic Intrusives

Big Creek granite

The hornblende gneiss-Big Creek granite contact in the study area is restricted to the SE/4 of section 4. The granite interfingers with and discordantly cuts hornblende gneiss and this contact is easily seen in the field because of the contrast of rock types and the abundance of outcrops of the more resistant granite. Most contacts are sharp and smooth.

Prospect Mountain granite

The Prospect Mountain granite occurs as a massive stock west of Prospect Mountain and as sills interlayered with hornblende gneiss south of Prospect Mountain. The sills of granite are generally long (up to 1 mile, 1.6 km) and may be thick (up to 250 ft, 80 m). The stock apparently has a generally comformable contact relation with the gneiss to the southwest although much of the contact is hidden under forest cover. The stock has an interfingering relationship with the hornblende gneiss that is interlayered with granite sills; thin layers of the gneiss extend as much as 750 feet (230 m) into the stock. Granite has sharp, conformable contacts with the hornblende gneiss.

Mullen Creek Mafic Complex and Older Felsic Intrusives

Big Creek granite

Contact relationships of the Mullen Creek mafic complex with the Big Creek granite are quite complicated due to the presence of abundant granite cupolas in the complex, hybridization of mafic complex rocks, and the Big Creek shear zone. Six relatively large (up to 1000 ft x 400 ft, 300 m x 120 m) granite cupolas form prominent north by northwest trending hills in section 33. Contacts of these cupolas with mafic complex rocks are typically sharp and cross-cutting, and the surrounding mafic rocks are locally hybridized.

Within and adjacent to the Big Creek shear zone, granite cupolas in the complex are characterized by elongation in the direction of shearing. Contacts are generally comformable with cataclastic foliation but interfingering contacts occur where the granite is discordant with host mafic complex rocks. The sheared mafic rocks in this area are characterized by plagioclase porphyroclasts in a dark gray groundmass that locally includes biotite that is a hybridization product related to granite intrusion and(or) an alteration product associated with metasomatism along the shear zone. Metabasalt is very common in this area and it is generally cut by mafic rocks that are in turn cut by granite. Contacts of metabasalt and mafic complex rocks with granite are generally sharp, but where intensely sheared they tend to be somewhat gradational. Within and southeast of the Big Creek shear zone in section 4, the granite is cataclasized and interlayered with metagabbroic rocks that are hybridized and(or) transitional to hornblende gneiss.

Cataclasis in the Big Creek shear zone and hybridization of mafic rocks by the Big Creek granite are less pronounced and restricted to a narrower zone northeast of sections 4 and 33. Apophyses of the Big Creek granite in section 34 trend sub-parallel to the shear zone. A series of sub-parallel sill-like younger felsic intrusives occur southeast of these apophyses. Both the apophyses and younger felsic intrusives are comformable to metamorphic foliation and have relatively straight, smooth, sharp contacts with the mafic complex. Hybridization effects are not significant along the eastern contact of the granite with the mafic complex.

Prospect Mountain granite

Contact relationships between the Prospect Mountain granite and mafic complex rocks seem to be much simpler than those of the Big Creek granite. The contact is generally smooth whether concordant or discordant, and interfingered to irregular cross-cutting relationships are common at the outcrop scale. Within 100 feet (30 m) of the massive stock of granite, rocks of the complex have become transitional through loss of their igneous texture by recrystallization. No hybridization effects were observed. Sills of Prospect Mountain granite appear not to have affected mafic complex rocks near mutual contacts.

Mullen Creek Mafic Complex and Mullen Creek-Nash Fork Shear Zone

The Mullen Creek-Nash Fork shear zone has a relatively smooth, straight, gradational contact with the Mullen Creek mafic complex in the study area that is generally conformable to cataclastic foliation in the shear zone. Interlayered, interfingered, and gradational relationships between metagabbroic and cataclastic rocks may be observed in the steep canyon walls of the North Platte River in sections

27 and 22. Pods and lenses of metagabbroic rocks occur within the shear zone and lenses of laminated mylonite occur within mafic complex rocks. Gradations are present both along and across strike. Dark gray mylonite with an average grain size of less than 0.1 mm can be traced along strike into very fine-grained metagabbro. Medium-grained metagabbro grades into porphyroclastic metagabbro that grades into very fine-grained metagabbro across strike as the main shear zone is approached. Within the mafic complex near the shear zone, the effects of retrograde metamorphism (such as abundant chlorite) are relatively prevalent and there is an abundance of quartzo-feldspathic and(or) epidote veins and veinlets.

Younger Felsic Intrusives and All Other Precambrian Rocks

Younger felsic rocks intrude all other Precambrian rocks in the study area. They are very common within the hornblende gneiss and the Mullen Creek-Nash Fork shear zone as generally conformable sills. Contacts of these younger felsic intrusives are sharp and smooth and the bodies generally pinch out along strike. Distinguishing between actual younger felsic intrusives and quartzo-feldspathic layers of the hornblende gneiss sequence was very difficult due to similarity of occurrence as well as appearance. Younger felsic rocks locally may have small scale cross-cutting features such as off-shooting veins that cut mafic layers of the gneiss.

Younger felsic intrusives are less common in the Mullen Creek mafic complex than in the hornblende gneiss or shear zone, although they may be abundant locally. They generally occur as sill-like bodies that are concordant with metamorphic foliation but cross-cutting irregularly shaped bodies also are present. One prominent sill parallels primary igneous layers in gabbroic rocks on Prospect Mountain. Contacts are sharp and smooth and no contact metamorphic effects were noted in the host metagabbroic and gabbroic rocks. The younger felsic intrusives commonly have cataclastic textures even though the host metagabbroic rocks are relatively undeformed. Felsic intrusive bodies near the Mullen Creek-Nash Fork shear zone in section 27 are similar in appearance to cataclastic quartzo-feldspathic layers of the shear zone whereas their host metagabbroic rocks retain relict igneous textures (e.g. subophitic).

Older felsic intrusives commonly are cut by younger felsic dikes. Elliptical cupolas of Big Creek granite in mafic complex rocks in section 33 are cut obliquely by felsic dikes that parallel the trend of the Mullen Creek-Nash Fork shear zone. These felsic dikes commonly cut across Big Creek granite-mafic complex contacts. Younger intrusives are locally concordant with metamorphic foliation within the Big Creek granite. Younger felsic dikes also cross-cut the Prospect Mountain granite. Contacts between younger and older felsic intrusives are generally sharp and smooth but may appear gradational where the rocks are highly sheared.

Pegmatites and bull quartz occur within all units, but are most common in the hornblende gneiss and least common in the mafic complex. Their occurrence ranges from clearly cross-cutting oval bodies to somewhat conformable elliptical bodies to concordant layers that can be traced up to 0.3 mile (0.5 km) within the hornblende gneiss and Mullen Creek-Nash Fork shear zone.

CHAPTER V

CENOZOIC DEPOSITS

Introduction

Cenozoic deposits in the study area consist primarily of the Tertiary North Park formation, a Quaternary-Tertiary lag gravel deposit, and Quaternary talus and alluvium-colluvium. They generally occur in areas of low relief (except for talus).

Tertiary (Miocene-Pliocene)

North Park formation

The North Park formation occurs dominantly in the western part of the study area, west of Big Creek. This area is the eastern edge of the Saratoga Valley which is primarily underlain by the North Park formation (Houston et al., 1968). Small (less than 850 ft x 425 ft, 200 m x 130 m), isolated bodies of the formation occur throughout other portions of the study area.

Outcrop of the North Park formation is scarce in the study area and this has necessitated mapping of the formation primarily on the basis of float and rocks brought to the surface by burrowing creatures. Most samples of the formation have been extensively weathered to white clay. The few relatively fresh samples that were found are soft white siltstone and shale.

Quaternary-Tertiary

Lag gravel

A lag gravel deposit occurs in a down-dropped fault block in section 2. It consists primarily of moderately sized (up to 5 in, 12 cm) rounded fragments of quartzite, granite, quartz porphyry and andesite. The presence of volcanic rock fragments that are probably Tertiary in age suggests that these fragments come from the south (the nearest source of volcanic rocks) and were transported by the ancient precursor of the North Platte River.

Quaternary

Talus

Talus deposits occur along the steep slopes of the North Platte River valley. They consist of large (up to 10 ft, 3 m) angular blocks.

Alluvium-colluvium

Alluvium and colluvium are undivided on the geologic map of the study area (Plate 1). They occur in stream drainages, especially along the North Platte River and Big Creek. Alluvium consists primarily of sand and gravel along active stream courses. Colluvium consists primarily of clay and silt that is common along non-active stream drainages and is associated locally with peat-rich bog deposits which have been included in this unit.

CHAPTER VI

STRUCTURE

Primary Igneous Structures in the Mullen Creek Mafic Complex

Layering and lamination

Primary igneous layering and lamination are common in several phases of the mafic complex. Gabbroic rocks at Prospect Mountain and vicinity exhibit well preserved layering, both large and small scale varieties. Resistant layers have formed northwest trending ridges that can be traced up to 0.3 miles (0.5 km) on the northwest slope of Prospect Mountain. Rock types of the layers (approximate widths in parentheses) encountered from southwest to northeast are gabbro (>165 ft, 50 m), microgabbro (33 ft, 10 m), magnetic gabbro (100 ft, 30 m), gabbro (50 ft, 15 m), a younger (?) felsic sill (33 ft, 10 m), microgabbro (33 ft, 10 m), leucogabbro (165 ft, 50 m), microgabbro (230 ft, 70 m), and leucogabbro (<165 ft, 50 m). These layers may continue along strike to the northwest, but are not traceable because of poor exposure.

Small scale mineralogical layering within large layers is common, especially in leucocratic phases, and individual layers may be less than 1 cm (Fig. 13). Contacts between small scale layers are generally concordant and smooth but may be locally discordant and irregular. Two types of graded (or gravity stratified) bedding are present locally: (1) mineralogical--a pyroxene- and(or) amphibole (after pyroxene)-rich

Fig. 13. Float block showing well developed igneous layering in gabbroic and related rocks in NW/4 of section 3. Note grading from pyroxenite (dark gray) to gabbro (medium gray) to leucogabbro (light gray) on right side of block. Hammer is 12 inches (30 cm) long.

Fig. 14. Outcrop showing mineralogic graded bedding in metagabbro in SW/4 of section 2. Note grading from metapyroxenite (hornblende, dark gray) to meta-porphyritic gabbro (spotted, medium gray), that abruptly changes into metapyroxenite again. Also note metamorphic overprint to the igneous layering as exhibited by nematoblastically aligned hornblende in a direction parallel to the pencil. Pencil is 5 inches (13 cm) long.

phase grades into a plagioclase-rich phase (Figs. 13 and 14), and(or) (2) grain size--a coarser-grained phase grades into a finer-grained phase. Rhythmic layering on a small scale also may be present. In one exposure a sequence of 1-2 inch (3-5 cm) layers of metapyroxenite (hornblende) separated by 1-3 inch (2-6 cm) layers of metagabbro is repeated three times. Contact between mineralogical layers may be gradational, as in the gravity stratified beds, or they may be relatively sharp as is common between rhythmic layers or the leucocratic "top" of the gravity stratified layers and the melanocratic "bottom" of the next layer. One scour channel and one channel filling were observed.

Layers generally dip steeply throughout the study area. Northwest to west-northwest trends predominate in the Prospect Mountain area, and they generally parallel the contact of the complex with the Prospect Mountain granite. In the east-central portion of section 3, layers trend northwest and a metapyroxenite layer was traced approximately 650 feet (200 m). In the southern part of section 34, layering trends north-northeast, which is the same direction as the contact between the complex and the Big Creek granite in that area. In the NE/4 of section 27, northwest trending layers are generally perpendicular to the contact of the mafic complex with the Mullen Creek-Nash Fork shear zone. Layers are well developed and trend northwest in an area centered in section 35 that was mapped by Donnelly (1979) in a previous study. West of the North Platte River, layers of the mafic complex trend predominantly to the northwest.

Thirty-six attitudes of igneous layers were recorded. Most attitudes were obtained from small scale mineralogical layers rather than large scale layers. A pole plot of the attitudes (Fig. 15) shows the

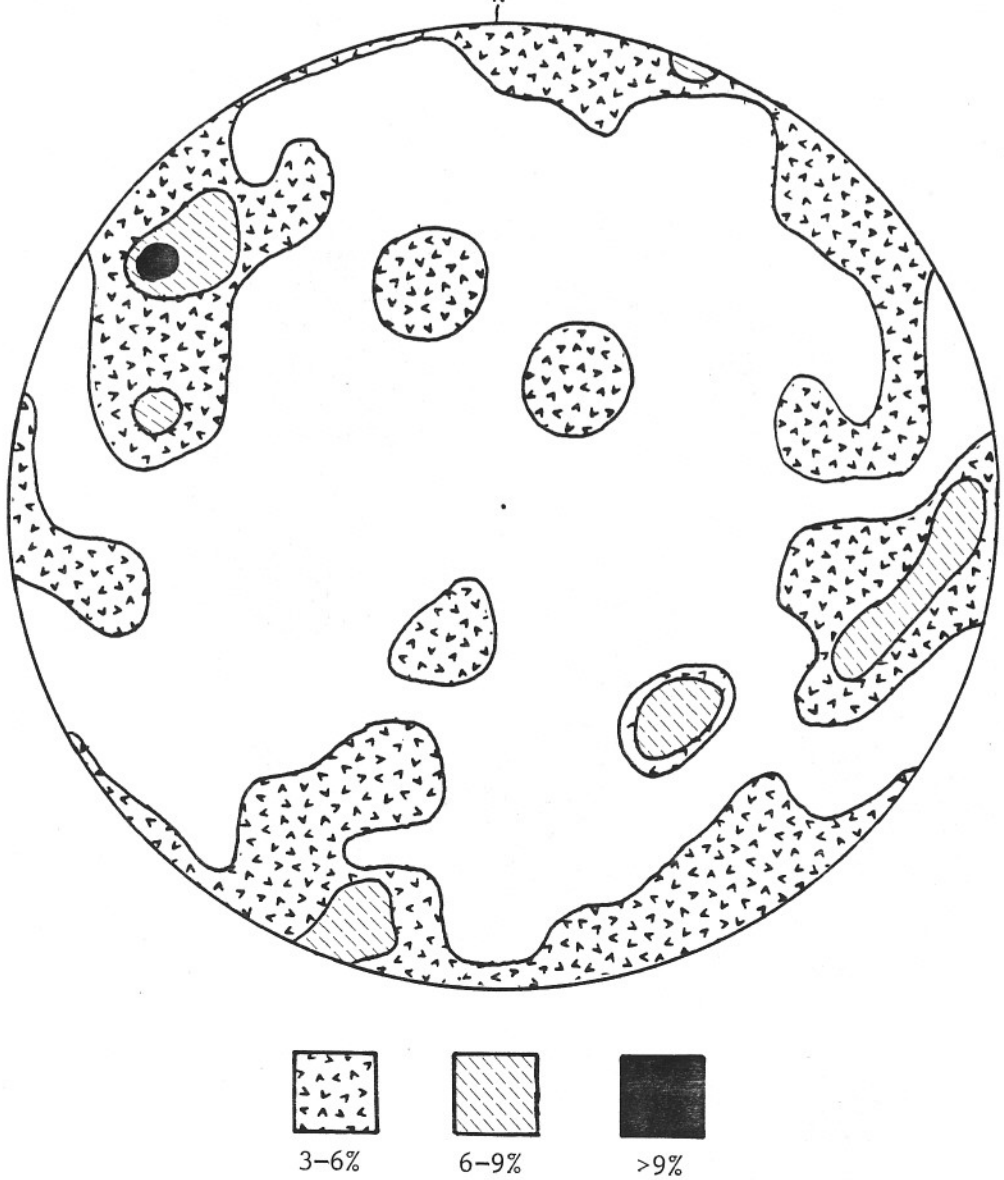


Fig. 15. Contour diagram of pole plots of igneous layers in the Mullen Creek mafic complex. n = 36.

steeply dipping nature of the layers and although the trends are somewhat dispersed, the dominant trend is to the northeast. This trend is different from the trends mentioned in the above paragraph that were noted in the field. This may be due to the fact that although small scale layers generally parallel large scale layers, there is greater deviation in the small scale layers because of local irregularities.

Igneous laminations are fairly common in the study area and are defined by alignment of platey or tabular plagioclase crystals which generally are the only primary igneous mineral phase still preserved in these rocks. Laminations occur in both massive and well layered rocks. Pole plots of thirty igneous laminations reveal two general trends, N25E and N35W, with some intermediate trends to the north (Fig. 16). Dips are generally towards the east and fairly steep. The N35W trend is approximately the same as observed for most large scale layers, whereas the N25E trend is similar to layers in the southern part of section 34 and the SW/4 of section 26.

Large and small scale layers, rhythmic layers, scour channels and gravity stratified bedding observed in this study, as well as cryptic layering and cross-bedding all occur in other portions of the complex (Donnelly, 1979; McCallum, pers. comm., 1982). Such features occur in most layered mafic intrusions (Wager and Brown, 1967) and are the best evidence supporting the layered nature of the Mullen Creek mafic complex.

The relationship of layering in the study area to the overall geometry of igneous layers of the Mullen Creek mafic complex is a further objective of this study. In the western part of Donnelly's (1979) study area, layers trend northwest and dip steeply to the southwest. Northeast of the North Platte River and north of Donnelly's (1979)

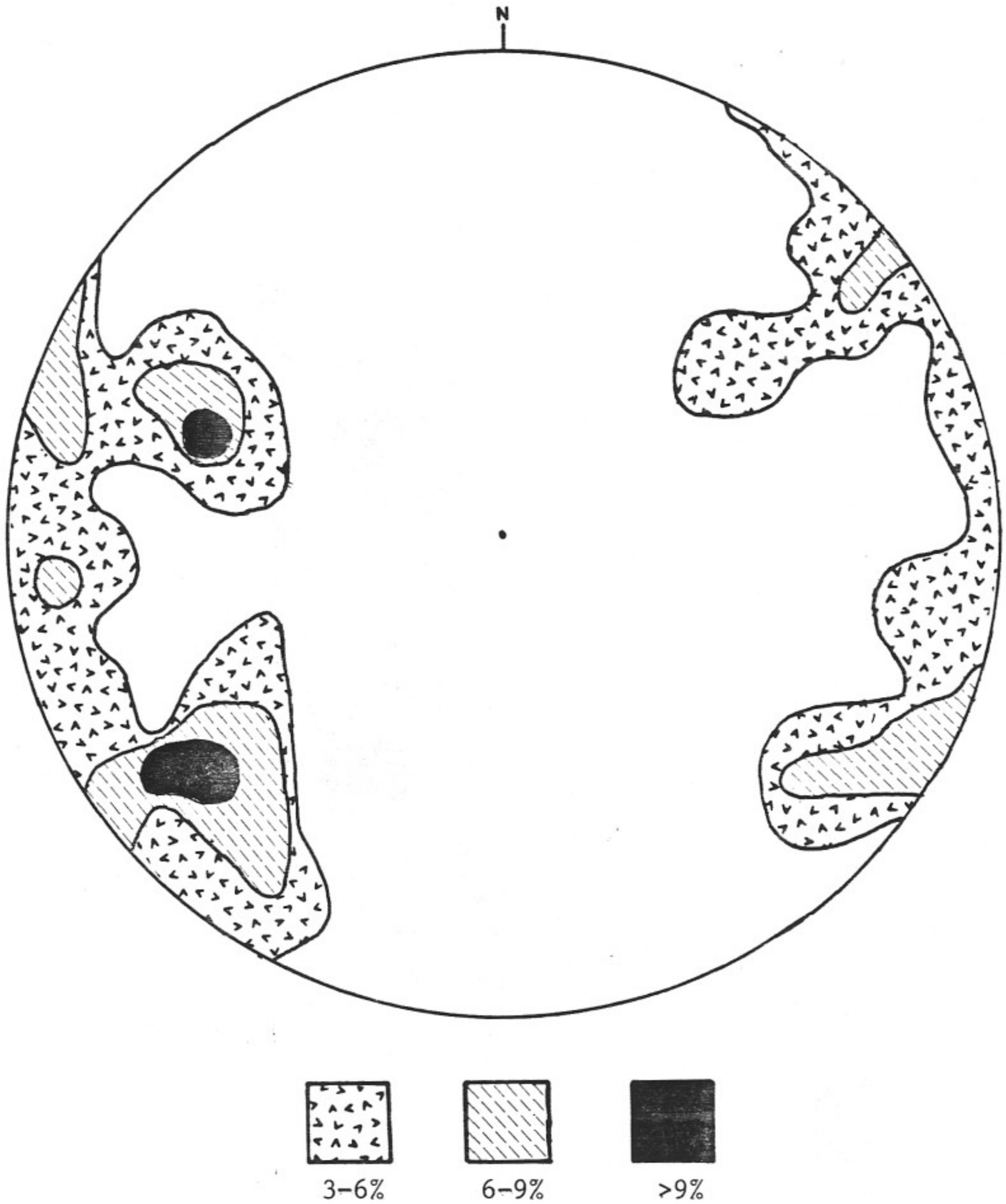


Fig. 16. Contour diagram of pole plots of igneous laminations in the Mullen Creek mafic complex. n = 30.

study area, layers trend northeast and dip steeply to the northwest and southeast (McCallum, pers. commun., 1982; McCallum and Kluender, 1983). These layers define an overturned anticline plunging to the northeast (Fig. 17). The fringes of this fold are observed in the area of this study, southeast of the Big Creek shear zone: layers trend northeast on Prospect Mountain and in the eastern portion of section 3, and layers trend northeast in sections 26 and 34.

The Big Creek shear zone apparently continues northeast across the North Platte River where it merges with the Mullen Creek-Nash Fork shear zone (McCallum, pers. commun., 1982). Between these two shear zones, the limited exposures of igneous layering and the trend of the cupolas of Big Creek granite in the mafic complex suggest that layers trend northwest in this area. The occurrence of the mafic complex in this area that is further southwest than is otherwise expected from the geometry of layers in the rest of the complex suggests that this "wedge" has undergone left-lateral movement along the Big Creek shear zone. This movement concurs with the left-lateral movement along the Mullen Creek-Nash Fork shear zone which resulted in drag folds of the metasedimentary rocks northwest of the shear zone (Houston et al., 1968).

Cross-cutting relationships

Cross-cutting relationships between different rock types of the Mullen Creek mafic complex are common. No pattern of one rock type consistently cutting another rock type of the complex could be ascertained except for those discussed below. Due to the similarity of and gradational nature between rock types of the complex, difficulty commonly was encountered trying to determine which rock type was intruding the other. Contacts are generally sharp and smooth but may be irregular

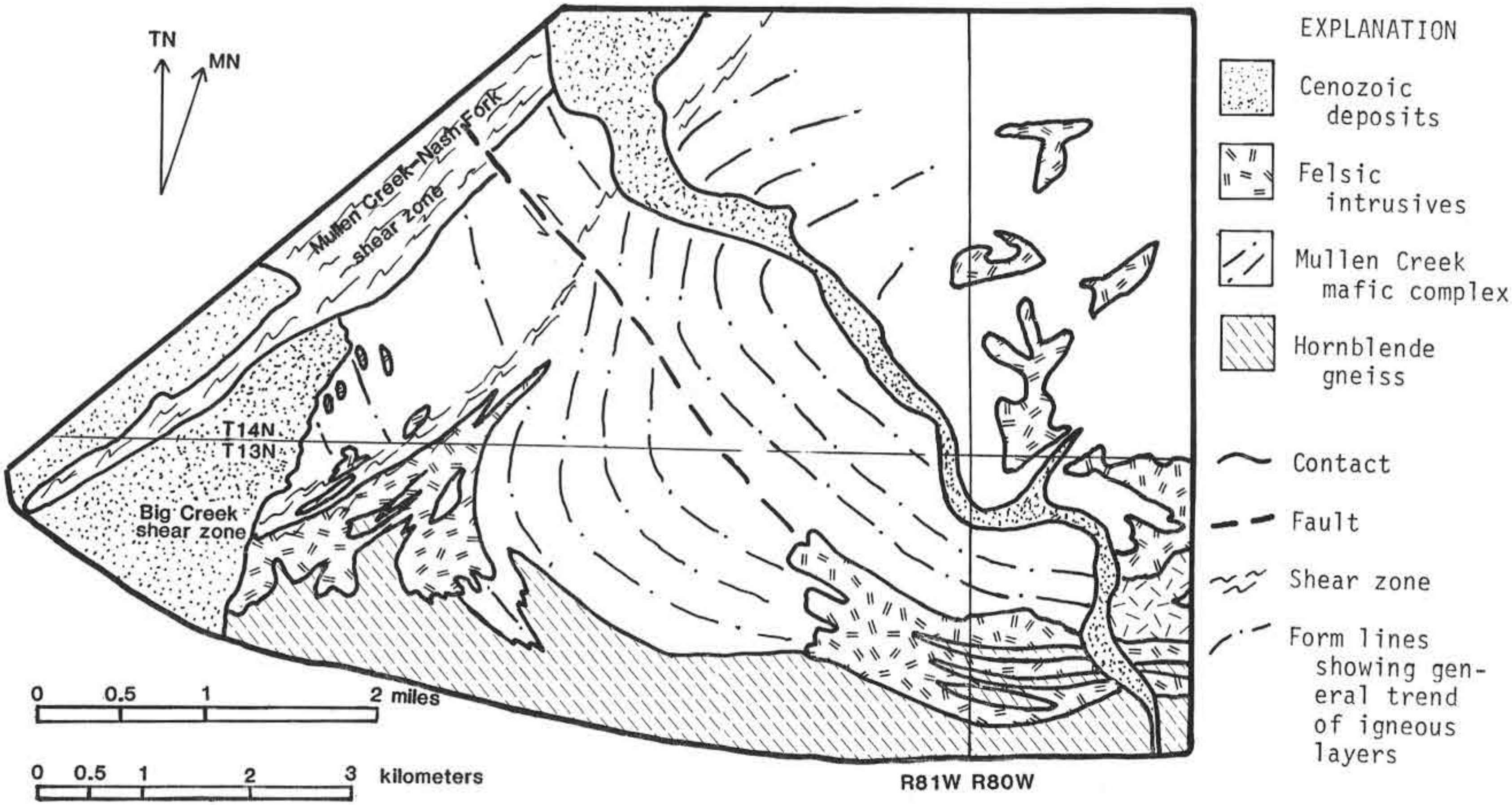


Fig. 17. Diagrammatic geologic map of the western portion of the Mullen Creek mafic complex and adjacent area. Modified from Houston and others (1968), Donnelly (1979) and McCallum (mapping in progress, pers. commun., 1982).

and show limited effects of contact metamorphism. For example, where metamicrogabbro cuts metagabbro, the metagabbro tends to be coarser-grained and have a more leucocratic border over approximately 0.4 inches (1 cm) (Fig. 18).

Metabasalt, metadiabase and diabase, in addition to having similar inconsistent cross-cutting relationships with much of the complex, as discussed above, also have some systematic cross-cutting relationships. Small metabasalt dikes are relatively abundant and a few are large enough to be mappable. Donnelly (1979) reports numerous metabasalt dikes in the mafic complex east of the study area and these represent at least two stages of emplacement. Massive bodies of porphyritic metabasalt are much more common than metabasalt dikes in the study area and are concentrated along the southern border of the complex. These bodies are commonly cut by metagabbroic rocks. Metabasalt is very common northwest of the main body of Big Creek granite where it is cut by metagabbro and granite, and in the eastern part of section 2 metabasalt is cut by metaleucogabbro.

Metadiabase dikes are distributed throughout the study area, but only one dike was large enough to be mapped (5-10 ft, 1.5-3 m wide extending for 650 ft, 200 m, in SE/4 section 34). These dikes have a typically diabasic texture although grain size may vary within individual dikes. The area of the mapped metadiabase dike has complex contact relationships: a 3 ft x 33 ft (1 m x 10 m) metabasalt dike trends N85E and an olivine diabase dike (sample 23-28) trends N60W in the same general area.

Late stage metagabbro has a limited occurrence in section 34 along a small north trending ridge that is apparently caused by a more

Fig. 18. Outcrop of microgabbro cutting and altering metagabbro in SE/4 of section 3. Note 0.4 inch (1.0 cm) wide zone of metaleucogabbro in metagabbro at contact with metamicrogabbro. Pencil is 5 inches (13 cm) long.

Fig. 19. Talus block of migmatitic metagabbro in west central part of section 6. Angular blocks of metagabbro cut by metaleucogabbro (across top) and quartzo-feldspathic veins (towards bottom). Magnet is 5 inches (13 cm) long.

resistant dike. This distinctive looking rock type is believed to correspond to Donnelly's (1979) late stage metagabbro that is considered to reflect a relatively minor late pulse of mafic magma.

Migmatitic metagabbroic rocks with cross-cutting relationships occur on Prospect Mountain in section 6. One type of migmatitic rock is comprised of small (up to 3 ft, 1 m), angular to sub-rounded xenoliths of metagabbro in a matrix of metaleucogabbro and(or) quartzo-feldspathic rock (Fig. 19). A second type of migmatitic metagabbro contains aligned lensatic metagabbroic rock that is cut by abundant quartzo-feldspathic veins. The first type probably formed by the injection of leucocratic-rich and quartz-rich mafic magma into fractured but relatively undeformed metagabbroic rock. The second type apparently resulted from shearing which developed zones of weakness along which silica-rich mafic fluids migrated.

Metamorphic Directional Fabric

Lineation

Lineations in the study area are defined by aligned quartz rods, long prismatic amphibole crystals, or tabular biotite trains. Only five lineations were recorded: 75, S35E; 70, S30E; 70, S75E; 65, S85E; and 50, S80E. These reflect the following two ranges of plunge and bearing: (1) 70-75, S30-35E, and (2) 50-70, S75-85E.

Foliation

Non-cataclastic metamorphic foliations in the study area are defined by planar alignment of nematoblastic amphibole, lepidoblastic mica, and lenses or layers of mineral aggregates (such as quartz, K-feldspar, plagioclase and(or) amphibole). Contour diagrams were constructed from pole plots of foliation attitudes by the method described by Billings (1972, p. 104-107). Foliation data were separated into the following groups: hornblende gneiss, Mullen Creek mafic complex, felsic rocks, and cataclastic fabric of all rocks (Figs. 20, 21, 22 and 23, respectively).

Hornblende gneiss has a dominant northwest foliation trend with steep dips to the northeast (N60W,75NE) (Fig. 20). At the 6% contour of 66 plotted foliations, the strike ranges from N80W to N25W and the dip varies from vertical to 65NE. This trend reflects the regional metamorphic fabric in the area.

The mafic complex has two relatively diffuse trends (Fig. 21). At the 3% contour interval of 63 plotted foliations, the dominant trend has a strike that ranges from N10W to N80E and the dip varies from 70SW to 50NE (centered at N40W,75 NE). A second less prominent trend has a strike that ranges from N10E to N60E and its dip varies from 75NW to 50SE (centered at N35E,60SE). The dominant trend reflects the regional fabric of the area, and the second trend reflects a fabric associated with the Mullen Creek-Nash Fork shear zone.

All felsic rock foliations were plotted on the same diagram because of the small number of attitudes recorded (45 total). The contour diagram shows two trends (Fig. 22): a very well defined trend centered at N65W,80NE and a second, more diffuse trend centered at N45E,70SE. The northwest trend is derived primarily from foliations of younger felsic intrusives and quartzo-feldspathic layers in the hornblende gneiss. The northeast trend reflects foliations in the Big Creek granite and quartzo-feldspathic layers in the Mullen Creek-Nash Fork shear zone along with some younger felsic intrusions.

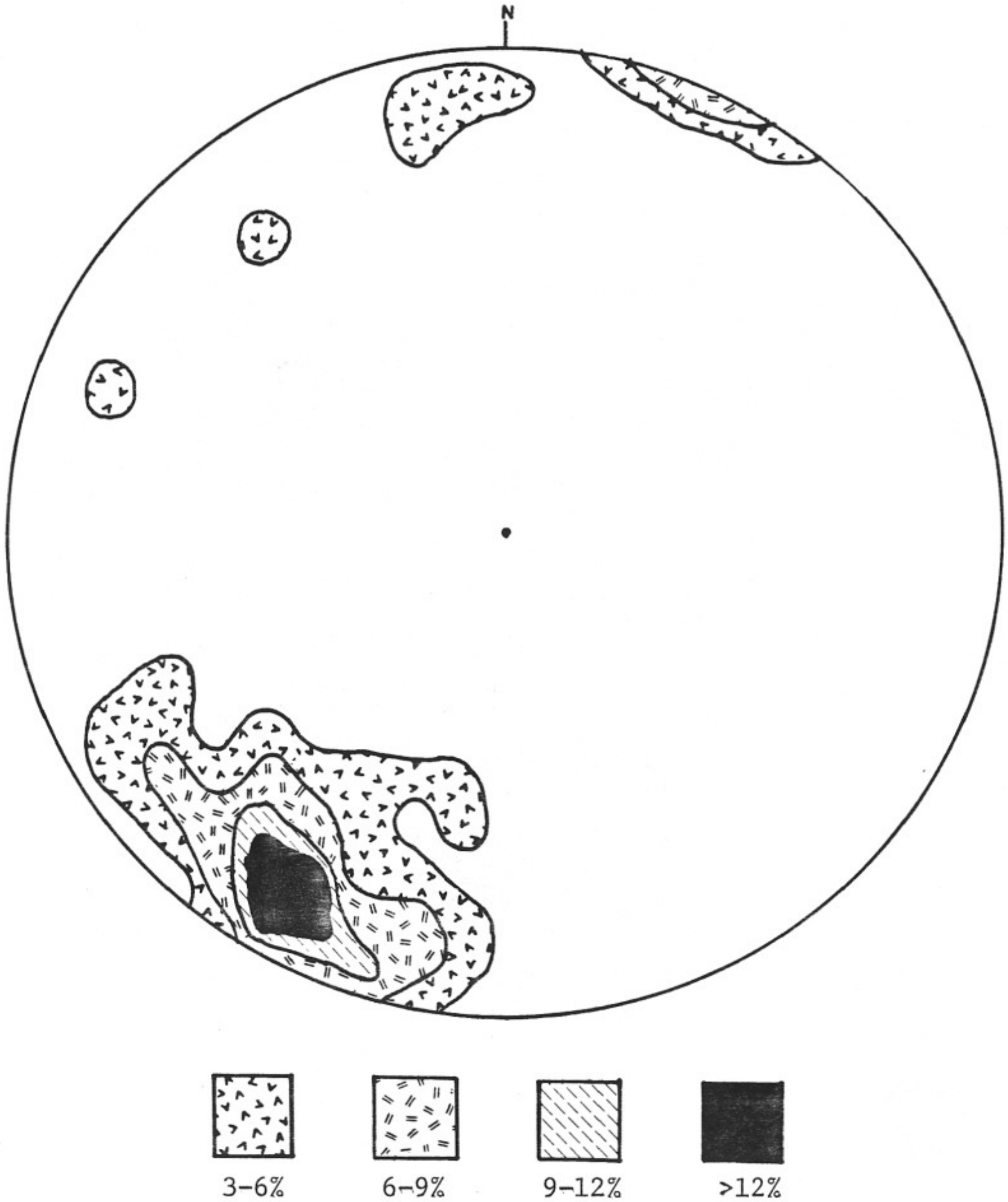


Fig. 20. Contour diagram of pole plots of metamorphic foliation in hornblende gneiss. n = 66.

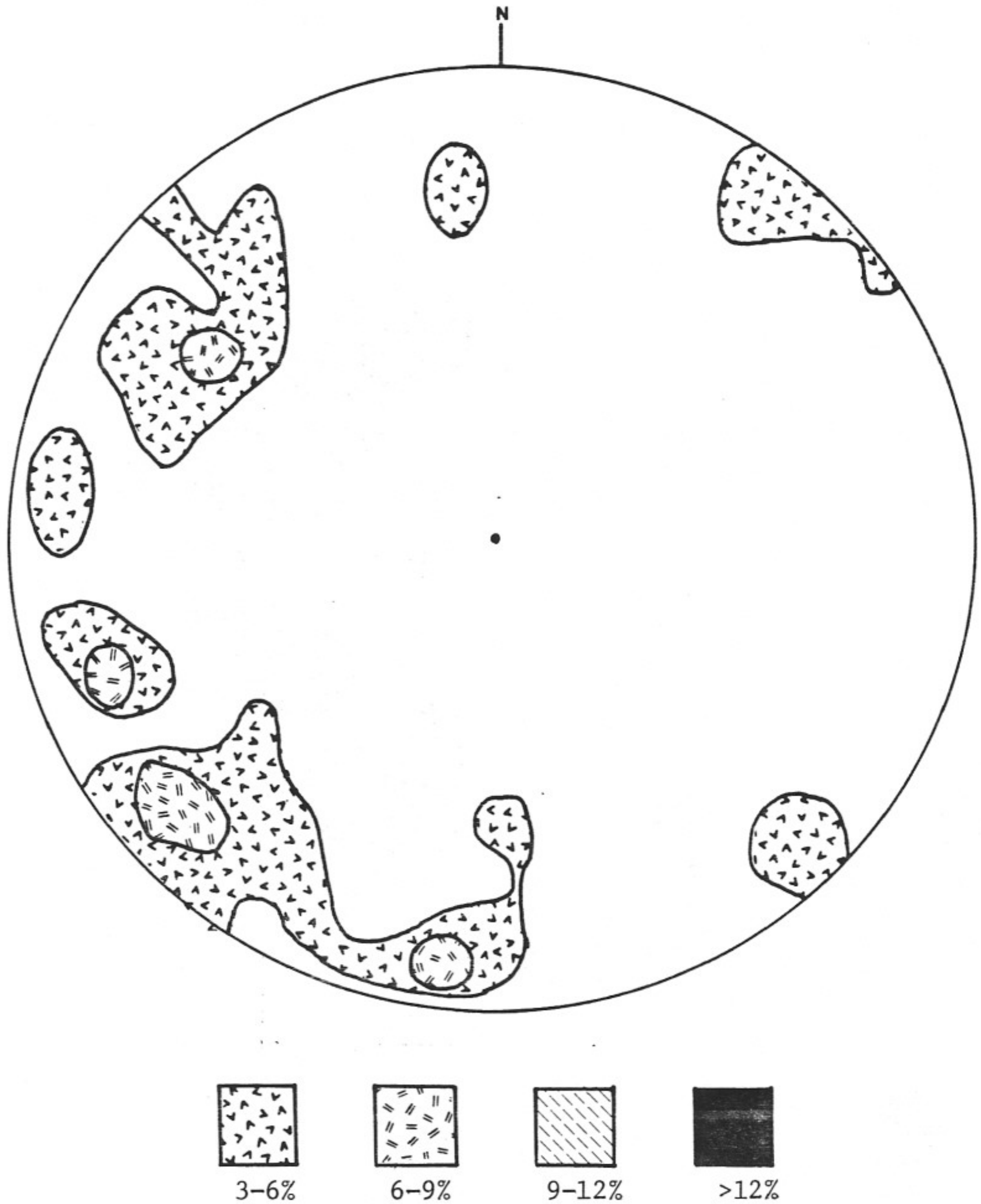


Fig. 21. Contour diagram of pole plots of metamorphic foliation in rocks of the Mullen Creek mafic complex. n = 63.

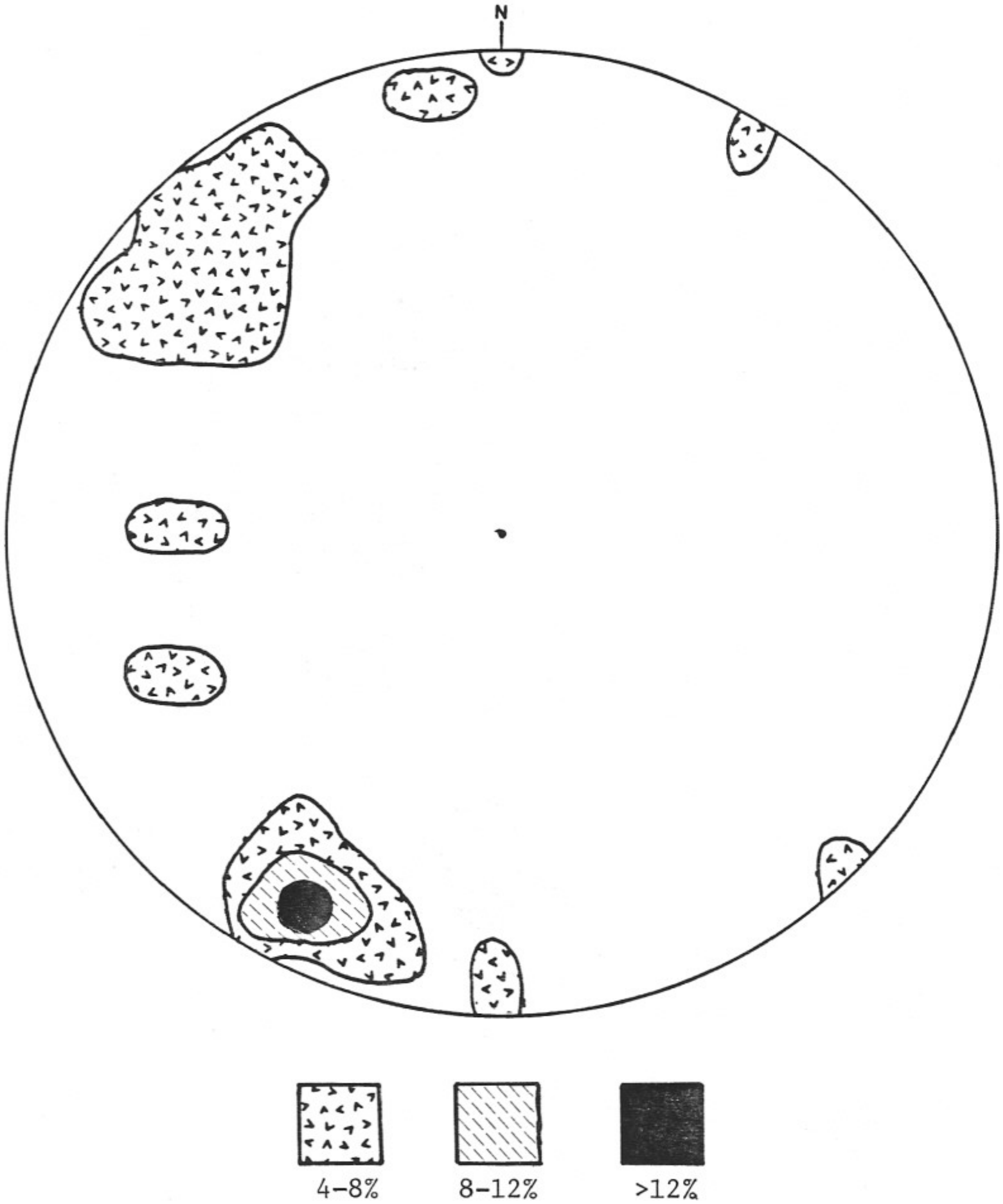


Fig. 22. Contour diagram of pole plots of metamorphic foliation of felsic rocks. n = 45.

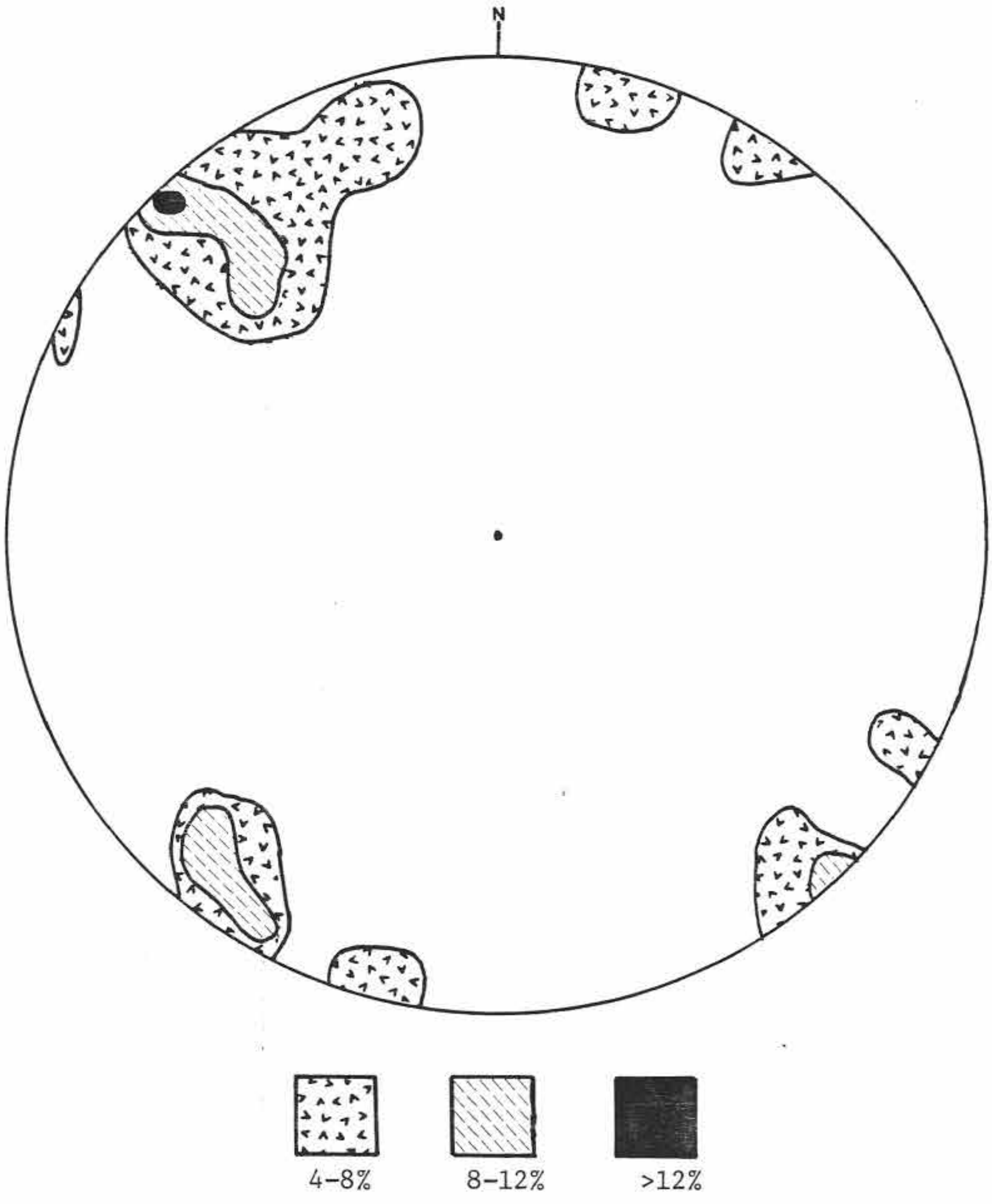


Fig. 23. Contour diagram of pole plots of cataclastic foliation of all rocks. n = 43.

Cataclastic foliations are defined by planar alignment of abundant tightly spaced fractures (less than 1 in, 3 cm apart), thin zones of mylonite (less than 0.5 in, 1 cm wide), and cataclastically derived lenses of mineral aggregates. Pole plots of these foliations (43 attitudes) also show a bimodal distribution (Fig. 23). A fairly well concentrated group centers at N55W, 85NE and is derived primarily from foliations of the Prospect Mountain granite. A second larger group centers at N55E, 75SE and is derived dominantly from foliations of rocks from the Mullen Creek-Nash Fork shear zone.

Metamorphic foliations in the study area define two distinct structural domains. In the southern domain of the area (south of 41°07'30" north latitude), the dominant fabric is defined by non-cataclastic metamorphic foliations that dip steeply to the northeast (Figs. 20, 21, and 22). This is most easily observed in hornblende gneiss but also may be observed in the Big Creek and Prospect Mountain granites, the younger felsic intrusives and the Mullen Creek mafic complex. The directional fabric of this area is believed to have been controlled by regional metamorphism. This fabric has been folded so that it is presently part of a synform that plunges steeply to the east-northeast (Houston et al., 1968, p. 129).

A second structural domain occurs in the northern portion of the study area and this is dominated by cataclastic foliation that trends northeast and dips steeply to the southeast. This domain is primarily comprised of rocks of the Mullen Creek-Nash Fork and Big Creek shear zones, the Mullen Creek mafic complex, the Big Creek granite and younger felsic intrusives. Shearing associated with movement along the shear zones is responsible for the fabric of this domain.

Faults

A number of faults occur within the study area but no regular pattern is evident. Faults were recognized by a variety of distinguishing features such as alignment of topograhic lows, springs and vegetation, offset of rock units, and the presence of abundant cryptocrystalline quartz and(or) epidote. The Big Creek fault (name by Houston et al., 1968, Plate 4) in sections 10 and 11 has an alignment of topographic lows and thicker sagebrush as well as a fairly drastic change in foliation of gneissic rocks from one side to the other. A northwest trending fault in sections 2 and 11 has a 1 ft wide zone of massive quartz and epidote bordered by mylonitized mafic rock and associated mylonitized granitic rock along strike. Two northwest trending faults in section 2 are marked by alignment of springs and lusher grass and have a lag gravel deposit between them that apparently was down-dropped. A northwest trending fault in section 27 shows left-lateral offset of a younger felsic dike of about 650 ft (200 m). A vertical northwest trending fault observed in a prospect pit in section 33 could not be traced beyond the limits of the pit. A northwest trending fault in the SW/4 of section 3 has a spring and aligned topographic lows along it. An east-west trending fault in the SW/4 of section 3 is reflected by topographic lows and a pegmatite has intruded along it.

Joints

Joints occur in all Precambrian rocks of the study area but are especially common in the Mullen Creek-Nash Fork shear zone. Outcrops generally have as many as three well developed joint sets. No obvious joint set pattern was discernable in the field or on a pole plot;

however, the 37 joint trends recorded in this study do not represent an adequate statistical population.

CHAPTER VII

PETROGENESIS OF IGNEOUS ROCKS

Mullen Creek Mafic Complex

Origin

The gabbroic rocks of the mafic complex provide maximum evidence for the composition of the magma that produced the complex. The least metamorphosed rocks are typical gabbros that are composed predominantly of plagioclase (labradorite to sodic bytownite) (35-65%) and clinopyroxene (augite ?) (10-35%) with lesser amounts (0-14% each) of orthopyroxene (hypersthene ?), olivine, magnetite, ilmenite and pyrite. Unfortunately, no compositional information was obtained for the pyroxenes and olivine, and no samples were analyzed for major element oxides. This lack of chemical data severely limits the extent and accuracy of genetic interpretations.

A basaltic parent magma with tholeiitic rather than alkalic affinities has been suggested for the complex by Donnelly (1979, p. 110) based on the presence of sparse olivine and relict calcium-poor and calcium-rich pyroxenes and on geochemical data. This data shows geochemical trends that indicate the Mullen Creek mafic complex underwent fractional crystalization of a tholiitic magma (Donnelly, 1979, p. 129). This conclusion is supported by the presence of olivine, orthopyroxene and clinopyroxene in relatively unmetamorphosed rocks of the complex in the study area.

Emplacement

Geologic mapping of the study area and other previously unmapped portions of the complex (McCallum, pers. commun., 1982) support Donnelly's (1979) contention that the layered mafic sequence crystallized from one or more pulses of mafic magma which produced a wide variety of rock types by differentiation processes. To speculate on emplacement of the Mullen Creek mafic complex one must consider its form, its contact relationships with host hornblende gneiss, and the environment of the host rocks at the time of intrusion. The mafic complex-hornblende gneiss contact is gradational, and the trace of the contact, the metamorphic foliation of the complex's rocks near this contact, and the foliation and layering of the gneiss are all parallel in the study area. Similar relationships occur along the rest of the southern border of the complex (Houston et al., 1968, p. 125). Mapping by Donnelly (1979), McCallum (pers. commun., 1982), and in this study has documented that trends of the igneous layers of the complex generally parallel the southern and eastern mafic complex-hornblende gneiss contact. Donnelly and McCallum (1977) and Donnelly (1979, p. 104) have suggested, based on structure and geochemistry, that the complex is overturned and therefore the rocks of the complex near its southern and eastern borders are the top of the layered mafic sequence. Igneous layers of layered mafic intrusions are generally assumed to have formed near the horizontal, therefore the layers of the hornblende gneiss were probably close to the horizontal at the time of crystallization of at least the upper part of the Mullen Creek mafic complex. This suggests the form of the intrusion was probably a sill, lopolith or funnel-shape in which the roof of the complex is relatively horizontal (Fig. 24A). This form

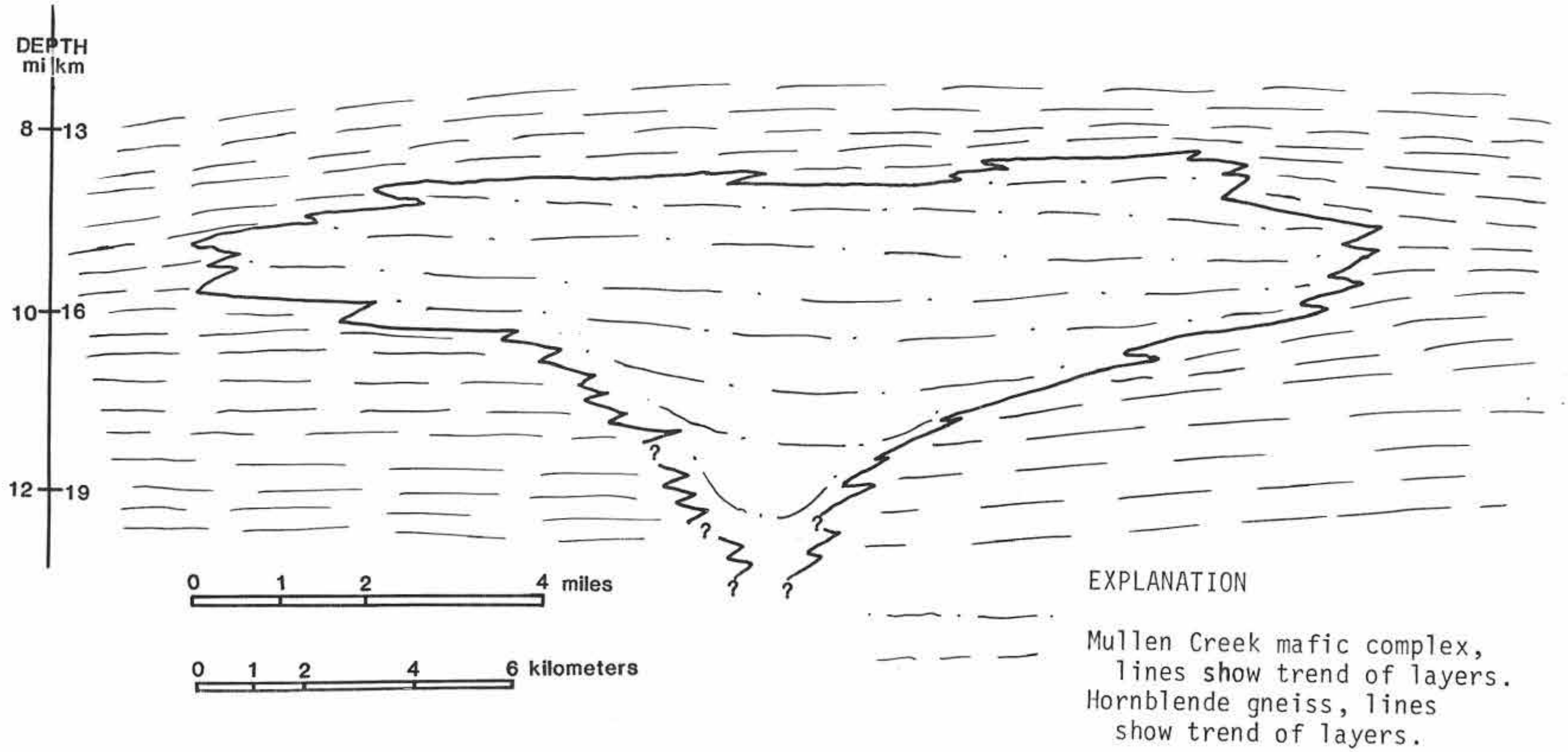


Fig. 24A. Diagrammatic cross-section of the Mullen Creek mafic complex before deformation.

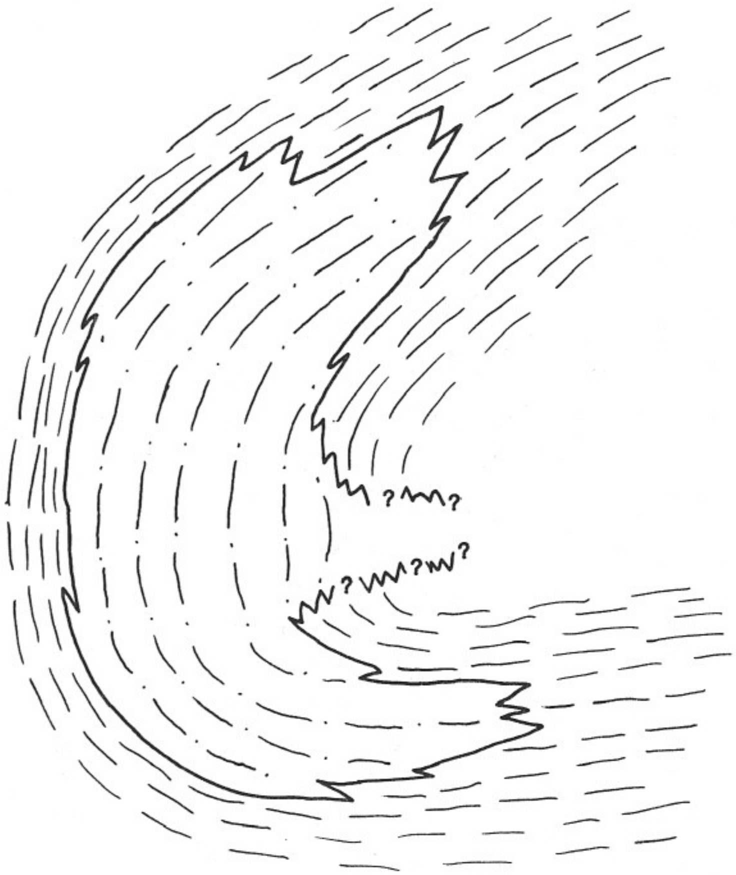


Fig. 24B. Diagrammatic cross-section of the Mullen Creek mafic complex during deformation. Explanation and scale same as Fig. 24A.

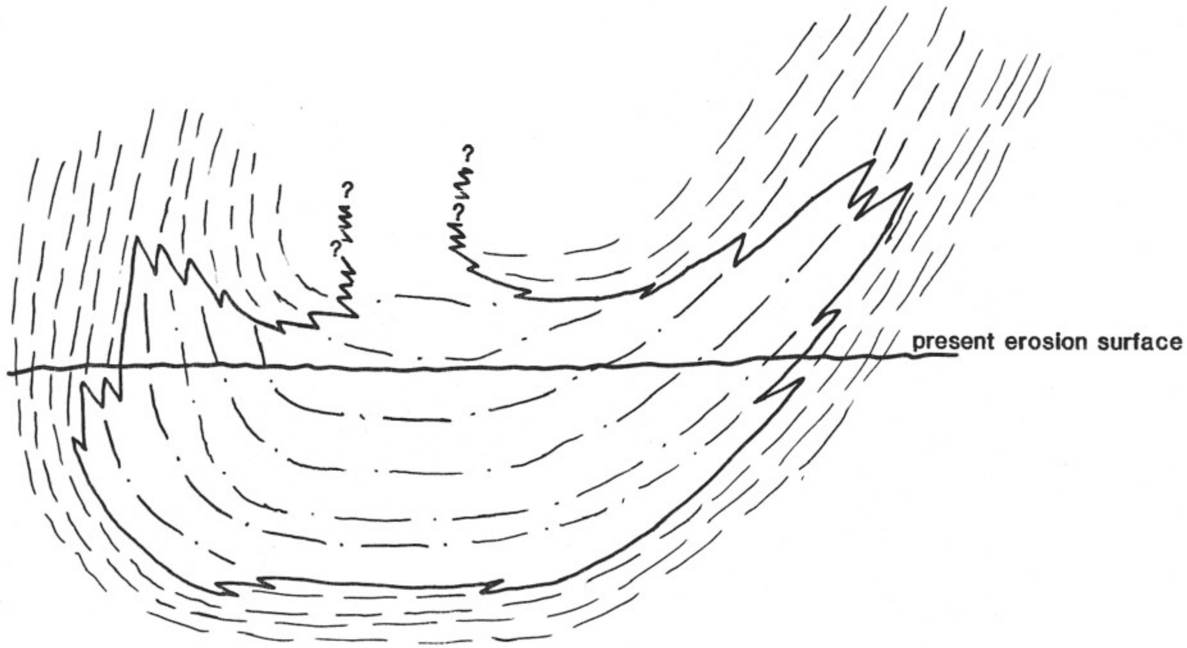


Fig. 24C. Diagrammatic cross-section of the Mullen Creek mafic complex after deformation. Explanation and scale same as Fig. 24A.

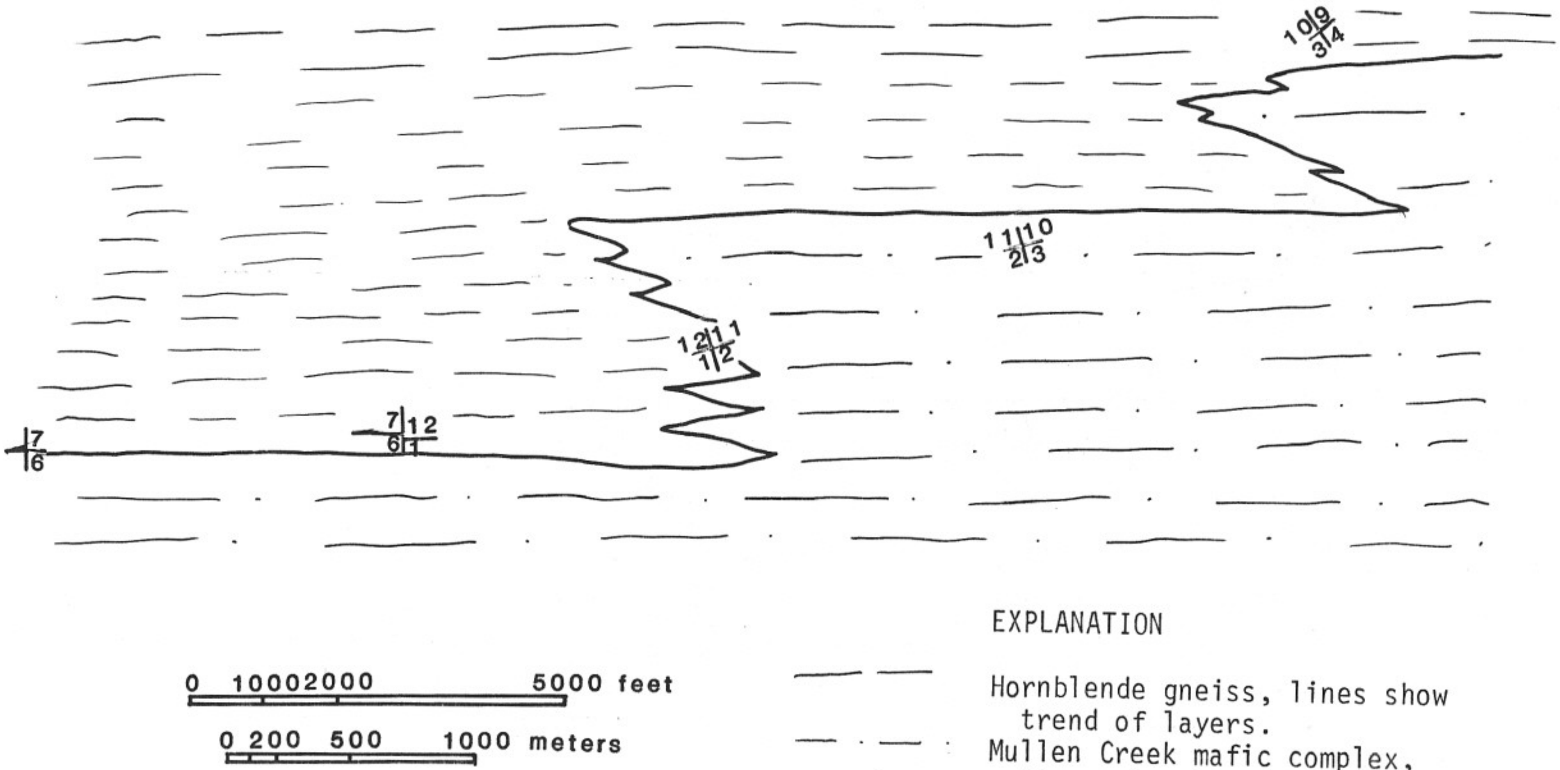
must have undergone considerable deformation to reach its present position (Figs 24B and 24C). Wager and Brown (1967, p. 541) suggest that funnel-shaped is the most characteristic form of layered mafic intrusions, based on a comparison of their form and steeply dipping margins. The pressure from the funnel-injection may be relieved by explosive expulsion of material at the surface, doming of roof rocks, and crustal down-sag subsequent to magma emplacement (Wager and Brown, 1967, p. 542). There is no evidence of any explosive expulsion of material associated with the Mullen Creek mafic complex. Doming of roof rocks was probably operative to some degree, but the conformity of igneous layering to the layering in the hornblende gneiss suggests down-sagging was chiefly responsible for the development of the magma chamber.

It has been suggested that the hornblende gneiss which hosts the mafic complex was originally a series of interbedded volcanics and sediments that have been regionally metamorphosed to amphibolite facies to such a degree that no primary textures and structures are recognizable (Houston et al, 1968, p. 58 and 135). The mafic complex must have intruded during or after this metamorphism because primary textures and structures commonly are retained in the complex even though much of it has been metamorphosed to amphibolite facies. The metamorphosed nature of the complex and the concordant nature of its contacts with host hornblende gneiss (which has been regionally metamorphosed) are typical of intrusions into the catazone at depths of 7 to 12 miles (11 to 19 km) with country rock temperature of 450°C to 600°C (Buddington, 1959; Billings, 1972, p. 368).

Emplacement of the Mullen Creek mafic complex's magma probably was accomplished by injection of a tholeiitic basaltic melt into the hornblende gneiss which was undergoing amphibolite facies metamorphism in the catazone. A lopolithic or funnel-shaped magma chamber formed with a relatively horizontal, conformable roof of hornblende gneiss.

The concordant nature of the igneous layers of the mafic complex and the layering of the hornblende gneiss is best observed in the study area at Prospect Mountain and northeast of the Platt mine in section 3. In both these areas the igneous layers of the complex and the layers of the gneiss as well as the mafic complex-gneiss contact trend northwest.

A non-concordant contact between the complex and the Prospect Mountain granite occurs in section 2 (Fig. 17). The igneous layers of the complex apparently truncate against the granite and do not continue to the east-southeast even where the granite no longer crops out. This truncation could be the result of an unconformable contact in the roof of the magma chamber of the mafic complex (Fig. 25). An alternative explanation is that the hornblende gneiss located south of Prospect Mountain originally was part of the mafic complex and has since been hybridized by granite and further metamorphosed by regional metamorphism and local cataclasis so that the mafic rocks have completely lost any resemblance to other rocks of the mafic complex. This second alternative, although difficult to disprove, is not favored by the author because the mafic rocks in this area appear to be typical hornblende gneiss whereas the mafic rocks just to the north are relatively unmetamorphosed gabbros. In addition, the mafic complex-gneiss contact mapped in this study correlates with the contact mapped by Rhuer (1961) just east of the study area. Another non-concordant mafic complex-gneiss contact occurs in the SW/4 of section 3. This areas has been sketched



EXPLANATION

Hornblende gneiss, lines show trend of layers.

Mullen Creek mafic complex, lines show trend of layers.

Section corner locations in the study area which correlate to where they occurred before deformation.

Fig. 25. Diagrammatic cross-section of part of the Mullen Creek mafic complex before deformation which has since occurred in the study area. This represents part of the roof zone of the mafic complex.

as it apparently appeared prior to subsequent folding and faulting (Fig. 25). Hornblende gneiss and the mafic complex both form wedges which extend into each other. This wedged relationship suggests that mafic complex magma intruded along favorable foliation layers of the gneiss instead of cutting smoothly across gneissic layering.

Numerous minor mafic magmas subsequently intruded the complex. Metabasalt, metadiabase and late stage metagabbro dikes are clearly later than the major intrusive phase(s). Relatively unmetamorphosed diabase surrounded by metagabbroic rocks probably was intruded after the metamoprhic event that altered the surrounding rock. However, some metabasalt, metadiabase and diabase apparently are phases of the major pulse(s) of magma. The massive porphyritic metabasalt associated with contacts of the mafic complex in sections 3 and 4 may represent a chilled border phase, but exposures are too poor to provide definitive evidence of this relationship.

Textures and internal structures

Rocks of the complex generally have sub-ophitic to poikilitic texture with plagioclase tending towards euhedralism. Utilizing the terminology of Wager and Brown (1967) for layered basic intrusions, most of the gabbroic rocks are orthocumulates with cumulate plagioclase and local cumulate olivine and orthopyroxene in intercumulate clinopyroxene and iron ore. Clinopyroxene with adcumulate growth is present in some mesocumulate samples. The accessory minerals apatite, rutile, ilmenite, pyrite, and magnetite are considered cumulate where euhedral and intercumulate where anhedral and interstitial. Plagioclase crystals generally are normally zoned, indicating non-adcumulate growth and may reflect crystallization of trapped liquid over a range of falling temperatures as described by Wager and Brown (1967, p. 65) for the Skaergaard intrusion. Olivine, where adjacent to plagioclase, has an inner rim of orthopyroxene and an outer rim of green spinel and amphibole. These rims may be due to the action of liquid residua at high temperatures (Hatch et al., 1972, p. 350) or a reaction between olivine and plagioclase during cooling of the intrusion at moderate to high pressure (Griffin and Heier, 1973).

Numerous internal structures typical of layered mafic intrusions similar to those described by Wager and Brown (1967) occur in the study area and other parts of the mafic complex (previously described in Chapter VI). The "classical" interpretation of these structures is that they were formed primarily as a result of crystal settling and convection currents in a large magma chamber (Wager and Brown, 1967). In situ crystallization has also been proposed as a dominant mechanism (Jackson 1961; McBirney and Noyes, 1979), and recent experiments by Irvine (1980) have shown that magmatic density currents may play an important role in the development of these features. Unfortunately, the metamorphosed nature and generally poor exposure of the Mullen Creek mafic complex does not lend itself to a critical evaluation of processes responsible for internal structures.

A generalized cross-section of the Prospect Mountain area infers that igneous layers persist at depth, and are generally conformable to the contact of the complex (Section B-B', Plate 1).

Older Felsic Intrusives

Origin

The older felsic intrusives (the Big Creek and Prospect Mountain granites) appear to be similar in mineralogy and occurrence. Both intrusive units group together in the monzogranite (granite-B) field (near the center of a QAP triangular diagram, Fig. 26), although there is a large spread of points that is believed to be mainly due to the effects of metasomatism that commonly accompanied cataclasis in these rocks. Also, both granites occur in part along the contact between the Mullen Creek mafic complex and the hornblende gneiss. These two granites are probably genetically related and may have evolved from a common magma source.

Petrochemical data on relatively fresh samples of the two granites might help resolve the question of their relationship. The contrasting appearance of the two bodies is due to the differing effects of metamorphism.

Numerous bodies of felsic intrusive rocks occur within the mafic complex east of the study area. One body, the Horse Creek granodiorite, forms a large irregular sill-like intrusion that may be a late stage differentiate of the mafic complex (Mussard and McCallum, 1977; Donnelly, 1979; Mussard, 1982; McCallum and Mussard, 1983). The Big Creek and Prospect Mountain granites do not appear to be related to the Horse Creek granodiorite and the possibility of their being late stage differentiates has not been investigated in detail.

Donnelly (1979) mapped younger felsic intrusive rocks in the central portion of the complex that range in composition from granodiorite to alkali granite. Some of these felsic intrusives may be equivalent to the Big Creek and Prospect Mountain granites, especially the larger monzogranite (granite-B) bodies that have hybridized adjacent mafic rocks.

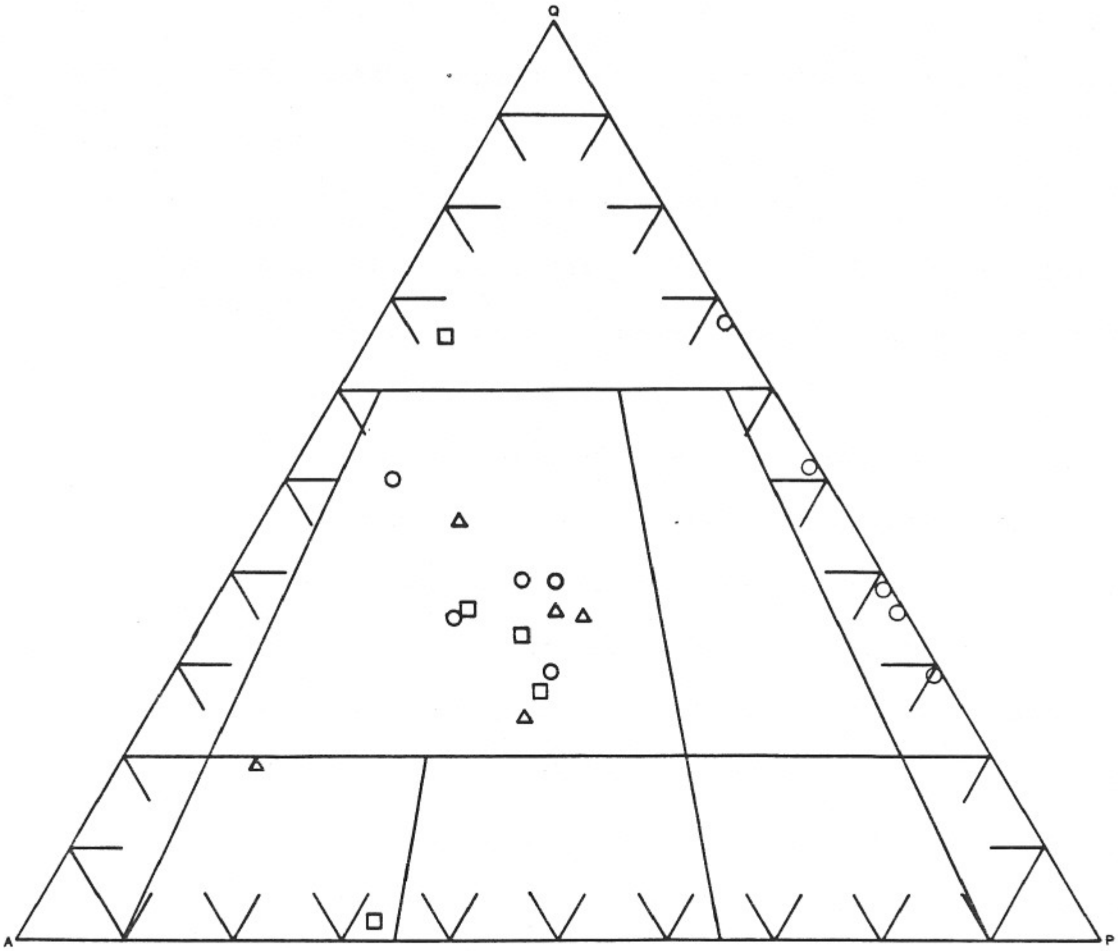


Fig. 26. Triangular QAP diagram of modal composition of felsic intrusive rocks in the study area. Triangles represent Big Creek granite, squares represent Prospect Mountain granite and circles represent younger felsic intrusives.

Emplacement of the Big Creek granite

The Big Creek granite has a generally discordant and interfingered relationship with hornblende gneiss and the Mullen Creek mafic complex in the SW/4 of section 3 and the SE/4 of section 4. It also cross-cuts and has hybridized portions of the western part of the Mullen Creek mafic complex. The main body of granite parallels the Big Creek shear zone and contacts between it and the mafic complex are conformable with metamorphic foliation. The granite and mafic complex are interlayered in part. Along the Big Creek shear zone, hybridization of mafic rocks by granite and(or) metasomatism associated with shearing is extensive and contacts are concordant to cataclastic fabric.

Emplacement of the main body of Big Creek granite apparently was controlled by the precursor of the Big Creek shear zone. Shearing developed a northeast trending zone of weakness into which the granite magma was injected. Syn- and post-emplacement shearing adjacent to and northwest of the main body of granite developed the Big Creek shear zone as it appears today.

Cupolas of the Big Creek granite in the western portion of the mafic complex are elliptical and trend north-northwest. The trend of the cupolas is similar to the general northwest trend of igneous layering in the complex northwest of the Big Creek shear zone and suggests that the cupolas may be sill-like intrusions. Hybridized metagabbroic rocks associated with the cupolas contain biotite and plagioclase that has been altered to finely crystalline muscovite, reflecting the introduction of potassium. These rocks commonly are recrystallized, and shear stress and(or) a high residual temperature of the mafic complex may have aided the hybridization and recrystallization processes.

Emplacement of the Prospect Mountain granite

The Prospect Mountain granite occurs both interlayered with hornblende gneiss and as a stock. The magma of the granite stock was emplaced such that it cut and caused recrystallization of the adjacent mafic complex without appreciable metasomatism. This relationship suggests that hybridizing fluids were either not produced by the granite or they could not penetrate the solidified mafic complex because the complex was cooler. Granitic magma was probably forcefully injected along the mafic complex-hornblende gneiss contact.

The interlayered granite sills have had no apparent effect on the mafic complex. This is probably because the thin sills of granite cooled too quickly to give off enough heat to cause recrystallization of mafic complex rocks. These sills appear to be the product of forceful injection of granitic magma along foliation planes in the gneiss.

Younger Felsic Intrusives

Origin

The younger felsic intrusives are a diverse group of quartzofeldspathic rocks that intrude all other Precambrian rock units in the study area. A QAP triangular diagram (Fig. 26) shows that most of these rocks are either tonalite or granite. The wide range of compositions and occurrences suggests that the younger felsic intrusives include several phases of felsic rocks that represent different ages and origins. Some of these intrusives penetrating hornblende gneiss may represent magma derived from felsic phases of the hornblende gneiss which became mobile during regional metamorphism. Some of the younger felsic intrusives in the Mullen Creek mafic complex and the hornblende gneiss may have originated from the same magma source as the older felsic intrusives. The Big Creek and Prospect Mountain granite (older felsic intrusives) are cut by younger felsic intrusives, some of which may be late stage products of the older felsic magma. Within the Mullen Creek-Nash Fork shear zone, some of the younger felsic intrusives may be derived from felsic components of rocks in the shear zone which were mobilized during shearing. Younger felsic intrusives may be cut by other felsic intrusives, and it is probable that some of these rocks originated after all the other Precambrian units had formed.

Pegmatites also apparently represent several intrusive events. They have similar possible sources as the younger felsic intrusives, including: (1) fluids liberated during regional metamorphism, (2) late stage fluids of the older felsic intrusives' magma, (3) fluids liberated during shearing, and (4) fluids related to sources of the younger felsic intrusives. A common magma source was suggested by close spatial relationships and locally gradational contacts between many pegmatites and felsic intrusives. Houston and others (1968) suggested the majority formed at approximately the same time as the older felsic intrusives, although some pegmatites cross-cut the Big Creek and Prospect Mountain granites.

Emplacement

Younger felsic intrusives, including pegmatites, are generally concordant and sill-like with respect to metamorphic foliation, especially in the hornblende gneiss and Mullen Creek-Nash Fork shear zone. Emplacement apparently was generally by forceful injection along planes of weakness, especially between layers in the well layered units. Evidence for this is the pinching and swelling that is common in the younger felsic intrusives in layered and well foliated rocks. Irregularly shaped bodies with cross-cutting relationships are common, especially in igneous host rocks, and controls on emplacement of intrusives with this relationship are unclear.

CHAPTER VIII

METAMORPHISM

General Statement

Metamorphism has affected all Precambrian rocks in the study area to some degree. Three types of metamorphism have occurred: (1) regional medium- to high-grade metamorphism that is best expressed in the hornblende gneiss and metagabbroic rocks of the Mullen Creek mafic complex, (2) localized cataclastic metamorphism that is well developed in the Mullen Creek-Nash Fork shear zone and in many felsic intrusives, and (3) retrograde low-grade metamorphism that commonly is associated with zones of cataclasis.

Hornblende Gneiss

Hornblende gneiss is composed dominantly of mafic rock with quartzo-feldspathic layers that may pinch and swell to form lenses and pods. Dominant minerals, in order of decreasing abundance, are hornblende, calcic andesine and quartz in the mafic phase, and andesine, quartz, microcline and biotite in the felsic layers. Apatite, sphene, ilmenite and magnetite are present as accessories in both phases. These mineral assemblages typify an amphibolite facies assemblage (Turner, 1968, p. 307-308) produced by medium-grade metamorphism at 500°C-650°C and 2-10 kb (Winkler, 1979).

Metamorphic grade of the hornblende gneiss is comparable to that of other gneissic units south of the Mullen Creek-Nash Fork shear zone

(Houston et al., 1968, p. 135). These gneissic units are considered to be a metamorphosed "series of rocks of mafic composition including flows, tuffs and graywackes with interbeds of limestone, quartzo-feldspathic sandstone, and rare beds of aluminous shale" (Houston et al., 1968, p. 58).

In the study area, parts of the hornblende gneiss that are rich in carbonate and alumina minerals (such as sillimanite) are rare, therefore interbeds of limestone and alumina shale probably did not occur here. Mafic layers of the gneiss probably are metamorphosed graywacke and(or) basaltic flows and tuffs, possible with minor gabbroic sills. Felsic layers in the gneiss probably are metamorphosed quartzo-feldspathic sandstone, possible with minor granitic sills. In summary, hornblende gneiss is part of the basement rock south of the shear zone that has undergone regional medium-grade metamorphism to the amphibolite facies.

Mullen Creek Mafic Complex

General statement

Rocks of the Mullen Creek mafic complex have a complicated but well exhibited history of metamorphism. The mafic complex as a whole has not been subjected to the pervasive regional metamorphism of the hornblende gneiss nor the extensive cataclastic deformation and retrograde metamorphism of the Mullen Creek-Nash Fork shear zone. Gradational metamorphism of the complex makes it possible to predict mineral assemblages and textures of primary gabbroic rocks from the metagabbroic and retrograde metagabbroic rocks. Metamorphism of the mafic complex is discussed in two parts: (1) medium-grade metamorphism that has produced rocks of the amphibolite facies, and (2) low-grade metamorphism that has produced rocks of the greenschist facies.

Regional metamorphism

Medium-grade regional metamorphism has had a fairly pervasive effect on the complex. Unmetamorphosed gabbroic rocks occur only in isolated areas, whereas metagabbroic rocks are widespread (this report; Ramirez, 1971; Donnelly, 1979; McCallum, pers. commun., 1982; McCallum and Kluender, 1983). Gabbroic plutons in metamorphic terrains are commonly essentially unchanged in their inner part because water has not had access to it (Winkler, 1979, p. 168). This is apparently the case for the Lake Owens mafic complex, the least altered mafic rock in the Medicine Bow Mountains (Houston et al., 1968, p. 76), but does not apply for the Mullen Creek mafic complex. Shearing associated with the Mullen Creek-Nash Fork shear zone has most likely developed fractures that facilitated the movement of water into the Mullen Creek mafic complex, and this resulted in metamorphism. Shear stress also promotes uralitization of pyroxene (Harker, 1950, p. 285).

Gabbroic rocks of the Mullen Creek mafic complex are distinguished by the presence of pyroxene and local olivine. The distinctive zonal sequence olivine-orthopyroxene-(amphibote + spinel)-plagioclase may be classified as a late magmatic feature that formed under the influence of high pressure, and which generally is more common in metamorphosed than unmetamorphosed basic rocks (Deer et al., 1966). Clinopyroxene and to a lesser extent orthopyroxene commonly exhibit partial pseudomorphic replacement by hornblende.

In the metagabbroic rocks the replacement of pyroxenes (and locally olivine) by hornblende is essentially complete and the rocks are labradorite-bytownite amphibolites. This replacement occurs under high-grade or the high temperature region of medium-grade to high-grade metamorphism (Winkler, 1979, p. 172). Inclusions of quartz blebs that are common in the hornblende are due to a liberation of silica during the conversion from pyroxene (Harker, 1950, p. 312). The general concentration of quartz inclusions away from hornblende rims and towards the core may be due to primary zoning in the pyroxene but is probably caused by expulsion of silica from the rim towards the core during the early stages of metamorphism.

Opaque mineral inclusions in hornblende may have been primary inclusions in pyroxene or were formed during the conversion of pyroxene. Both quartz and opaque mineral inclusions in hornblende locally define a schiller structure that is probably a result of preferred solution along crystallographic directions of the original pyroxene but may be due to directional stress (Harker, 1950, p. 165).

Locally throughout the complex, more pervasive medium-grade metamorphic conditions, probably under the influence of greater shear stress, have caused recrystallization of plagioclase and hornblende. Plagioclase recrystallizes first at the grain boundaries and along cleavage planes where the crystals are most susceptible to the fluids and(or) pressure of metamorphism. However, some plagioclase is not recrystallized because it is insulated from the effects of metamorphism by the hornblende oikocrysts that surround them. The formation of granoblastic hornblende in the complex may be accomplished in three ways: (1) from fluids introduced along fractures, (2) as a direct product from replacement of pyroxene, and (3) by recrystallization of hornblende. Near the mafic complex-hornblende gneiss contact and locally throughout the complex very pervasive medium-grade metamorphism has produced transitional metagabbroic rocks in which hornblende, quartz and plagioclase components have been segregated to form lenses and layers of nematoblastic hornblende and granular quartz and plagioclase.

Other products of medium-grade metamorphism are sphene and scapolite; both generally form along grain boundaries. Sphene replaces rutile and an opaque mineral believed to be ilmenite or titanium-rich magnetite. Scapolite replaces plagioclase as large, poikilitic crystals and indicates the presence of volatiles such as chlorine or more likely carbon dioxide.

The reactions of medium-grade metamorphism are controlled by grain boundaries and, to a lesser extent, crystallographic planes. Shear stress and directional pressure play an important role as metamorphism becomes more intense and pervasive. Igneous texture may be well preserved by pseudomorphic replacement of pyroxene by hornblende, and partially preserved where recrystallized aggregates retain the original crystal's shape. Primary textures are obliterated if recrystallization has been accompanied by appreciable migration of components.

Cataclastic and retrograde metamorphism

Cataclastic and retrograde metamorphism are discussed together, in that they are closely related in the study area. Spatial relationships are commonly seen in thin section between low-grade mineral assemblages and shear planes, fractures and veinlets. A similar spatial relationshipe was noted in the field; retrograde metagabbroic rocks are more prevalent within or near shear zones, especially in the Mullen Creek-Nash Fork shear zone.

Mild cataclasis of metagabbroic rocks is best exhibited by fractured and bent plagioclase crystals and an abundance of fractures and veinlets of secondary minerals such as epidote. Shear stress and the availability of fluids along fractures causes plagioclase and hornblende to recrystallize to fine-grained granoblastic crystals adjacent to these fractures. With more intense cataclasis, these minerals are comminuted and completely recrystallized to granular aggregates that form lenses and crude layers up to 0.2 inches (0.5 cm) wide (greater width with greater original grain size), and all relict igneous texture is lost.

Cataclastic deformation has partially or wholly obliterated primary igneous layering in some areas. In the NE/4 of section 27, a north-northeast trending ridge has a series of humps in it that trend northwest. Each hump reflects a different rock type and apparently represents a different primary igneous layer. These layers are preserved because the rocks on each side of the ridge have been subjected to shearing that has lowered their resistance to weathering, thus only remnants of layering persist locally.

Gabbroic rocks reflect the effects of low-grade metamorphism on orthopyroxene and olivine. Orthopyroxene alters along fractures to talc and magnetite. Some of the ferrous iron in orthopyroxene has been oxidized in the presence of water to the ferric iron which enters in to the magnetite structure; the resultant hydroxyl ions combined with magnesium and silica to form talc. Fractures in olivine commonly have magnetite along them, and whole grains of olivine may be replaced by magnetite, chrysotile, and minor iddingsite. The process of iddingsitization also could be responsible for the generation of ferric iron in the presence of water (Deer et al., 1965, p. 5). The abundance of magnetite probably is indicative of iron-rich olivines. Where olivine has reaction rims of orthopyroxene and amphibole plus spinel, talc may replace olivine and its inner rim of orthopyroxene, a process that indicates magnesium-rich olivine and orthopyroxene. The outer rim of amphibole and spinel remain stable. Chrysotile also occurs as rims on orthopyroxene and in veinlets. Talc and chrysotile indicate introduction of water into magnesium-rich rocks under low-grade metamorphic conditions (Deer et al., 1966).

Retrograde gabbroic rocks exemplify the relationship between initial medium-grade and later low-grade metamorphism. Early amphibolite facies metamorphism produced rims of hornblende around clinopyroxene in many gabbros. During later greenschist facies metamorphism, cores of clinopyroxene were altered in part to tremolite-actinolite, which characteristically forms under low-grade metamorphic conditions (Deer et al., 1966).

Metapyroxenite and meta-ultramafic rocks in the complex were particularly susceptible to retrograde metamorphism because of their original abundance of pyroxene and olivine, minerals that are unstable at low-grade metamorphic conditions. Abundant chlorite, talc, antigorite and tremolite-actinolite in these rocks are indicative of a low-grade metamorphic environment.

Secondary minerals in the mafic complex that are characteristic of greenschist facies low-grade metamorphism include: epidote, chlorite, tremolite-actinolite, saussurite, sericite, paragonite, talc, antigorite, chrysotile, clinozoisite, zeolite (undetermined variety), calcite and prehnite. Other secondary minerals include hornblende, quartz, potash feldspar, and magnetite. All the secondary minerals commonly are associated with veins, veinlets and fractures. Retrograde metagabbroic rocks generally reflect varying degrees of brittle deformation, and water, carbon dioxide, silica, potassium and other mobile constituents involved in metasomatic reactions apparently were introduced during and following cataclasis.

Temperature and pressure estimates for retrograde metamorphic reactions are difficult to establish because of a general lack of clearly defined equilibrium assemblages. However, these retrograde minerals are in general typical of greenschist facies assemblages (Turner, 1968) produced by low-grade metamorphism at 250°C-550°C and 2-10 kb (Winkler, 1979).

Felsic Intrusives

Both the older and younger felsic intrusives are discussed together because they have similar mineral components that reacted similarly during metamorphism. Quartz, plagioclase (An_{26-40}) and microcline constitute the bulk of the felsic intrusive assemblages that have persisted, but these commonly have been recrystallized or otherwise altered, and the assemblages generally reflect medium-grade metamorphism. Microcline probably was converted from orthoclase during this metamorphic event, producing pericline twins that along with preserved albite twins generate the gridiron or "tartan" twin pattern (Deer et al., 1966, p. 297). Quartz has been strained during metamorphism, as reflected by its undulatory extinction (Deer et al., 1966, p. 350).

Felsic intrusive minerals generally are xenoblastic with sutured grain boundaries. These textures are believed to be due to recrystallization along grain boundaries, and a relic hypidiomorphic-granular texture can commonly be inferred from the equant (relict subhedral to euhedral) shape of microcline and, to a lesser degree, plagioclase. With more pervasive metamorphism, quartz, plagioclase and(or) microcline have segregated into lensatic aggregates and crude layers which impart a well developed foliation. Foliation is also commonly exhibited by lepidoblastically aligned muscovite and biotite. This foliation indicates the rocks recrystallized under directional stress.

Mild cataclasis is common and has produced fractures and veinlets with which most of the secondary minerals are associated. Secondary minerals include epidote, biotite, muscovite, sericite, chlorite, and sphene, and their association with veinlets indicates introduction and exchange of water, potassium, iron, magnesium and titanium through these veinlets under low-grade metamorphic conditions.

More intense cataclastic deformation of the felsic intrusives involved fracturing, rotation, granulation, and recrystallization of the dominant minerals. The resulting rock has thin zones of extreme mylonitization in which the minerals have been crushed and recrystallized to a very fine-grain size. Mylonitized zones contain aligned mineral aggregates that are segregated by mineral assemblages and(or) grain size, which impart well developed foliation and layering. Medium- and coarse-grained crystals, especially microcline, commonly are fractured and local rotation results in rounding of otherwise equant crystals.

The older felsic intrusives locally have undergone intense cataclasis, but have responded to stress quite differently. Brittle deformation of the Prospect Mountain granite has caused an abundance of pore space and fractures, indicating that the rock failed brittlely instead of deforming plastically. The Big Creek granite reacted in a more ductile fashion which is reflected by the bending (rather than breaking) of feldspar and the elongation of feldspar and quartz in the direction of shearing. This infers higher temperatures and confining pressure (Billings, 1972, p. 21) for the Big Creek granite than for the Prospect Mountain granite at the time of their shearing.

Cataclastic Rocks

Cataclastic rocks have been classified as those rocks whose dominant textural features were produced by shearing. These rocks occur throughout the study area, especially in localized zones of moderate to intense cataclastic deformation. In the Mullen Creek-Nash Fork shear zone, mafic rocks are primarily composed of hornblende, sodic andesine and quartz with minor epidote, chlorite and biotite, and these rocks grade into felsic rocks primarily composed of quartz, calcic andesine and microcline with minor hornblende, biotite, epidote, and muscovite. This mineralogy can be utilized to estimate the environment at the time of cataclasis in the shear zone. The dominant minerals (quartz, andesine, microcline, and hornblende) are generally indicative of amphibolite facies medium-grade metamorphism which occurs at 500°C-650°C and 2-10 kb (Winkler, 1979). Biotite, muscovite, chlorite and epidote occur locally, most commonly within and adjacent to fractures and veinlets. These minerals are typical of greenschist facies low-grade metamorphism at 250°C-350°C and 2-10 kb (Winkler, 1979) and reflect a late stage metamorphic event that overprinted the previous amphibolite facies mineral assemblage.

Shearing generally developed prominent foliation expressed by alignment of lensatic mineral aggregates, amphibole, mica and(or) fractures that may contain secondary minerals. Porphyroclasts are common where one mineral (generally plagioclase in mafic rocks and microcline in felsic rocks) is more resistant to cataclasis. Porphyroclasts are generally medium- to coarse-grained whereas groundmass minerals are very fine- to fine-grained. Where deformation was brittle, porphyroclasts are fractured and rotated. Augen have been formed by the stretching and recrystallization of porphyroclasts into lensatic crystal aggregates. Where flaser structure is developed, the groundmass shows plastic flowage around augen. With increased shear stress and subsequent movement, augen are crushed and stretched out and may merge into one another to form lenses and crude layers, as suggested by McCallum (1964b) for cataclastic rocks associated with the Mullen Creek-Nash Fork shear zone northeast of the study area.

The most intense granulation and recrystallization caused by shearing produced massive to finely laminated mylonite. Massive mylonites result from mechanical breakdown of relatively massive parent rocks, whereas laminated mylonites result from further granulation of cataclastically foliated and layered rocks and(or) metamorphic differentiation associated with shear stress. Mylonites are almost the only rocks of the study area in which quartz does not have undulatory extinction. This implies that quartz in the mylonites recrystallized at the end of the last period of stress that affected all other rocks in the study area.

Contacts of the shear zones are somewhat gradational: they are not as sharp as contacts of felsic intrusive rocks with host units, but appear to be less gradational than hornblende gneiss-mafic complex contacts. Subparallel zones of less intense shearing occur in rocks bordering shear zones. This gradational aspect of shearing is best seen at the contact of the Mullen Creek-Nash Fork shear zone where moderately sheared and unsheared rocks of the mafic complex are interlayered with more abundant sheared layers in the complex as the shear zone is approached.

The presence of sheared rock enclosed within relatively undeformed rock, the irregular nature and the lack of observable offset of some shear zones imply that shear stress and localized movement are as important as large scale movement in the development of some shear zones. The Big Creek shear zone occurs as an irregular zone in sections 27 and 34 but is inferred to be continuous because of sub-parallel alignment of small dispersed shear zones in areas of generally poor exposure. The shear zone in the NW/4 of section 11 has caused local interfingering of the mafic complex with hornblende gneiss, but no large scale offset of the mafic complex-gneiss contact is observed.

CHAPTER IX

MINERALIZATION

Trace Element Geochemistry

Analyses

Trace element analyses were conducted on 127 rock chip and 56 stream sediment samples by the United States Geological Survey's Branch of Exploration Research (McCallum et al., 1983b). Locations of analyzed samples in the study area are given on Plate 2. Semi-quantitative spectrographic analysis (6-step d.c. Arc) was utilized to analyze for numerous elements including Au, B, Ba, Be, Bi, Cd, Co, Cr, Cu, La, Mo, Nb, Ni, Pb, Sb, Sc, Sn, Sr, Th, V, Y, Zn, and Zr. In addition, Ag and Te were analyzed by atomic absorption, As was analyzed by the Gutzeit method, W was analyzed by colorimetric method, and U was analyzed by fluorimetric method.

Rock chip geochemistry

Different trace elements exhibit selective enrichment in the rock units of the study area (McCallum et al., 1983b). Cataclastic rocks and mafic layers of the hornblende gneiss exhibit no systematic enrichment of analyzed trace elements and cataclastic rocks exhibit inconsistent enrichment of a wide variety of trace elements (e.g. B, Ba, Nb, Pb, Sr, Te, Y, U, Zn, Zr). The latter probably is due to the diversity of parent rocks that have cataclasized.

Ultramafic rocks of the Mullen Creek mafic complex are enriched in Co, Cr, Ni, and Zn (Table 23A). These trace elements substitute for Mg and(or) Fe in olivine, orthopyroxene, clinopyroxene, and magnetite, and may be concentrated in sulfide phases such as pyrite. The only trace elements that are consistently enriched in the mafic rocks of the mafic complex are Sr, which probably substitutes for Ca in plagioclase, and Cr, which substitutes for Mg and(or) Fe in olivine, pyroxene and magnetite (Table 23B).

Felsic rocks of the study area, including the quartzo-feldspathic layers in the hornblende gneiss, felsic layers in the Mullen Creek-Nash Fork shear zone and the older and younger felsic intrusions generally are enriched in Ba, La, Nb, and(or) U (Table 23C). These elements are commonly enriched during differentiation of magma into the residual melt which yields granitic rocks.

Stream sediment geochemistry

Stream sediment samples, two from each site (a panned concentrate sample and a sample of finer sediments and clays), were collected at 28 locations in and near the study area (see Chapter I for sampling methods). Elements that exhibit anomalously high values are divided into three categories based on their pathfinder potential for types of deposits most likely to occur in the study area (pathfinder elements as established by Levinson, 1980, p. 863-889).

Pathfinders for pegmatites include B, Be, La, Nb, Sc, U, W, Y and Zr, and high values of these elements occur in two areas. Mica-bearing pegmatites in the western portion of section 12 and the eastern portion of section 11 and on the ridge south of Prospect Mountain are probably responsible for the anomalous values of pegmatite pathfinder elements

Table 23. Chemical analyses for selected elements of different rock types (from McCallum et al, 1983b).

A. Ultramafic rocks of the Mullen Creek mafic complex, including hybridized melanocratic phases (samples 23-25A, -25B, -25C, -82A, -82B, -86, -87; total = 7 samples).

Element	Range (ppm)	Average (ppm)
Co	50 - 150	80
Cr	300 - 1500	600
Ni	300 - 2000	750
Zn	<200 - 300	225

B. Mafic rocks of the Mullen Creek mafic complex (samples 23-8, -9, -10, -12, -15, -16, -18, -19, -19A, -22, -23B, -26, -27, -28, -29, -30, -31, -33, -34, -35, -36, -41, -43, -44, -45, -48, -49, -50, -53, -54A, -54B, -67, -68, -71, -73, -75, -77, -78, -79, -80A, -83, -84, -85, -88, -89, -91, -92, -93, -94, -95, -97, -102, -105, -106, -107, -108, -110, -111, -112, -113; total = 60 samples).

Element	Range (ppm)	Average (ppm)
Cr	10 - 1000	220
Sr	200 - 2000	940

C. Felsic rocks in the study area (samples 23-1, -5, -6, -7, -11A, -11B, -13, -14, -17B, -20, -23A, -24, -32A, -32B, -37, -38, -39, -47, -52, -55, -56, -57, -58, -61, -62, -81, -90; total = 27 samples).

Element	Range (ppm)	Average (ppm)
Ba	50 - 3000	780
La	0 - 150	40
Nb	0 - 30	7
U	0 - 2.2	1

in samples 23-S-25, -26, and -27 in section 12 (Table 24A). A second area of anomalous values for pegmatite pathfinder elements occurs in section 5 along Big Creek and Bear Creek (samples 23-S-12 and -19, respectively, Table 24A). Pegmatites south of the study area are probably responsible for these anomalies. There is a surprising lack of pegmatite pathfinder elements in the sample (23-S-18) downstream from the Platt Mine in section 3. This may be due to the distance from the mine to the sample and the general absence of running water in the vicinity of the mine.

Pathfinders for a possible magmatic deposit in the Mullen Creek mafic complex include Ag, Co, Cr, Cu, Ni, Te, and V. The highest values of these elements, especially Cr and Ni, occur in samples from the Prospect Mountain area (23-S-21, -22, and -24, Table 24B). Other samples with relatively high values of these elements generally are located along streams and dry stream beds that drain the mafic complex (samples 23-S-8, -9, -10, -11, and -16, Table 24B). Relatively high concentrations of these elements are expected from samples associated with the mafic complex, but no samples had high enough concentrations of elements to indicate a substantive deposit in the study area.

Pathfinders for hydrothermal sulfide deposits include Ag, Ba, Cu, Pb, Te, V, and Zn. A few samples have high values for some of these elements but no pattern of elemental or spatial association was exhibited.

Minor Deposits

Introduction

Small deposits of economically important minerals have been found in three major geologic settings in the study area: (1) pegmatites and

Table 24. Chemical analyses for selected elements of stream sediment samples (from McCallum et al, 1983b).

A. Samples with anomalous amounts of pegmatite pathfinder elements (samples 23-S-12, -19, -25, -26, -27; total = 5 samples).

Element	Range (ppm) [panned:fine]	Average (ppm) [panned:fine]
B	20-70:30	48:30
Be	0-5:2-3	2.2:2.4
La	0-300:0-150	100:52
Nb	0-100:0-30	74:14
Sc	30-50:10-15	38:14
U	1.2-2.0:1.7-3.4	1.7:2.3
W	0-10:0-7	2.0:2.6
Y	100-200:30-100	160:56
Zr	2000:700-1000	2000:760

B. Samples with anomalous amounts of pathfinders for a magmatic deposit of the Mullen Creek mafic complex (samples 23-S-8, -9, -10, -11, -16, -21, -22, -24; total = 8 samples).

Element	Range (ppm) [panned:fine]	Average (ppm) [panned:fine]
Ag	0-0.06:0-0.11	0.01:0.08
Co	30-70:15-20	60:19
Cr	100-500:70-100	225:90
Cu	50-150:30-70	90:60
Ni	50-150:50-100	110:70
Te	0:0	0:0
V	500-1500:200	900:200

bull quartz, (2) the Mullen Creek mafic complex, and (3) the Mullen Creek-Nash Fork shear zone. The area has been extensively prospected (Ralph Platt, pers. commun., 1980) and prospect pits are very common, especially in pegmatites and bull quartz.

Pegmatites and bull quartz

Several copper-bearing and rare earth element-bearing pegmatites have been reported from the southwestern flanks of the Medicine Bow Mountains (Houston, 1961). Significant amounts of euxenite, monazite and columbite were recovered from a pegmatite in the study area, the Platt Mine in the SE/4 SW/4 of section 3 (marked by a shaft symbol on Plate 1). The pegmatite was mined predominantly for uranium, but was abandoned after the U.S. Government stopped subsidizing the price of uranium in the 1950's (Ralph Platt, pers. commun., 1980). The Platt Mine is a zoned pegmatite that is 50 feet (21 m) wide, 160 feet (48 m) long which cross-cuts the host hornblende gneiss (Houston, 1961). A more detailed description and geochemistry of the rare earth minerals of the Platt pegmatite are provided by Houston (1961). No other pegmatites with economically important minerals were found in the study area.

Quartz veins and pods in the Medicine Bow Mountains are locally mineralized. Some bull quartz in the study area reportedly contains gold (Ralph Platt, pers. commun., 1980). Copper and gold-bearing quartz-carbonate veins occur within the Mullen Creek mafic complex (Donnelly, 1979) and throughout the central Medicine Bow Mountains (McCallum et al., 1976). No mineralization of bull quartz or quartz veins in the study area was recognized by the author.

Mullen Creek mafic complex

Mineralized prospects within the mafic complex occur in a stream valley in the NE/4 SW/4 of section 1, northwest of Prospect Mountain. A short adit north of the stream penetrates a magnetic gabbro layer with 11% magnetite (sample 23-65) that can be traced 500 feet (150 m) to the northwest, although magnetite content is not uniform. Gabbroic rock with up to 3% very fine- to fine-grained interstitial pyrite occurs on the adit's dump.

In the same magnetic gabbro layer across the stream to the south, a 10 foot (3 m) deep prospect pit was excavated at the intersection of two thin granophyric quartz-plagioclase veins (up to 4 in-, 10 cm-wide, sample location 23-64). Minor amounts of chalcopyrite and bornite occur as coatings on fractures in the felsic veins and gabbro. Mafic minerals of the gabbroic rocks have been progressively replaced by magnetite and minor chalcopyrite (as much as 54% opaque minerals). Where mineralization is relatively minor, opaque minerals replace mafic minerals along grain boundaries and plagioclase is altered to white mica and(or) kaolinite. This mineralization locally is spatially related to shear planes. Where mineralization is more pervasive, opaque minerals completely replace mafic minerals, and plagioclase is pseudomorphically replaced by tremolite-actinolite.

Another pit is located in the magnetic gabbro layer about 0.3 miles (0.5 km) southeast of the stream-side prospects. This gabbro contains 8% opaque minerals that are mostly magnetite with minor chalcopyrite (sample 23-66).

Magnetic gabbro samples from the pits and adit are enriched in Ag, Co, Cu, Te, and V (Table 25A). The enrichment of the 23-64 sample site

Table 25. Chemical analyses for selected elements of mineralized samples (from McCallum et al., 1983b).

A. Magnetic gabbro near Prospect Mountain in prospect pits and adit (samples 23-64A, -64B, -64C, -64D, -65, -66; total = 6 samples).

Element	Range (ppm)	Average (ppm)
Ag	0.25-1.8	1.0
Co	100-150	120
Cu	1000-3000	1500
Te	0.1-0.5	0.3
V	500-3000	1400

B. Mylonitic rocks from the dump of the shaft in section 32 (samples 23-104A, -104B, -104C, -104D).

Element	Range (ppm)	Average (ppm)
Ag	<0.5-0.7	0.23
Be	1-20	8.5
Cu	150-3000	900
Nb	0-50	13
U	0.3-6.4	2.1
Zn	0-500	175

is probably augmented by hydrothermal activity which is implied by the quartz-plagioclase veins and mineralization along fractures seen in the pit. The magnetic gabbro layer contains abundant magnetite which probably is the host for the anomalous V, and minor sulfides which probably host Ag, Co, Cu, and Te. This layer appears to be a fair target for further exploration.

Mullen Creek-Nash Fork shear zone

A 50 foot (15 m) deep shaft has been sunk in mylonitic rocks in the shear zone in the SE/4 SW/4 of section 32 (sample location 23-104). The mylonitic rock is composed dominantly of quartz and plagioclase with lesser amounts of hornblende, biotite and epidote. Some of the more mafic rocks are magnetic and contain cubic pyrite crystals. The rock breaks readily along abundant fractures that are coated locally with earthy malachite associated with thin quartz-plagioclase-epidote veins. Prominent red-brown goethitic or yellow limonitic stain and locally well developed slickensides are common on dump rocks from the shaft. Four samples from the dump (23-104A, -104B, -104C, -104D) contain anomalously high values of Ag, Be, Cu, Nb, Te, U, and Zn (Table 25B).

Recommendations

No deposits were found that show much potential of becoming an orebody. Ore was shipped from the Platt Mine (Houston, 1961) but the easily accessible mineralized rock has been extracted. Any body in pegmatite or bull quartz veins would be a small scale, low tonnage deposit.

A potential for economic mineralization would be a deposit of hydrothermal platinoid-bearing copper ore similar to the New Ramber mine orebodies (McCallum et al., 1976). The mine, located approximately 10 miles (16 km) northeast of the study area (Fig. 2), has rocks with high concentrations of palladium and platinum associated with copper ores in metagabbroic rocks of the Mullen Creek mafic complex (McCallum et al., 1976). The ore is at the intersection of a mylonite zone, several closely spaced faults, and a branch of the Mullen Creek-Nash Fork shear zone (McCallum et al., 1976). Although no indication of large scale sulfide mineralization was found in the study area, more detailed mapping and geochemical sampling of the Mullen Creek-Nash Fork shear zone could reveal a platinoid deposit.

The greatest potential for a large scale orebody in the study area is the possibility of a chromite- and(or) platinoid-bearing layer within the Mullen Creek mafic complex. A detailed study of the least altered portion of the complex with the best developed layering that occurs in sections 2 and 3 (and 35, Donnelly, 1979) and the Prospect Mountain area, especially the slightly mineralized magnetic gabbro layer there, could lead to the discovery of a mineralized horizon. A less likely type of deposit in the mafic complex would be a copper-nickel sulfide body that may have formed from an immiscible liquid which could have evolved during the early stages of gabbroic magma emplacement.

Recommendations for further mineral exploration of the study area include analysis for Pt, Pd and Au of rock chip and stream sediment panned concentrate samples. Also, a geomagnetic survey in the area would probably help delineate layering of the mafic complex and therefore aid in the exploration for mineralized horizons. Although economic Au deposits may exist in the study area, a Pt-Pd-bearing deposit has the greatest potential as an orebody.

CHAPTER X

TECTONIC HISTORY

Regional Tectonic History

Precambrian rocks of the Wyoming Medicine Bow Mountains are part of two distinct geologic provinces that are separated by the Mullen Creek-Nash Fork shear zone. The origin of the Mullen Creek-Nash Fork shear zone is the subject of considerable research and speculation. The shear zone is part of the Cheyenne belt that separates the Archean Wyoming Province to the north from the Proterozoic Central United States Province to the south (Houston et al., 1979). This boundary extends westward to the Sierra Madre (Divis, 1977) and eastward to the Laramie Range, where the younger Laramie Anorthosite-Syenite complex has intruded along it (Hills and Houston, 1979). A plate tectonics model has been proposed for this boundary in which an Atlantic-type continental margin to the north collided with an island arc formed by subduction to the south (Hills and Houston, 1979). This suture zone may have become the site of later strike-slip movement that resulted in at least 4.3 miles (7 km) of left lateral displacement (Houston et al., 1979).

Similarity of gross structural and stratigraphic characteristics of Proterozoic rocks in southern Wyoming and northern Colorado with the Great Lakes region has led to correlation of the structural evolution of the two areas and suggestion of extension of the Cheyenne belt to the Great Lakes area (Hills and Houston, 1979). Warner (1978) suggests that the shear zone is the northern margin of the northeast trending "Colorado Lineament" that includes a major belt of Precambrian faults in the Colorado Mineral Belt, and that the lineament is a middle Precambrian wrench fault system that may extend beneath the high plains to the northern mid-continent region. A long narrow belt of rocks with very high conductivity has led Camfield and Gouch (1977) to hypothesize that a Proterozoic plate boundary extends 870 miles (1,400 km) from the Cheyenne belt to the edge of the Canadian shield in Saskatchewan.

Rocks south of the shear zone in Wyoming are continuous with the metamorphic-igneous province of central and northern Colorado. Basement rocks of this province in Wyoming yield apparent ages of poor quality that range between approximately 1400 and 1800 m.y. (Hills and Houston, 1979). In Colorado, Hedge and others (1967) suggest that comparable basement rocks of this province were formed by sedimentation, volcanism, folding and metamorphism followed by a major period of regional amphibolite facies metamorphism and plastic folding at 1750 m.y. ago.

Intrusions in these basement rocks are common. Mafic intrusions have not been adequately dated, except for the 1780 m.y. old Elkhorn Mountain gabbro complex in the Park Range in Colorado (Hills and Houston, 1979). The oldest reliable dates on felsic intrusives are approximately 1730 m.y. for the Rambler Granite and the granite on Horse Creek and 1760 ± 100 m.y. for the Buffalo Pass pluton of the Sierra Madre (Hills and Houston, 1979). The Rambler Granite and the granite on Horse Creek are the youngest rocks known to be truncated by the Mullen Creek-Nash Fork shear zone (Hills and Houston, 1979).

Syn- and late-tectonic plutons in Colorado have been dated at 1710±70 m.y. (Hedge et al., 1967). Many felsic intrusives south of the shear zone in Wyoming and Colorado yield dates of 1660±50 m.y. old and are considered part of the Boulder Creek plutonic event (Hills and Houston, 1979). The oldest of these intrusives to cut the shear zone is the 1640±20 m.y. old "red granite" in the Sierra Madre (Hills and Houston, 1979). These pre-, syn-, and post-tectonic rock dates bracket major displacement along the shear zone at between approximately 1640 and 1730 m.y. ago (Hills and Houston, 1979).

Hills and others (1968) report, "one or more episodes of metamorphism in the Medicine Bow area between 1600 and 1455±40 m.y. ago" that is reflected by metamorphism of metasediments north of the shear zone and generation of pegmatites to the south. Hills and Houston (1979) suggest that, "perhaps metamorphism continued and pegmatites formed throughout the interval between approximately 1500 and 1650 m.y. ago, but more probably the rocks remained deeply buried and hot enough to promote loss or exchange of ^{87}Sr between minerals for several tens of millions of years after metamorphic recrystallization and pegmatite formation had ceased".

A thermal event of anorogenic plutonism between 1380 and 1435 m.y. ago produced the Laramie Anorthosite-Syenite complex and the widespread Sherman and Silver Plume granites (Hills and Houston, 1979). No intrusives of this age have been recognized north of the Cheyenne belt (Hills and Houston, 1979).

Exposure of the Medicine Bow Mountains was accomplished by uplift during the Laramide orogeny and subsequent erosion (Houston et al., 1968). Folding during this orogeny apparently was unrelated to

Precambrian structures whereas much of the Laramide faulting was controlled by reactivation of Precambrian faults and shear zones (Houston et al., 1968).

Local Tectonic History

The tectonic history of the study area includes metamorphic recrystallization of the hornblende gneiss, intrusion of the Mullen Creek mafic complex, two major episodes of shearing along the Mullen Creek-Nash Fork and Big Creek shear zones, and at least two intrusions of felsic magma. The most perplexing aspect of this history is the timing of these events, especially in relation to regional metamorphism. A regional medium-grade amphibolite facies metamorphic event produced the hornblende gneiss unit from interlayered sediments and mafic volcanics and sills at approximately 1800 m.y. ago (based on data from Hills and Houston, 1979).

Ages of the intrusive rocks of the study are somewhat questionable. The Mullen Creek mafic complex is cut by and is therefore older than the 1730 m.y. old granite on Horse Creek (Hills and Houston, 1979). Dating of the Big Creek granite does not define a single isochron but rather two at 1470 ± 60 and 1715 ± 50 m.y. (Houston et al., 1968, p. 78). Development of the Big Creek shear zone was probably concurrent with movement along the Mullen Creek-Nash Fork shear zone that occurred between 1640 and 1730 m.y. ago, and this implies that the 1715 ± 50 m.y. isochron is probably the age of emplacement of the Big Creek granite because the granite has locally been affected by shearing which must have occurred, at least to some degree, after emplacement. Age of the Prospect Mountain granite is unknown but it is likely similar to that of the Big Creek granite and other felsic intrusives that cut the mafic complex. These felsic intrusives may be derivations of the same basaltic magma that formed the mafic complex (Mussard, 1982; McCallum and Mussard, 1983), although the Big Creek and Prospect Mountain granites may be related to the 1660 ± 50 m.y. old Boulder Creek pluton event.

Generally conformable, gradational and(or) interfingered contacts and abundant interlayered relationships between the mafic omplex, older and younger felsic intrusives and hornblende gneiss imply that the intrusive rocks were emplaced into the catazone during a medium- to high-grade metamorphic event. The Mullen Creek mafic complex, Big Creek and Prospect Mountain granites, younger felsic intrusives and the cataclastic rocks of the Mullen Creek-Nash Fork and Big Creek shear zones have undergone medium-grade metamorphism to varying degrees, as evidenced by the amphibolite facies mineral assemblages and granoblastic and foliated fabric (see Chapter VIII). The closeness of age of these rock units with hornblende gneiss suggests they were generated and then metamorphosed during one continuous regional metamorphic event of varying intensity rather than during numerous distinct medium-grade metamorphic events. Varying intensity of this metamorphic event is probably a function of varying stress as evidenced by the generation of shear zones during the event, rather than variations in temperature and pressure. During or after the waning stages of this regional metamorphic event, cataclasis was renewed under low-grade metamorphic conditions as evidenced by fractures and veinlets which contain greenschist facies mineral assemblages (see Chapter VIII). This later cataclastic event and the accompanying low-grade metamorphism is exhibited locally and was not as pervasive as the early regional medium-grade metamorphic event.

This interpretation of the local cataclastic history is similar to a scheme suggested by McCallum (1964b) for the Mullen Creek-Nash Fork shear zone northeast of the study area. He proposed two periods of kinetometamorphism: (1) an early extensive episode at amphibolite grade, and (2) a later less extensive period with local zones retrograded to greenschist facies (McCallum, 1964b).

CHAPTER XI

CONCLUSIONS

Detailed geologic mapping and petrographic study of the rocks in the southwestern portion of the Mullen Creek mafic complex and adjacent area has revealed numerous mafic and felsic intrusions that were emplaced into a hornblende gneiss sequence during a regional amphibolite facies metamorphic event. An early episode of cataclastic deformation during this regional metamorphism formed one major and numerous minor shear zones. This was followed by a later episode of cataclastic deformation that was accompanied by greenschist facies retrograde metamorphism.

The hornblende gneiss in the study area is a well foliated fine- to medium-grained rock composed dominantly of dark gray layers of hornblende, plagioclase and quartz and lesser amounts of light gray layers of plagioclase, quartz, microcline, and biotite (minerals in order of decreasing abundance). It is thought to represent a series of interlayered quartzo-feldspathic sandstone, graywacke and mafic volcanic rocks and sills that have undergone regional medium-grade amphibolite facies metamorphism.

Tholeiitic basaltic magma intruded hornblende gneiss and crystallized as a gabbroic layered complex (Mullen Creek mafic complex). The part of the complex adjacent to the hornblende gneiss is believed to be the roof zone of the complex (Donnelly, 1979). Contacts between the complex and gneiss in the study area and elsewhere (Houston et al., 1968; Donnelly, 1979) are generally gradational and concordant to layering of both the complex and gneiss. The gradational nature of the contact suggests emplacement in the catazone, and the concordance of layering suggests the roof of the complex and layering of the gneiss were relatively horizontal since the igneous layers of the complex were probably deposited at or near the horizontal. Locally in the study area, the complex apparently forced the gneiss apart to form wedge-shaped bodies that are generally discordant to the gneiss.

The mafic complex in the study area is composed of a variety of gabbroic phases that are generally dark gray, fine- to coarse-grained with sub-ophitic to poikilitic textures, and which apparently were composed primarily of plagioclase (An_{54-76}) and clinopyroxene with lesser amounts of orthopyroxene, olivine, magnetite and ilmenite. The complex is cut by a number of mafic intrusives that include variously metamorphosed basalt, diabase and gabbro in the form of dikes and irregularly shaped bodies. At least some of these cross-cutting intrusives probably are genetically related to the magma that formed the complex.

Regional medium-grade amphibolite facies metamorphism caused progressive replacement of pyroxene and olivine by hornblende whereas plagioclase remained relatively stable. Locally and especially near contacts of the mafic complex with the hornblende gneiss, metamorphism was more pervasive because of more shear stress and availability of water, thus hornblende and plagioclase are progressively more recrystallized. Progressive amphibolitization and recrystallization both occurred initially along grain boundaries and fracture planes, and proceeded gradually inward from grain boundaries and away from fractures until the process was complete. Igneous texture is completely obliterated where metamorphism was most pervasive, and the resulting rock is difficult to distinguish from hornblende gneiss. This transitional rock has lenses and crude layers of mosaic aggregates of quartz and plagioclase with minor hornblende in a matrix of nematoblastic hornblende with minor quartz and plagioclase. The quartz is generated from excess silica released during amphibolitization of pyroxene.

Localized retrograde metamorphism of the mafic complex is closely related to shearing on both a large and small scale reflecting the importance of shear stress and the opportunity to exchange components through the movement of water in fractures. Large areas of retrograded mafic complex rocks are very common near the Mullen Creek-Nash Fork and Big Creek shear zones. Retrograde metamorphic minerals are spatially related to shear planes, fractures and veinlets on the small scale. Retrograde metamorphism is responsible for the alteration of plagioclase to saussurite (epidote, albite, calcite, and white mica), orthopyroxene and olivine to magnetite plus talc or serpentine, clinopyroxene to tremolite-actinolite, hornblende to tremolite-actinolite and biotite or chlorite, tremolite-actinolite and biotite to chlorite, and opaque minerals (magnetite?) to epidote and prehnite. These retrograde products are generally typical of low-grade greenschist facies metamorphism.

Older felsic intrusives (Big Creek and Prospect Mountain granites) occur at the mafic complex-hornblende gneiss contact. These intrusives may be late stage differentiates of the magma which formed the mafic complex (Mussard, 1982). They generally have granitic compositions (plagioclase An_{26-40}), are light brown to light red, fine- to medium-grained with minor coarse-grained microcline phenocrysts and are locally well foliated.

The main body of Big Creek granite, and its cupolas near the main body and its apophyses into the mafic complex, are interlayered and have sharp generally interfingered to concordant (to metamorphic foliation) contacts with the complex. This part of the granite appears to have been emplaced in areas of weakness associated with early movement along the Big Creek shear zone. The granite also has cupolas in the mafic complex away from the main body that are cross-cutting and have sharp contacts. These cupolas have a trend similar to that of igneous layering in the complex in the area and may have been emplaced between these layers. Alkali- and silica-rich fluids from this granite have locally hybridized adjacent rocks of the mafic complex, and this is reflected by an increase in biotite and quartz and recrystallization of hornblende and plagioclase in the metagabbroic rocks. Hybridization infers the complex was not completely cooled and(or) was under stress at the time of Big Creek granite emplacement, permitting migration of the fluids.

The Prospect Mountain granite occurs as a stock and as extensive sills within hornblende gneiss. The granite stock cross-cuts mafic complex rocks but has caused only limited recrystallization and no hybridization of adjacent units. Emplacement of the stock was probably by forceful injection along the mafic complex-hornblende gneiss contact, and the lack of hybridization infers that this part of the mafic complex was relatively cool and(or) under little stress at the time. The granite sills have sharp conformable contacts with layers of gneiss and with igneous layers of the complex, and apparently have had no effect on the mafic complex. These sills probably were forcefully injected between layers of the hornblende gneiss.

At least two periods of cataclastic deformation have had varying effects on the rocks in the study area. An early period of shearing produced the Mullen Creek-Nash Fork and Big Creek shear zones and numerous smaller zones of cataclasis. The shear zones are comprised of cataclastic rocks that are gradational in composition from mafic (dominantly hornblende and plagioclase with minor quartz) to felsic (dominantly quartz, plagioclase, microcline, and biotite) and range from weakly deformed intrusive rock with relict igneous textures to gneiss with or without augen to very fine-grained mylonite. Mineral assemblages and textures indicate that this shearing most likely accompanied regional medium-grade amphibolite facies metamorphism. Movement along the Big Creek shear zone produced left lateral offset which moved that portion of the Mullen Creek mafic complex between the Big Creek and Mullen Creek-Nash Fork shear zones to the southwest. This shearing most likely occurred during regional metamorphism.

A later less extensive episode of shearing caused deformation of the Prospect Mountain granite and cataclastic reactivation of earlier shear zones. This deformation was generally more brittle than the earlier period as shown by the greater abundance of fractures and zones of granulation. Retrograde metamorphism was associated with this later deformation as evidenced by the abundance of minerals typical of low-grade greenschist facies metamorphism (such as chlorite) that occur within or near fractures and shear planes.

Younger tonalitic and granitic intrusives, quartz-potash feldspar-albite ± garnet ± tourmaline ± mica pegmatites and bull quartz intrude all Precambrian rock units in the study area. They generally form sill-like bodies with contacts that are sharp and conformable to metamorphic foliation, and emplacement probably was controlled chiefly by foliation planes. However, some of these bodies are irregularly shaped and cross-cut foliation. The bodies apparently represent at least two (and probably more) ages of emplacement.

Steeply dipping metamorphic foliations have two dominant trends that define two domains. A domain in the southern portion of the study area has a northwest trend that is dominated by non-cataclastic foliation of hornblende gneiss. A second domain in the western and northern portion of the study area trends northeast and has been developed by shearing in and related to the Mullen Creek-Nash Fork shear zone.

Faults were apparently developed during the later episode of shearing and during the Laramide orogeny. The orogeny uplifted the Medicine Bow Mountains and erosion exposed the Precambrian core.

Mineralization is confined to uranium- and rare earth-bearing pegmatites in hornblende gneiss, small hydrothermal copper sulfide deposits in the Mullen Creek mafic complex and the Mullen Creek-Nash Fork shear zone and a Fe-sulfide-bearing magnetic gabbro in the mafic complex. Deposits that have orebody potential in the study area include platinoid-bearing hydrothermal copper deposits in the Mullen Creek-Nash Fork shear zone, copper-nickel sulfide ore associated with the Mullen Creek mafic complex, and chromite and(or) platinoid-rich layers in the mafic complex.

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Appendix, Table 1. Diagnostic characteristics of rock types in the Mullen Creek mafic complex. (Symbols refer to designations used on Plate 1).

gabbro (g)	medium- to coarse-grained, dark green to dark brown, pyroxene content exceeds that of amphibole.
leucogabbro (lg)	similar to gabbro but with more plagioclase (>65%) which imparts a lighter color.
olivine gabbro (og)	similar to gabbro but contains olivine that generally has rims of pyroxene and green amphibole.
microgabbro (fg)	similar to gabbro but very fine- to fine-grained with an equigranular texture, forms distinctive brown, rounded outcrops.
pegmatitic gabbro (pg)	very coarse-grained (up to 4 cm), composed dominantly of pyroxene and plagioclase.
porphyritic gabbro (sg)	medium-grained with very coarse-grained pyroxene phenocrysts that give the rock a distinctive spotted appearance, may have a leucocratic groundmass (slg).
diabase (d)	very fine- to fine-grained, ophitic texture, dark gray, dense.
anorthosite (a)	medium- to coarse-grained, light gray to buff, dominantly plagioclase (>90%) rock.
metagabbro (mg)	medium- to coarse-grained, dark green to dark gray, weakly to thoroughly metamorphosed gabbro in which pyroxenes have been mostly or entirely converted to amphibole.
metaleucogabbro (mlg)	similar to metagabbro but with more plagioclase (>65%) which imparts a lighter color.
metamicrogabbro (mfg)	similar to metagabbro but very fine- to fine-grained with an equigranular texture.
metapyroxenite (mpx)	fine- to coarse-grained, green to dark green, dominantly mafic minerals (>90%), abundant chlorite and(or) biotite that imparts a schistose fabric.
meta-pegmatitic gabbro (mpg)	very coarse-grained (up to 4 cm), composed dominantly of amphibole and plagioclase.

Appendix, Table 1. (continued)

meta-porphyritic gabbro (msg)	medium-grained with very coarse-grained amphibole clusters that give the rock a distinctive spotted appearance, may have a leucocratic groundmass (mslg).
metadiabase (md)	similar to metagabbro but very fine- to fine-grained, well developed ophitic texture.
metabasalt (mb)	aphanitic to very fine-grained, commonly fine-grained plagioclase phenocrysts, very dark gray to black.
late-stage metagabbro (lsmg)	metaleucogabbro with distinctive coarse-grained euhedral equant plagioclase crystals, thought to correspond to Donnelly's (1979) late-stage metagabbro.
migmatitic metagabbro (mig)	metagabbro cut by metaleucogabbroic veins and(or) quartzo-feldspathic veins.
transitional metagabbro (tmg)	recrystallized metagabbro which has lost its igneous fabric, is transitional with and has a texture similar to hornblende gneiss.
hybrid metagabbro (hmg)	similar to metagabbro but with appreciable biotite, commonly recrystallized, probably formed by contamination of the mafic complex rocks by felsic intrusives.
retrograde metagabbroic rocks [rock type symbol preceded by (r)]	rocks of the mafic complex that have undergone retrograde metamorphism and typically have appreciable amounts of chlorite, epidote, biotite, and(or) tremolite-actinolite.
magnetite-rich mafic complex rocks [rock type symbol preceded by (mt)]	rocks of the mafic complex that are enriched in magnetite (attract a hand magnet).