THESIS

PETROLOGY AND STRUCTURE OF A PORTION OF THE P€ MULLEN CREEK METAIGNEOUS MAFIC COMPLEX, MEDICINE BOW MOUNTAINS, WYOMING

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY MICHAEL EDWARD DONNELLY ENTITLED PETROLOGY AND STRUCTURE OF A PORTION OF THE P€ MULLEN CREEK METAIGNEOUS MAFIC COMPLEX, MEDICINE BOW MOUNTAINS, WYOMING BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

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ABSTRACT OF THESIS

PETROLOGY AND STRUCTURE OF A PORTION OF THE P-Є MULLEN CREEK METAIGNEOUS MAFIC COMPLEX, MEDICINE BOW MOUNTAINS, WYOMING

The Mullen Creek mafic complex, located in the central Medicine Bow Mountains of Wyoming, is a Precambrian sequence of layered metaigneous mafic rocks intruded by several small, irregular plutons of felsic composition. The sequence consists of a diversified assemblage of rock types that exhibit variable degrees of regional and kinetic metamorphism as well as hybridization resulting from subsequent intrusion of felsic bodies. The main mafic body is a layered metagabbroic mass that has undergone gravitational differentiation to form gabbro-anorthositic gabbro-anorthosite-pyroxenite differentiates. Convectional motion appears to have been operative during crystallization as evidenced by cross-bedding, scour channeling, igneous laminations, and localized rhythmic layering. Systematic changes in the bulk composition of the layered sequence are suggested by increasing phosphorous, sodium, titanium, vanadium, zirconium, iron to magnesium ratio, and decreasing nickel in similar units with increasing stratigraphic height. Reversals in compositional variations are indicated by mineralogic and geochemical changes.

Diabase, late stage gabbro, two periods of basalt dikes, and a minimum of two felsic phases intrude the layered sequence. One felsic body, the Horse Creek granodiorite, may represent a late stage differentiate of the layered gabbroic sequence.

Regional amphibolite grade metamorphism has masked most of the primary mineralogy of the mafic units, but numerous relict textures are present throughout most of the complex. A late stage of kinetic metamorphism at lower amphibolite-upper greenschist facies has imparted a cataclastic and accompanying retrograde metamorphic overprint locally. Emplacement of younger felsic rocks during the waning stages of the regional metamorphic event is responsible for hybridization of surrounding mafic units.

The mafic complex has been subjected to at least two folding episodes and multiple episodes of faulting and shearing. The complex has been folded anticlinally about a slightly overturned axis plunging steeply to the northwest with indeterminate internal folding. Refolding is reflected by a shallow westerly trending synanticlinal fold. Local shearing produced a penetrative fabric that subparallels the Mullen Creek-Nash Fork shear zone. Many Precambrian faults apparently were reactivated during the Laramide orogeny.

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INTRODUCTION

Purpose

Detailed geologic investigations were conducted in a portion of the Mullen Creek Mafic Complex in southeastern Wyoming in an effort to achieve the following objectives: (1) to subdivide phases of the mafic complex into mappable units, (2) to establish a better understanding of the structure of the complex, (3) to establish geochemical trends in the complex, (4) to study relationships of felsic bodies within the complex, (5) to confirm the layered nature of the complex, and (6) to locate and evaluate mineralized zones.

Location and Description of Study Area

The area included in this report is situated in the central part of the Mullen Creek Mafic Complex which lies on the western slope of the Medicine Bow Mountains, Carbon and Albany counties, Wyoming (Fig. 1). The study area encompasses approximately twenty-two square miles (57 square Km.) in Townships 13 and 14 North and Ranges 79 and 80 West in the western part of the $7\frac{1}{2}$ minute Keystone Quadrangle and the southeastern part of the $7\frac{1}{2}$ minute Overlook Hill Quadrangle.

Access to the area is provided by Woming state highways 130 and 230 (Fig. 1). Secondary all-purpose roads originating from

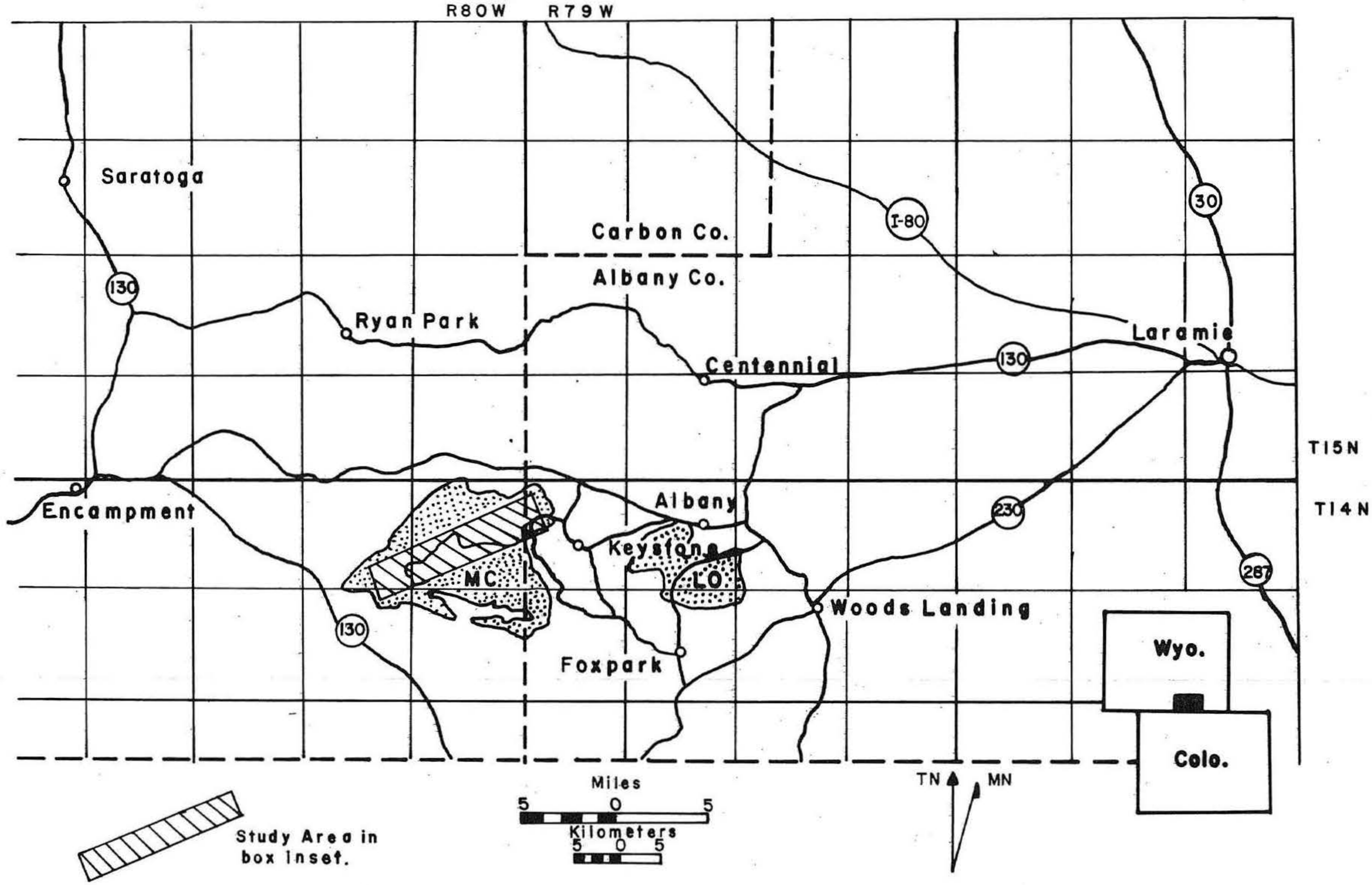


Fig. 1. Index map of study area. Mullen Creek mafic complex (MC) and Lake Owen mafic complex (LO) are shown as stippled areas.

the villages of Albany and Fox Park provide access to the North Platte River and provide excellent access to the study area. Secondary roads are not maintained during the winter, which limits vehicular travel to the summer months. The portion of the area west of the North Platte River may be reached only through privately held land on a series of jeep trails branching off highway 230 in the vicinity of the Big Creek Ranch.

Elevations range from 7, 400 feet (2, 257 meters) in the western part of the area along the North Platte River to 9, 750 (2, 974 meters) atop Jays Roost in the east. With the exception of small clearings along drainages, the eastern region is covered with dense stands of lodgepole pine, spruce, and fir. The west central portion of the area is covered with sparse stands of lodgepole pine, spruce, and sporadic groves of aspen. The terrain gradually becomes more open to the west, where grass and sagebrush covered hills predominate.

Outcrops are uncommon in the east but are increasingly more abundant to the west. Good exposure predominates along the North Platte River and the area directly east of the River.

Previous Investigations

Very little detailed geologic work has been done on the Mullen Creek Mafic Complex. Houston and others (1968) conducted preliminary geologic mapping of the mafic complex as a part of an excellent compilation of the regional geology of the Medicine Bow Mountains. The mafic complex also is included in a regional geologic map of the Southwestern Medicine Bow Mountains and Sierra Madre Range (scale 1:125, 000) by Houston and Ebbett (1977).

Ramirez (1971) conducted geologic mapping in the Savage Run area within the metaigneous mafic complex, and Ruehr (1961) mapped the southwestern corner of the mafic complex as part of his investigation in the Devils Gate area. Other detailed work in the immediate vicinity of the metaigneous mafic complex includes regional geologic studies by McCallum (1964) north and northeast of the study area, and investigations of dedolomitized lenses in the Mullen Creek-Nash Fork shear zone (McCallum, 1964, 1974). Continuing efforts are being made by McCallum to provide reconnaissance geologic maps of the Keystone and Overlook Hill $7\frac{1}{2}$ minute Quadrangles as part of a U. S. Geologic Survey Precambrian mapping program (McCallum, per. commun., 1977). A brief review of several structural, petrographic and geochemical points presented in this report are available in an abstract by Donnelly and McCallum (1977). A petrographic and geochemical evaluation of felsic rocks in the vicinity of the study area is currently being conducted by M. E. McCallum and D. E. Mussard of Colorado State University (Mussard and McCallum, 1977; McCallum and Mussard, 1979a), and analyses of all rock types in the area have been compiled by McCallum and Mussard (1979b).

Other investigations include work by Currey (1959) in the Keystone district east of the study area, a study of the Big Creek Pegmatites to the southwest by Houston (1961), and work by Childers (1957) to the north on a low grade metasedimentary sequence. Investigations of mineralization in the Medicine Bow Mountains in the vicinity of the Mullen Creek mafic complex have been made by Theobald and Thompson (1968), McCallum and Orback (1968), McCallum and others (1976), Loucks (1977), on the New Rambler Mine, and McCallum (1968) on the Centennial District to the northeast. Further work is being conducted on gold mineralization in the Medicine Bow Range by McCallum and Loucks (per commun., 1977).

The Lake Owens Mafic Complex, which is similar to the Mullen Creek mafic complex, lies approximately six miles (9.7 Km.) to the east and has been investigated by numerous workers (e.g., Catanzaro, 1956; Stensrud, 1963; Ridgley, 1972). A geologic map of the $7\frac{1}{2}$ minute Lake Owens Quadrangle by Houston and Orback (1976) includes the eastern part of the Lake Owens Mafic Complex. The western part of this complex is in the $7\frac{1}{2}$ minute Albany Quadrangle which has been mapped by McCallum and Houston (McCallum, per. commun., 1977). A detailed study of the cyclic units in the Lake

Owens Mafic Complex is currently being conducted by Houston and Ridgley (Houston, per. commun., 1977).

Methods of Investigation

Field work was conducted during the summers of 1974 and 1975. Portions of the U. S. Geological Survey $7\frac{1}{2}$ minute Keystone and Overlook Hill Quadrangles, Wyoming, were enlarged to a scale of approximately 1:18, 000 for base maps. Aerial photographs of the 1947 U. S. G. S. GS-CM series (approximate scale 1:32, 000) were also used but were limited in value.

Representative rock samples were collected from all map units, and 145 rock samples were thin-sectioned for petrographic study. In addition, 96 representative rock samples and accompanying thin sections were made available to the author by M. E. McCallum from the eastern part of the study area.

Modal analyses were conducted on 95 samples, utilizing a petrographic microscope with an integrating mechanical stage and a nine bank Lab Count Denominator. Between 500 and 1000 counts were made in each modal analysis. Potash and soda staining techniques (Bailey and Stevens, 1960) were used to distinguish potash feldspar from plagioclase in polished rock slabs. Plagioclase compositions were determined by the Michel-Levy twin method described by Kerr (1965, p. 257) and by oil immersion methods using determinative plagioclase composition curves (Tsuboi, 1923) where plagioclase was poorly twinned or where very calcic plagioclase prevailed. Relative percentages of feldspars in granitic rocks were determined by conducting point counts on stained rock slabs using a petrographic microscope with attached reflected light source. In addition, standard thin section modal analyses were conducted on felsic rocks to determine relative percentages of accessory minerals.

Electron microprobe analyses were conducted on eight mafic rock samples containing unaltered primary minerals. Olivine, clinopyroxene, and orthopyroxene compositions were determined quantitatively. Analyses were performed on a Hitachi Model XMA-S electron microprobe at the University of Wyoming. One to five grains of each mineral were analyzed per polished thin section. Results of the microprobe analyses are given in the Appendix, Tables 1-3.

Assay and whole rock analyses (McCallum et al., 1979) were performed on 64 and 34 samples respectively by the U.S. Geological Survey as part of the Medicine Bow Mountains, Wyoming Platinum Project under the supervision of M. E. McCallum. Analyses were performed using atomic absorption and semiquantitative emission spectrographic analysis for 30 elements. In addition, part of the assay analyses were made utilizing a combined fire assay-emission spectrographic method described by Cooley et al. (1976). Assay and whole rock data are presented in the Appendix, Tables 4 and 5 respectively.

REGIONAL GEOLOGY

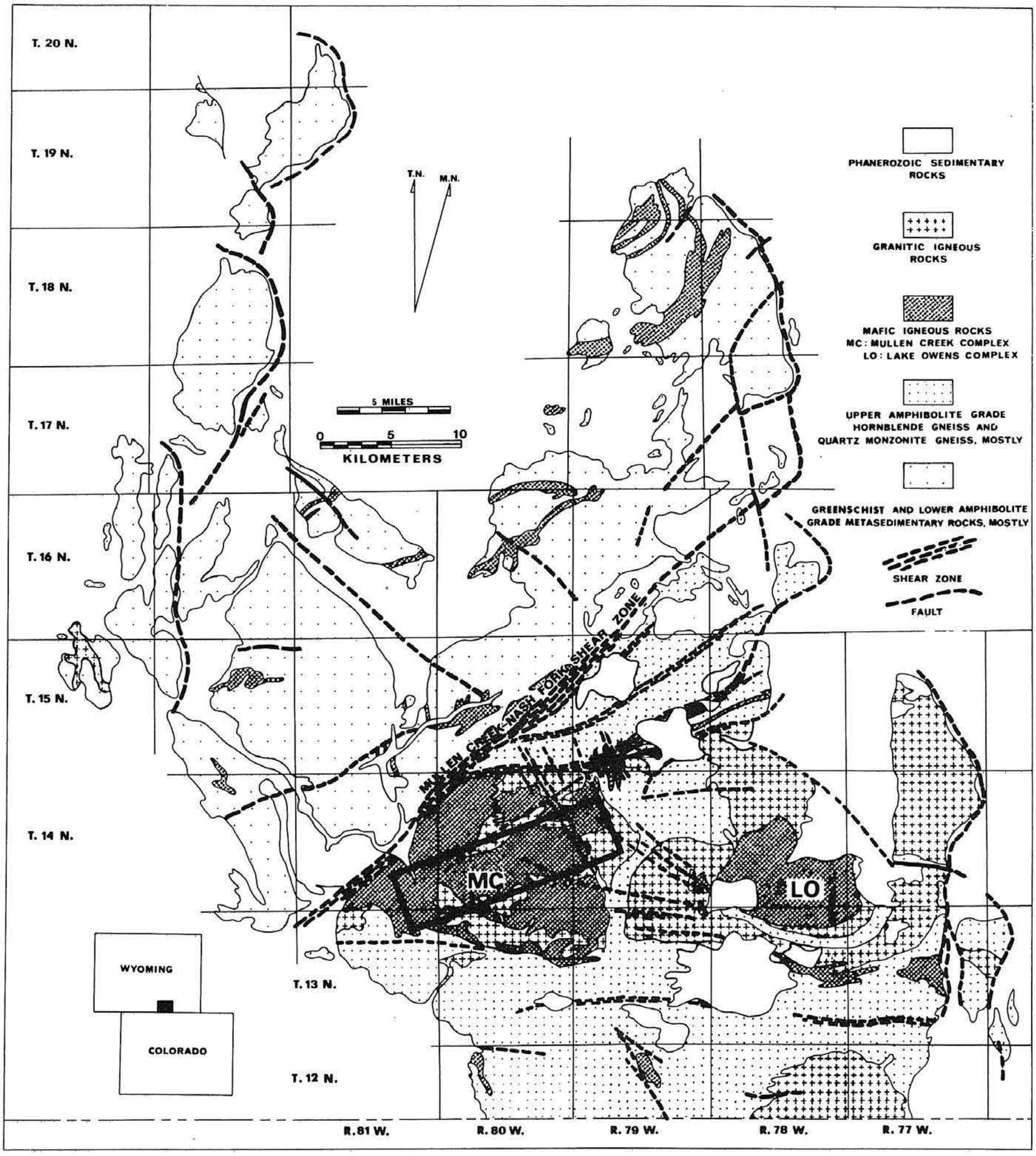
General Statement

The Medicine Bow Mountains define a large asymmetrical anticline with an exposed Precambrian core flanked by Late Paleozoic, Mesozoic and Tertiary sedimentary rocks of the Laramie Basin and Laramie River Valley on the east and Saratoga Valley and North Park Basin on the west. The central part of the Medicine Bow Mountains is structurally dominated by a series of northeast trending shear zones collectively termed the Mullen Creek-Nash Fork shear zone (Houston and McCallum, 1961; McCallum, 1974). This zone of shearing separates the Precambrian rocks of the range into two distinct geologic provinces that are distinguished by differences in structure, rock type, and geochronology. Extension of the Mullen-Creek-Nash Fork shear zone is present in the Sierra Madre Range to the southwest (Divis, 1977), and has been tentatively traced through the Laramie Range to the northeast (Houston and McCallum, 1961; Hills and Armstrong, 1974). A large body of anorthosite is situated where the shear zone is considered to pass through the Laramie Range, suggesting emplacement of the anorthosite along the shear zone (Houston et al., 1968; Hills and Armstrong, 1974, p. 223-224).

Rocks northwest of the Mullen Creek-Nash Fork shear zone include a complex sequence of mostly low grade metasedimentary rocks and quartzofeldspathic gneisses, intruded by numerous granitic, quartz diorite, and gabbroic bodies (Fig. 2). Gneissic units are of the amphibolite facies and represent the oldest rocks northwest of the shear zone. Conformably overlying the gneissic units are metasedimentary rocks ranging from greenschist to amphibolite facies (Houston et al., 1968) Rb/Sr age dates for the gneiss and granitic intrusions in the gneiss indicate that the rocks have been affected by two thermal events, one at 2, 400 m. y. and another at 1, 500-1, 600 m. y. (Hills et al., 1968), setting a minimum age of 2, 400 m. y. for the oldest rocks northwest of the shear zone. These rocks reflect at least two deformational events: a northeast-trending fold pattern that controlled intrusion of gabbroic magma and a refolding episode that produced northwest-trending structures. Older gneissic units are characterized by north-northwest-trending structures (Houston et al., 1968).

Rocks southeast of the Mullen Creek-Nash Fork shear zone include felsic and mafic gneisses, granite, and gabbroic intrusives that are continuous with the Precambrian rocks of the igneous-metamorphic province of central and northern Colorado. Hornblende gneiss and quartzofeldspathic gneiss predominate and are intruded by variably sized bodies of quartz diorite and gabbro. Gneisses, quartz diorite, and some of the gabbroic intrusives are in turn

Fig. 2. Generalized Precambrian outcrop map of the Medicine Bow Mountains, Wyoming (after McCallum et al., 1976, Fig. 1). Study area is in box inset. Diagram provided by courtesy of M. E. McCallum.


T. 20 N.
T. 19 N.
T. 18 N.
T. 17 N.
T. 16 N.
T. 15 N.
T. 14 N.
T. 13 N.
T. 12 N.
R. 81 W.
R. 80 W.
R. 79 W.
R. 78 W.
R. 77 W.
T.N.
M.N.
5 MILES
0 5 10
KILOMETERS
MULLEN CREEK-NASH FORK SHEAR ZONE
MC
LO
WYOMING
COLORADO
PHANEROZOIC SEDIMENTARY ROCKS
GRANITIC IGNEOUS ROCKS
MAFIC IGNEOUS ROCKS
MC: MULLEN CREEK COMPLEX
LO: LAKE OWENS COMPLEX
UPPER AMPHIBOLITE GRADE HORNBLENDE GNEISS AND QUARTZ MONZONITE GNEISS, MOSTLY
GREENSCHIST AND LOWER AMPHIBOLITE GRADE METASEDIMENTARY ROCKS, MOSTLY
SHEAR ZONE
FAULT

intruded by granite of two ages: 1,700 m.y. old foliated granite and a younger coarsely crystalline phase referred to as the Sherman Granite and dated at 1,335± 40 to 1,570± 40 m.y. old (Hills et al., 1968). Although age dating results on gneissic units are discordant, analytical results do not suggest the presence of any rocks older than 1,700-1,900 m.y. (Hills and Armstrong, 1974).

Rocks southeast of the shear zone are structurally complex. Geometry of folds and associated lineations suggest two periods of deformation. Refolding coupled with obliteration of primary structures in some dikes indicate that rocks south of the Mullen Creek-Nash Fork shear zone have been affected by structural and metamorphic events that are not defined north of the shear zone (Houston et al., 1968).

Geochronologic studies in the Sierra Madre Range show two distinct geochronologic provinces similar to those found in the Medicine Bow Mountains. Rb/Sr age dates for rocks southeast of the Mullen Creek-Nash Fork shear zone range from 1,680± 20 m.y. to 1,980± 70 m.y., whereas older rocks northwest of the shear zone have been dated at 2,560± 100 m.y. and possibly as old as 2,830 m.y. (Divis, 1977).

The contrast in structure and age of rocks on either side of the Mullen Creek-Nash Fork shear zone suggest that the central Medicine Bow Mountains lie in a transition zone between ancient

Precambrian rocks of Central Wyoming and younger Precambrian rocks of the Front Range of Colorado. Houston and others (1968, p. 101-102) suggest that this discontinuity may represent a major boundary between two geologic provinces that existed in Precambrian time. The possibility that the shear zone represents a Proterozoic subduction zone is suggested by Hills and others (1975) and Camfield and Gough (1977). Warner (1978) interprets the Mullen Creek-Nash Fork shear zone as part of a Precambrian counterpart of Phanerozoic wrench fault systems that commonly form along continental plate margins during episodes of mountain building.

Review of Mafic Intrusions South of the Mullen Creek-Nash Fork Shear Zone

Numerous mafic bodies have been mapped in the Medicine Bow Mountains south of the Mullen Creek-Nash Fork shear zone. All of these mafic bodies show variable degrees of cataclasis and metamorphism. In general, the mafic rocks in the northeastern part of the area immediately south of the Mullen Creek-Nash Fork shear zone are more strongly foliated and more highly metamorphosed because of pervasive deformation related to the shear zone (Houston et al., 1968). The mafic bodies show a wide range of sizes, varying from small lensatic features that rarely exceed one mile (1.6 m.) in length to the large complexes of the Lake

Owens and Mullen Creek areas that cover approximately 21 and 60 square miles (57 and 155 square Km.) respectively. Both the Lake Owens and Mullen Creek mafic complexes have been recognized as gravity stratified masses.

The Lake Owens mafic complex has received considerable attention because of the predominantly unmetamorphosed nature of the rocks, generally good exposures, and good access. The intrusion is a relatively small cup-shaped body dipping concavely to the north. Several of the mafic units display well developed layering, and, utilizing the terminology of Jackson (1970), show planar lamination, isomodal layers, and chemically graded layers (Ridgley, 1972). The intrusion also contains sedimentation features such as cross-beds and channels (Houston and Orback, 1976; Houston, per. commun., 1977). Layering defines the structure of the complex as a steeply dipping semicircular intrusion concave to the north (Houston et al., 1968). Systematic sampling of the complex at closely spaced intervals has revealed repetitive units, and three or more major cycles may be present (Houston, per. commun., 1977). Rocks are predominantly leucocratic, and major types include leucogabbro, leuconorite, leucotroctolite, and anorthosite. Houston (per. commun., 1977) indicates that the most significant variation is the progressive decrease in the proportion of mafic minerals from the base of the complex to the top.

The Mullen Creek mafic complex is located approximately six miles (9.7 km.) to the west of the Lake Owens mafic complex. The Mullen Creek complex shows more intense metamorphism and deformation than its Lake Owens counterpart and prior to the author's investigation, very little detailed geologic mapping had been done in the west-central part of the body. As previously noted, Houston and others (1968, p. 75-76, pl. 1) conducted reconnaissance mapping of the mafic complex, and reported a wide variety of variably metamorphosed mafic rock types including metagabbro, olivine gabbro, diorite, quartz diorite, and metabasalt. Olivine gabbro interlayered with anorthositic olivine gabbro was recognized in a small region in the western part of the complex.

Reuhr (1961) mapped the extreme southwestern part of the mafic complex in the Devils Gate area and reported a predominance of metagabbro along with minor occurrences of olivine-bearing gabbros and metapyroxenites.

Ramirez (1971) gives a good account of the mafic rocks in the northeastern part of the Mullen Creek mafic complex where he conducted detailed work over approximately five square miles (13 square km.). Unfortunately, the area studied by Ramirez is one of the more poorly exposed sequences of mafic rock in the complex. Very little relict mineralogy is preserved in rocks of that area due to pervasive metamorphism and widespread cataclasis. However, Ramirez reports that metagabbro and hybridized metagabbro predominate and lesser amounts of metadiabase, metapyroxenite, metaleucogabbro, metadiabase dikes, and orthoamphibolites are present. Based upon variation in plagioclase composition, general lithology, local occurrences of cumulate texture, layering, igneous lamination, and an inferred tholeiitic parent magma, Ramirez suggested that the Mullen Creek mafic complex may represent a layered gabbroic complex.

Review of Felsic Rocks South of the Shear Zone

Numerous felsic intrusives occur in the Medicine Bow Mountains, but unfortunately, limited crosscutting relationships, diverse lithology, and sparse radiometric age dates make genetic and chronologic interpretations difficult.

Two granitic units cutting the Mullen Creek mafic complex have been dated by the Rb/Sr method. Both Horse Creek granite and Rambler granite yield ages of 1,760± 60 m.y. (Hills, per. commun., 1977). Age dating of the Big Creek granite, which cuts metagabbro in the western part of the mafic complex, has defined isochrons of 1,470± 160 and 1,715± 50 m.y. old (Hills et al., 1968). The discrepancy in these age dates has yet to be resolved (Hills, per. commun., 1977). Petrographic studies by the author of felsic units in the area where felsic rocks were reportedly collected for age dating show widespread crushing and shearing, suggesting a kinetic metamorphic event that postdated emplacement of the felsic rocks. This metamorphic event may explain the apparent discrepancy in age dates.

All felsic rocks in the vicinity of the Mullen Creek mafic complex have been grouped under the heading of Older Granite by Houston and others (1968, p. 77). These rocks range from granite to granodiorite, show variable degrees of cataclasis, and transitions from granite to porphyroblastic augen gneiss have been noted. Felsic units show conformable to gradational contacts with hornblende gneiss, and clearly cross-cut the mafic rocks of the Mullen Creek complex.

In addition to the larger bodies of granitic rock previously described, small dikes, sills, and pegmatites are common throughout the Medicine Bow Mountains south of the shear zone. The small dikes and sills are similar in mineralogy to larger granitic units and are interpreted by Houston and others (1968, p. 81) as being genetically related to the larger felsic units.

Three types of pegmatites have been described by Houston (1961) in the Big Creek area in the vicinity of the western and southwestern part of the Mullen Creek mafic complex. These include: (1) conformable pegmatites that are younger than the host rock, (2) cross-cutting pegmatites, and (3) a replacement type found chiefly in the North Park fluorspar district. As in the case with larger granitic bodies, no definite age relationships between different types of pegmatites have been established. However, it has been suggested that the pegmatites are dissimilar in age and that some pegmatites with similar field characteristics may have been formed during events greatly separated in time (Houston, 1961; Houston and others, 1968, p. 81). Houston and others (1968, p. 81) also suggest that the majority of the conformable and cross-cutting pegmatites formed or were intruded at approximately the time of intrusion of the larger felsic bodies of the region.

PRECAMBRIAN ROCKS

General Statement

With the exception of thin covers of Quaternary alluvial and colluvial material, Precambrian rocks are the only rocks exposed in the study area. Mafic rocks predominate and comprise a portion of a metaigneous layered mafic complex that has been intruded by felsic rocks which apparently reflect several different episodes of intrusion.

The layered portion of the mafic sequence consists principally of metagabbro and metaleucogabbro, but metapyroxenite, hybridized metagabbro, and variably metamorphosed anorthosite, troctolite, olivine gabbro, and norite are abundant locally. Cross-cutting relationships between metagabbro and metadiabase suggest that some phases of diabase predate the major gabbroic event. Basaltic to diabasic dikes cross-cut some felsic intrusives, and are cut by others indicating several intrusive episodes.

Felsic rocks show a wide variation in composition, ranging from alkali granite to granodiorite. Two felsic rock phases have been distinguished and mapped, although similar variations in composition, structure, and texture of the units make it difficult to clearly separate them.

All rocks in the study area reflect varying degrees of cataclasis and well developed shear zones are present locally. The following descriptions are presented in an inferred order from oldest to youngest.

Hornblende-Andesine-Quartz Gneiss

The oldest (?) exposed Precambrian unit in the study area is a hornblende-andesine-quartz gneiss that occurs near the eastern boundary of the mafic complex in sections 18 and 19, T14N, R79W. This gneiss has been interpreted as part of the hornblende gneiss sequence mapped to the south by Houston and others (1968). The gneiss is preserved as xenoliths in the Horse Creek granodiorite and in the mafic complex near mutual contacts. The xenoliths are generally small, rarely exceeding 65 feet (20 meters) in width and 250 feet (76 meters) in length. Partial assimilation of gneissic xenoliths is common, and those found in the Horse Creek granodiorite locally display a halo of biotite-rich granodiorite.

Gneissic xenoliths become increasingly abundant near the mafic complex-granodiorite contact to the south (Plate 2), and gradually grade into a predominantly hornblende gneiss sequence south of the study area (McCallum, per. commun., 1977).

The gneiss is predominantly a hornblende-rich rock containing lesser amounts of quartz and andesine. It is well layered, strongly foliated and generally dark in color. Layering is expressed by mineral segregations that show pronounced differences in color and texture. Individual layers range from 0.1 to 10 mm in thickness. Locally, gneissic rocks are highly deformed into a series of tight minor folds and crenulations. Poor exposure prohibited detailed analysis of these structures.

A small diopside-garnet-epidote skarn assemblage occurs south of the Golden Key prospect and indicates the presence of a once more calcareous phase in the original sequence. The gneiss appears to be similar to quartz-biotite-andesine gneiss and hornblende gneiss reported to the south by Houston and others (1968). The quartz-biotite-andesine gneiss is gradational both vertically and horizontally with hornblende gneiss, and was mapped as a separate unit primarily because of its quartz-rich nature (Houston, et al., 1968).

Petrography

Gneissic samples display a medium to fine-grained equigranular texture in thin section and are invariably layered. Individual mafic and felsic laminae range from .5 mm to 10 mm. Hornblende is commonly aligned in a nematoblastic fashion, but the gneiss is typically granoblastic grading to porphyroblastic. Calcareous phases are composed primarily of granoblastic garnet and diopside with lesser amounts of epidote, quartz, and calcite. Accessory apatite and magnetite generally occur in trace amounts as inclusions in diopside.

Hornblende commonly shows a pleochroic scheme of X = yellowish brown, Y = deep green, and Z = bluish green. Biotite is found altering from hornblende and as ragged spongy crystals enclosing quartz and plagioclase. Biotite displays a pleochroic scheme of X = deep to light brown and $Y \simeq Z$ = dark reddish brown to deep brown.

Plagioclase compositions range from An_{41} to An_{48} in the three samples studied (Table 1). Grains are generally poorly twinned and sericitically altered.

Other accessory minerals include magnetite, ilmenite with associated sphene and leucoxene, microcline, and tiny zircon and apatite crystals.

Metaigneous Mafic Complex

General Statement

Mafic rocks in the study area comprise part of a layered gabbroic intrusion that has subsequently been intruded by late stage gabbro, diabase (age relationships uncertain), and basaltic to diabasic dikes. A complex assemblage of mafic rocks is exposed in the mafic sequence and variable degrees of metamorphism and later metasomatism related to felsic intrusives are evident. Amphibolite grade metamorphism is pervasive throughout the

Table 1. Modal analyses (volume percent) for hornblende-andesine-quartz gneiss.

Sample number	22-382	22-566	22-570
Hornblende	27.4	33.0	57.0
Plagioclase	61.8	50.0	37.5
An content	(48)	(41)	(45)
Quartz	7.3	5.5	3.5
Biotite	1.3	5.0	2.0
Magnetite	2.2	trace	trace
Ilmenite	trace	trace	trace
Leucoxene	trace	--	trace
Calcite	--	trace	--
Sphene	trace	trace	trace
Zircon	trace	trace	trace
Epidote	trace	6.5	trace

metaigneous mafic complex, and although primary textures are generally recognizable, relict mineralogy is preserved in only a few isolated areas.

Based on field observations and petrographic study, it appears that metagabbro, metaleucogabbro, hybrid rocks of dioritic composition, and metadiabase are the most common phases in the mafic complex. However, lesser amounts of metapyroxenite, metabasalt, anorthosite, and slightly metamorphosed olivine gabbro and norite are also present. Hybrid rocks that have compositions similar to diorite are derived from gabbroic units that have undergone varying degrees of metasomatism due to intrusion of felsic rocks. Ramírez (1971) reports similar hybrid phases north of the study area, and gives a good account of their occurrences and petrography.

Gabbroic Rocks

General Features

As previously noted, metagabbro is the principal rock type in the study area. Metagabbro grades locally into metaleucogabbro, and several occurrences of anorthosite were observed. Fresh olivine gabbro and norite were found in a few isolated localities, but comprise only a small proportion of total mafic rocks in the complex.

Metagabbro is characteristically medium grained, dark gray to greenish gray, and shows a granular to macroophitic texture.

Primary foliations, defined by coarse igneous layering and lamination, are present in several parts of the complex. Weak to strong cataclastic foliation may also be present. A spotted metaleucogabbro is prominent in the Jays Roost area. The spotted appearance is due to the presence of large (1.0 cm) decussate clots of amphibole formed from the breakdown of large intercumulate grains of pyroxene.

Numerous mafic pegmatites were observed cross-cutting metagabbro. Pegmatites are generally quite small, very irregular, and consist of coarsely crystalline amphibole and plagioclase. Mafic pegmatites are considered to be contemporaneous with formation of gabbro, and the result of localized build-ups of volatiles. All of the pegmatites encountered are too small to map at the utilized scale.

Many of the structural features observed in the metagabbroic rocks are similar to those reported from classic layered gabbroic intrusives (Wager and Brown, 1968; Morse, 1969). Features noted include igneous lamination (the alignment of tabular plagioclase), layering, and mineral graded bedding, which will be discussed in a later section. One small scour channel was observed and rare cross-beds have been noted both in the study area and elsewhere in the complex (McCallum, per. commun., 1977). Fine layering occurs in the vicinity of Jays Roost in the eastern part of the study area. Layers are defined by alternating segregations of metaleucogabbro and metagabbro that range to anorthosite and metapyroxenite respectively. Layers range from one mm to one meter and because of poor exposure, can rarely be traced more than four meters. Excellent layering has been found in the western part of the area in section 35, west of the North Platte River. Individual layers range from 10 mm to approximately one meter in thickness. The layers range in composition from metapyroxenite to anorthosite, and one metapyroxenite zone was traced intermittently for approximately 0.4 km.

Small anorthosite lenses and pod-like segregations enclosed in metaleucogabbro were observed in section 7 in the eastern part of the study area. Individual pods rarely exceed six to seven meters in strike length and two meters in width. The anorthosite grades laterally into metaleucogabbro and probably formed by localized segregation of plagioclase. Other occurrences of anorthosite are interlayered with more mafic phases and apparently are cumulate in nature.

Metabasalt inclusions were found in metagabbro east of Jays Roost in the NW $\frac{1}{4}$ of section 19. The inclusions measure approximately three to six meters in diameter, and were clearly engulfed by metagabbro (Fig. 3). Metabasalt-metagabbro contacts are very sharp and display little or no interaction between the two units. None of the inclusions are large enough to map at the scale of this study.

Fig. 3. Metabasalt xenolith in metagabbro in section 19 east of Jay's Roost. Three inch pen knife for scale.

Petrography

Gabbroic rocks are characteristically hypidiomorphic granular and may show alignment of plagioclase, relict ophitic texture, and local occurrences of cumulate texture. Primary igneous textures are very well preserved, reflecting the magmatic history of the rocks despite the alteration of most primary minerals. Medium-grained phases predominate, however, fine-grained micro-gabbros and coarse-grained units prevail locally.

Plagioclase and amphibole form the primary constituents of the metagabbro, and some olivine, orthopyroxene, and clino-pyroxene is preserved in olivine gabbros and norites. Accessory minerals include apatite, zircon, magnetite, ilmenite, pyrite, chalcopyrite, pentlandite, and allanite. Common secondary minerals are biotite, epidote, muscovite, sericite, calcite, leucoxene, sphene, and scapolite. Tables 2, 3 and 4 list modal analyses for selected gabbros, metagabbros, metaleucogabbros, and anorthosites.

Plagioclase. Plagioclase is the least altered principal mineral phase in the mafic complex rocks. Only in areas of hybridization and shearing has plagioclase composition and primary textural disposition been appreciably modified.

Plagioclase ranges from anhedral grains to euhedral lath-like crystals 0.4 to 7.0 mm long. Subhedral crystals with roughly tabular

Table 2. Modal analyses (volume percent for gabbro).

Sample number	22-91	22-92	22-155	22-160
Plagioclase	52.9	46.6	41.2	48.5
An content	(89)	(65)	(68)	(86)
Clinopyroxene	15.0	18.8	28.9	31.3
Composition (Wo-En-Fs)	(48.0-42.5-9.5)	(48.3-38.4-13.3)	(42.8-46.1-11.2)	(44.0-43-46.1-11.2)
Olivine	5.0	--	2.0	8.4
Fo content	(86)	--	(86)	(67)
Orthopyroxene	0.5	4.4	2.4	0.8
Composition (Wo-En-Fs)	(1.8-70.8-27.4)	(2.3-68.6-29.1)	(2.71-75.4-21.9)	(2.02-66-75.4-21.9)
Hornblende	12.4	28.4	24.1	5.8
Biotite	1.5	0.9	0.2	--
Apatite	--	0.3	0.2	--
Magnetite	1.2	0.3	0.6	3.9
Ilmenite	--	--	trace	trace
Sphene	--	trace	--	--
Rutile	trace	trace	trace	trace
Pleonaste (Hercynite)	trace	--	--	--
Talc	5.6	--	trace	--
Serpentine	0.5	--	--	1.1
Iddingsite	trace	--	trace	0.2
Hematite	trace	--	--	--
Chlorite	0.3	trace	trace	--
Chlorophaeite	trace	--	--	--
Sericite	2.3	--	trace	--
Epidote	2.8	trace	trace	--
Scapolite	--	0.3	--	--
Calcite	trace	--	trace	--

Table 2 (Continued).

Sample number	22-160	22-403	22-470	22-471	22-475
Plagioclase	48.5	38.3	63.9	55.6	--
An content	(86)	(77)	(73)	(57)	--
Clinopyroxene	31.3	8.1	13.7	17.9	--
Composition (Wo-En-Fs)	(44.0-43.0-13.0)	(no analysis)	(44.5-46.1-9.5)	(43.3-40.4-16.4)	(no analysis)
Olivine	8.4	20.9	15.9	--	17.4
Fo content	(67)	(80)	(74)	--	(81)
Orthopyroxene	0.8	5.9	0.7	18.7	10.1
Composition (Wo-En-Fs)	(2.02-66.0-31.9)	(0.2-81.4-18.4)	(2.51-74.5-23.0)	(1.7-59.4-38.9)	(2.53-68.9-28.6)
Hornblende	5.8	22.8	trace	3.2	48.7
Biotite	--	.2	1.3	0.3	2.8
Apatite	--	--	trace	--	--
Magnetite	3.9	2.9	2.1	3.0	4.0
Ilmenite	trace	--	--	--	--
Sphene	--	--	--	--	--
Rutile	trace	--	--	--	--
Pleonaste (Hercynite)	--	trace	trace	--	0.8
Talc	--	--	trace	0.5	--
Serpentine	1.1	trace	0.4	--	0.4
Iddingsite	0.2	--	--	--	--
Hematite	--	--	--	--	--
Chlorite	--	--	1.1	0.8	trace
Chlorophaeite	--	trace	--	--	--
Sericite	--	trace	trace	--	--
Epidote	--	--	0.9	trace	trace
Scapolite	--	--	--	--	--
Calcite	--	0.4	--	--	trace

Table 3. Modal analysis (volume percent) for metagabbro.

Sample number	22-66	22-86B	22-199	22-414	22-485
Plagioclase	23.4	36.5	43.8	46.9	12.1
An content	(74)	(73)	(69)	(52)	(57)
Clinopyroxene	--	2.9	0.8	--	--
Hornblende plus actinolite-tremolite	62.5	43.6	45.0	49.6	51.6
Apatite	trace	--	0.4	trace	trace
Magnetite	trace	trace	0.6	2.2	0.4
Ilmenite	trace	--	--	--	--
Sphene	trace	0.2	trace	?	0.3
Biotite	trace	trace	0.2	trace	--
Chlorite	0.2	--	0.6	--	--
Muscovite	0.2	trace	trace	?	--
Sericite	1.3	1.0	0.6	1.3	16.1
Epidote	12.4	15.8	7.8	trace	--
Clinozoisite	--	--	--	--	19.5
Scapolite	--	--	0.2	--	--
Zircon	trace	--	trace	--	trace
Pyrite	--	trace	trace	--	--
Hematite	--	--	trace	--	trace
Allanite	--	--	--	--	--
Calcite	--	--	--	--	--

Table 4. Modal analysis (volume percent) for metaleucogabbro and anorthosites.

Sample number	Metaleucogabbro						Anorthosites	
	22-5	22-137	22-320	22-370	22-417	22-149	22-459	22-318
Plagioclase	62.7	64.7	68.1	70.9	61.1	73.4	91.6	93.2
An content	(71)	(69)	(67)	(75)	(63)	(77)	(64)	(67)
Clinopyroxene	9.9	0.9	2.3	--	--	1.2	--	--
Hornblende plus actinolite-tremolite	25.6	26.0	19.0	25.3	32.2	18.2	2.3	1.3
Apatite	.2	trace	--	trace	trace	trace	--	trace
Magnetite	trace	trace	0.2	trace	trace	0.4	0.2	trace
Ilmenite	trace	?	trace	--	trace	?	--	trace
Sphene	trace	trace	--	--	0.2	trace	--	trace
Biotite	0.4	--	--	trace	--	--	--	--
Chlorite	--	2.0	3.5	trace	trace	0.4	1.8	1.9
Muscovite	0.1	--	1.3	trace	trace	trace	--	trace
Sericite	--	0.5	--	0.9	1.7	trace	3.4	trace
Epidote	0.8	3.5	--	2.9	4.8	4.1	--	--
Clinozoisite	--	--	4.4	--	--	--	0.7	3.3
Scapolite	--	2.2	--	--	--	2.3	--	--
Zircon	--	--	--	--	--	--	trace	--
Pyrite	0.3	--	0.7	--	--	trace	--	trace
Hematite	trace	--	trace	--	trace	--	--	--
Allanite	--	--	--	trace	--	--	--	--
Calcite	--	0.2	trace	--	--	--	--	0.3

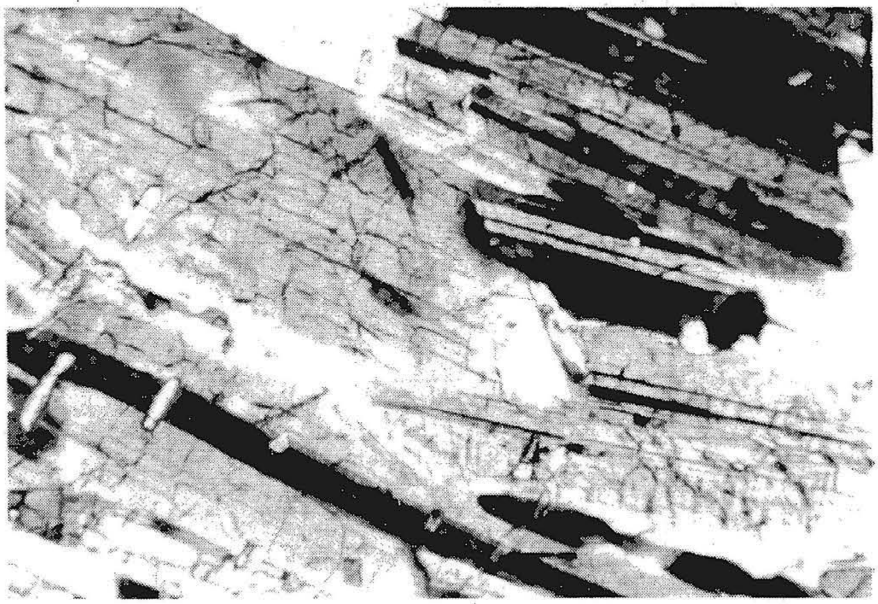
form are most common, but become increasingly more lath-shaped with increasing anorthite content. Inclusions of apatite, amphibole, and iron oxides are abundant. Minute granular hematite (?) inclusions impart a pink to reddish coloration to some plagioclase especially in areas of hybridization. Igneous lamination, formed by the parallelism of tabular plagioclase crystals (Fig. 4), is well preserved in layered units and to a lesser extent in rocks with little or no layering. The alignment of plagioclase probably reflects deposition of crystals from a moving magma, as was suggested by Wager and Brown (1968, p. 23).

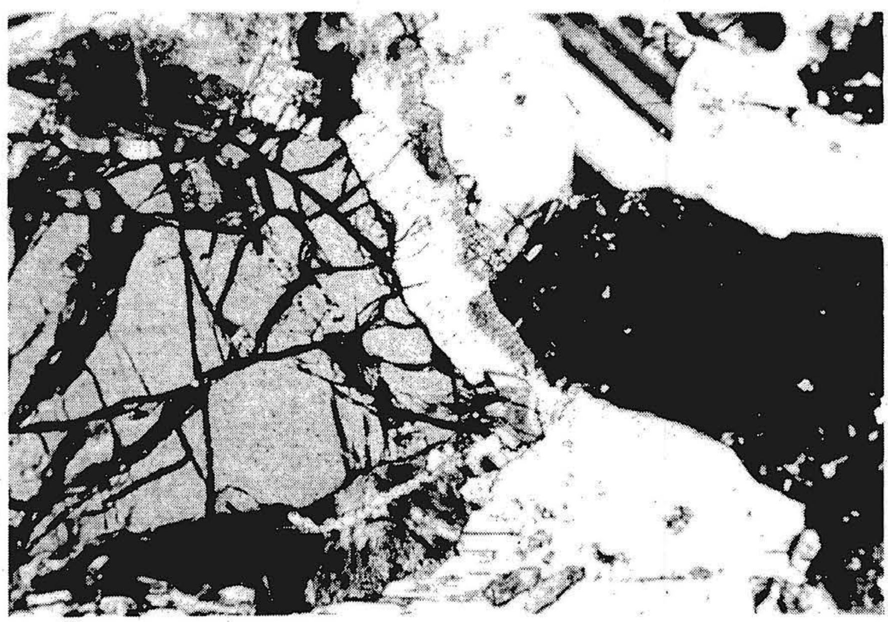
With few exceptions, plagioclase shows well developed twinning, especially in the more calcic varieties. Zoning is quite complex, and normal, reverse and oscillatory zoning was observed; normal zoning is the most evident.

With increased metamorphic grade and shearing, plagioclase shows increased sericitization and/or saussuritization. Over 95% of all thin sections studied show variable degrees of alteration of plagioclase. Secondary products include epidote, clinozoisite, sericite, hydromuscovite (?), clay products, and scapolite. Secondary epidote sometimes forms myrmekitic fringes on plagioclase and may rim entire grains. Scapolite occurs as tiny veinlets cutting plagioclase crystals, as irregular patches, and as a replacement of plagioclase grains in cataclastic rocks.

Fig. 4. Cumulate plagioclase with small apatite inclusions displaying strong igneous lamination. Sample 22-318, crossed nicols, X 79.

Fig. 5. Complex corona rimming olivine. Mineral species from olivine outward are: orthopyroxene - amphibole - fibrous amphibole. Sample 22-470, crossed nicols, X 27.5.





Olivine. Olivine was observed in six thin sections and compositions determined by electron microprobe analysis range from Fo_{81} to Fo_{68} (Appendix, Table 1). The microprobe determinations for four samples fall within limits of allowable error; however, analyses of the other two samples are questionable and are indicated by an asterisk in Table 1 (Appendix). Nearly all olivines show small amounts of manganese and three samples show trace amounts of chromium. The presence of manganese is relatively common in olivine, and represents substitution for magnesium and iron. Small amounts of aluminum present apparently substitute for silicon. The presence of small amounts of chromium may represent spinel inclusions that were not visibly detectable.

Olivine occurs as equigranular anhedral crystals and is generally interpreted as a cumulate phase. Individual grain sizes range from 0.4 mm to 3.7 mm.

Olivine is strongly altered in most samples, and secondary products include magnetite, brownish-red iddingsite, talc, and a colorless to light green serpentine identified as antigorite. Pseudomorphs of serpentine after olivine were found in several altered samples.

Two thin sections containing olivine show well developed complex coronas (Fig. 5). Mineral phases in a corona in sample 22-403 were analyzed by electron microprobe and compositions from olivine outward are as follows: olivine (Fo_{80}), orthopyroxene ($Wo_{0.2}$ $En_{81.4}Fs_{18.4}$), amphibole (composition not determinable), fibrous amphibole (composition not determinable), and plagioclase (An_{76}). Pleochroic orthopyroxene forms small parallel prisms perpendicular to olivine. Amphibole occurs both as an inner rim of small perpendicular prisms and as a tightly woven fibrous mat intergrown with plagioclase. Small, granular, green spinel crystals (hercynite?) occur sporadically in corona amphibole rims. Other coronas are not as complex and generally are composed of orthopyroxene or amphibole rimming olivine.

Pyroxenes. Both orthopyroxene and clinopyroxene were observed in less altered gabbroic phases. Orthopyroxene compositions (Appendix, Table 2) range from $Wo_{2.7}En_{75.4}Fs_{21.9}$ to $Wo_{1.7}$ $En_{59.4}Fs_{38.9}$ and define a hypersthene series (Fig. 6). Clinopyroxene analyses do not show a range, but tend to cluster at approximately $Wo_{44}En_{43}Fs_{13}$ in the augite field (Fig. 6). Orthopyroxene is thought to represent a cumulate phase in all analyzed samples whereas clinopyroxene is considered intercumulate. Thus, pyroxene pairs, even though analyzed from the same sample, do not represent equilibrium phases. Although there are insufficient pyroxene analyses at present to determine a fractionation trend for pyroxenes in the layered sequence, it is evident from Figure 6 that orthopyroxene is deficient in calcium compared with orthopyroxene analyses from other layered mafic intrusions. However, it was noted in four of five samples containing clinopyroxene and orthopyroxene that both pyroxenes show a systematic iron enrichment.

Orthopyroxene occurs as small (0.6 to 3.0 mm) anhedral crystals all of which show pale green to pink pleochroism, light brown coloration and varying degrees of alteration to amphibole. Intercumulate clinopyroxene poikilitically encloses plagioclase, orthopyroxene, and iron oxides in crystals ranging up to seven mm in diameter (Fig. 7). The clinopyroxenes also commonly show variable degrees of alteration to amphibole. Many amphibole crystals retain relict augite cores and the optically continuous poikilitic texture of the primary clinopyroxene phase.

<u>Amphibole</u>. Amphibole occurs in varying proportions in all mafic rocks of the mafic complex. Both primary and secondary alteration phases were observed in thin section. Primary hornblende was found in several thin sections as an intercumulate phase of large optically continuous poikilitic grains enclosing plagioclase and pyroxene. Primary hornblende is optically negative, and shows a pleochroic formula of X = greenish brown, Y = sepia brown, and Z = reddish brown. These hornblende grains are generally partially altered to tremolite-actinolite with some reddish brown rutilated biotite.

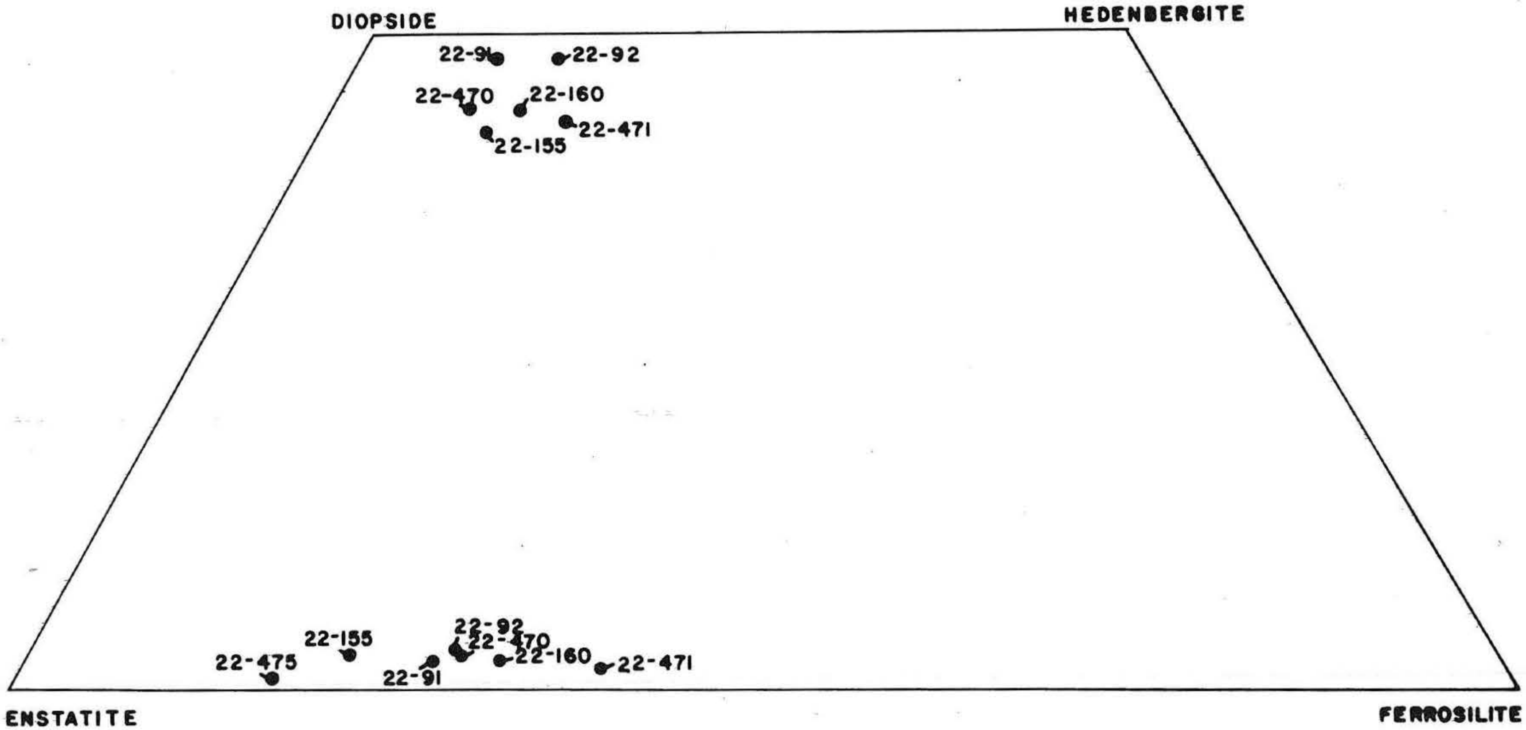


Fig. 6. Electron microprobe analyses of calcium-rich and calcium-poor pyroxenes. Numbers refer to sample number.

Secondary amphibole ranges from small euhedral hornblende prisms enclosed in plagioclase to anhedral fibrous mats of tremolite-actinolite. Relict augite cores are preserved in many samples (Fig. 7), and relict poikilitic textures are commonly retained (Fig. 8). Large relict poikilitic crystals of hornblende may range up to 7.0 mm across. Larger hornblende crystals have been broken down to decussate aggregates in rocks having undergone cataclasis. Relict schiller and diallage structures are commonly preserved. Secondary quartz, from the breakdown of pyroxenes, occurs as rounded blebs poikilitically enclosed in hornblende.

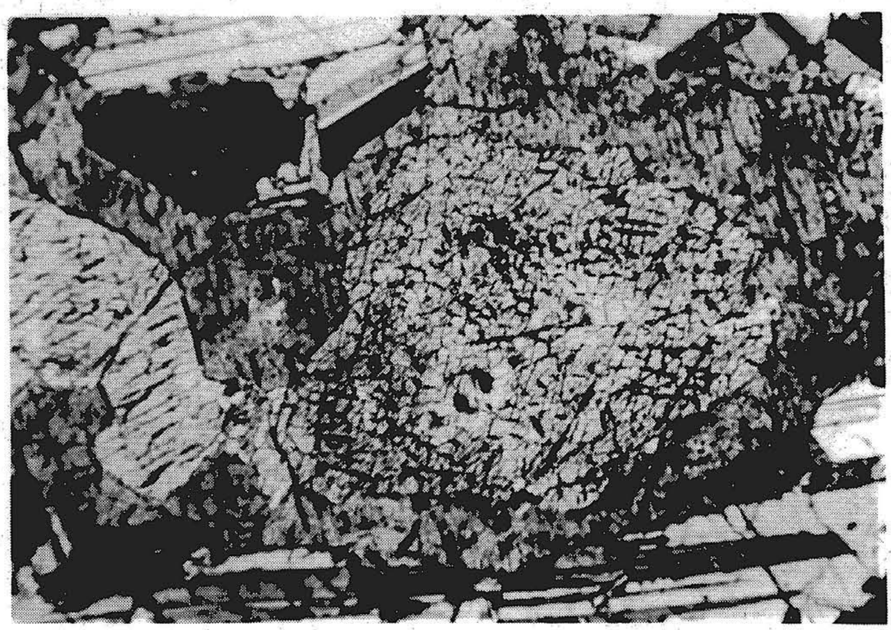
Colorless to light green actinolite-tremolite forms a fibrous rim on many hornblende crystals, and numerous samples show optically continuous crystals with a nearly colorless core rimmed by darker, pleochroic hornblende. Secondary hornblende forms a variety of pleochroic schemes, the most common being:

X = light yellowish green	Y = green	Z = bluish green
X = pale brown	Y = greenish	Z = dark green
X = yellowish green	Y = olivine green	Z = dark green

Blue-green varieties are the predominant type with lesser amounts of brownish varieties. Most amphiboles show incipient alteration to biotite and chlorite.

Fig. 7. Relict pyroxene cores surrounded by amphibole showing schiller inclusions of iron oxides. Sample 22-5, crossed nicols, X 79.

Fig. 8. Optically continuous grain of poikilitic hornblende enclosing plagioclase. Sample 22-496, crossed nicols, X 27.5.



Accessory Minerals. Allanite is a common accessory mineral that occurs as highly pleochroic reddish brown to brown subhedral crystals up to 2.0 mm in diameter. It may be mantled by epidote and sphene, and in some gabbro samples epidote was observed in zoned rims around allanite nuclei.

Secondary biotite is generally found as ragged flakes derived from amphibole. The most common pleochroic schemes for biotite are:

X = light yellow	$Y \simeq Z$ = reddish brown
X = light yellow	$Y \simeq Z$ = light brown
X = light yellowish brown	$Y \simeq Z$ = dark brown

Reddish brown biotite commonly envelopes opaque grains and is thought to have a high TiO_2 content. Several samples show alteration of biotite to light green chlorite. Muscovite was also noted altering from biotite generally along granulated grain margins.

Apatite is present in nearly every thin section studied. Apatite ranges from anhedral to subhedral and grains average 0.2 mm in length. Elongate cigar-shaped crystals as much as 2.0 mm in length were found in leucocratic rocks.

Sphene occurs as euhedral to anhedral crystals that commonly mantle allanite and ilmenite. Granular crystals range up to 2.5 mm in length.

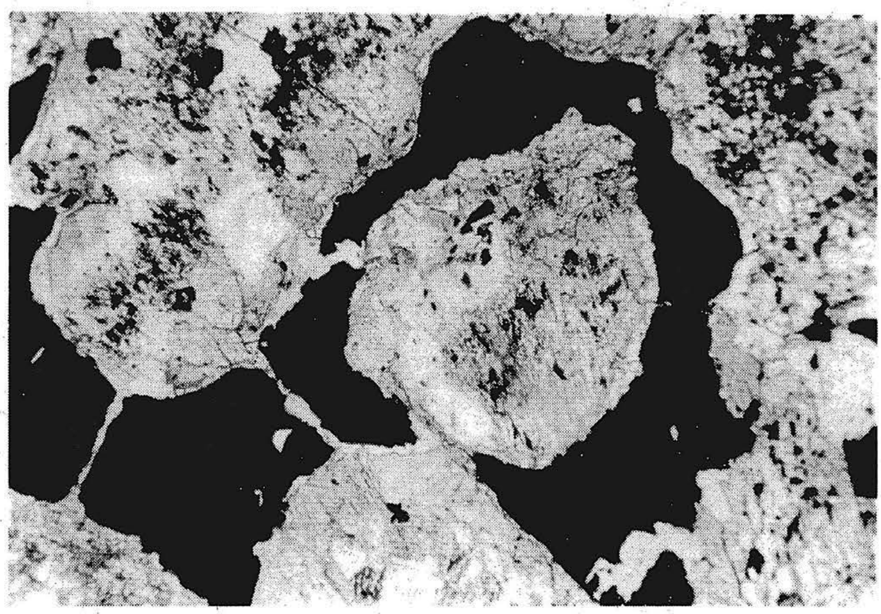
Zircon was observed in only a few thin sections, and it occurs as minute anhedral crystals. Metamict halos in biotite were attributed to zircon inclusions.

Opaque minerals are present in most samples and they were evaluated in reflected light in eight polished sections. Minerals identified in decreasing order of abundance are: magnetite, ilmenite, pyrite, hematite, pyrrhotite, chalcopyrite, and pentlandite.

Magnetite occurs both as an intercumulate phase and as a secondary phase. Intercumulate magnetite is found as anhedral bleb-like crystals partially enclosing plagioclase and hornblende (Fig. 9), and comprises nearly 14% of magnetite-rich metagabbros (Table 3). Exsolution lamellae of ilmenite are generally present in primary magnetite crystals. Secondary magnetite produced from the breakdown of olivine and pyroxenes occurs as small granular to rod-like crystals in the cores of amphibole and pyroxenes, and as irregular fracture-filling veinlets in olivine. Magnetite crystals may be rimmed by pleochroic epidote.

Ilmenite, in addition to forming exsolution lamellae, occurs as dendritic growths and small granular crystals. Ilmenite is commonly altered to pearly white leucoxene and may be rimmed by granular sphene.

Fig. 9. Intercumulate magnetite enclosing hornblende.
Sample 22-418, crossed nicols, X 79.



Pyrrhotite is found as small anhedral grains in less altered gabbros. It is commonly rimmed by pentlandite and irregular exsolution lamellae of chalcopyrite were observed. Chalcopyrite is also found as minute bleb-like crystals randomly disseminated in pyrrhotite.

Pyrite was observed both as cubes and small irregular crystals. Oxidized rims of hematite on pyrite are common. Larger crystals of pyrite (up to approximately 15. mm) are common in more leucocratic gabbroic phases.

Hybrid Rocks

General Features

Gabbroic rocks that were contaminated by felsic intrusives have been termed hybrid rocks in this report (after the usage of Moorhouse, 1959, p. 153). Hybrid rocks generally are found in contact with felsic rocks, but may occur in isolated areas suggesting the presence of underlying felsic rocks or the former presence of felsic rocks that have since been eroded away. Hybrid units are found most commonly in the central part of the study area and along the margins of the Horse Creek granodiorite sill. Metagabbroic rocks that have undergone the most extensive hybridization (i.e., metagabbroic rocks in closest proximity to felsic intrusives) are dark gray to greenish gray, fine grained, generally equigranular, and show development of small macroscopic non-foliated flakes of biotite. Hybrid rocks that have undergone less extensive modifications are medium to fine grained, show a decrease or absence of biotite, and commonly contain light pink to reddish plagioclase. Both varieties of hybrid rocks generally contain abundant closely spaced fractures filled with epidote. Fine grained hybrid phases are similar to metadiabase, and where the ophitic texture of metadiabase has been obliterated, it is extremely difficult to distinguish from fine grained hybridized metagabbro.

North of the study area, Ramirez (1971, p. 31) recognized hybridized mafic phases and divided them into Type A and Type B varieties that are distinguishable both in the field and in thin section. Type A hybrid rocks are those mafic rocks found closest to granitic bodies and which have undergone the most extensive alteration. These rocks are characterized by recrystallization of plagioclase to more sodic andesine, development of biotite, and loss of primary gabbroic textures. Type B varieties retain relict textures and show less alteration of plagioclase, although they appear to be highly altered in thin section. This writer also was able to utilize textural changes and degree of biotite development as criteria for distinguishing hybrid rocks in the field, however, in thin section, every gradation between extensively hybridized rocks to weak development of biotite in metagabbro was observed.

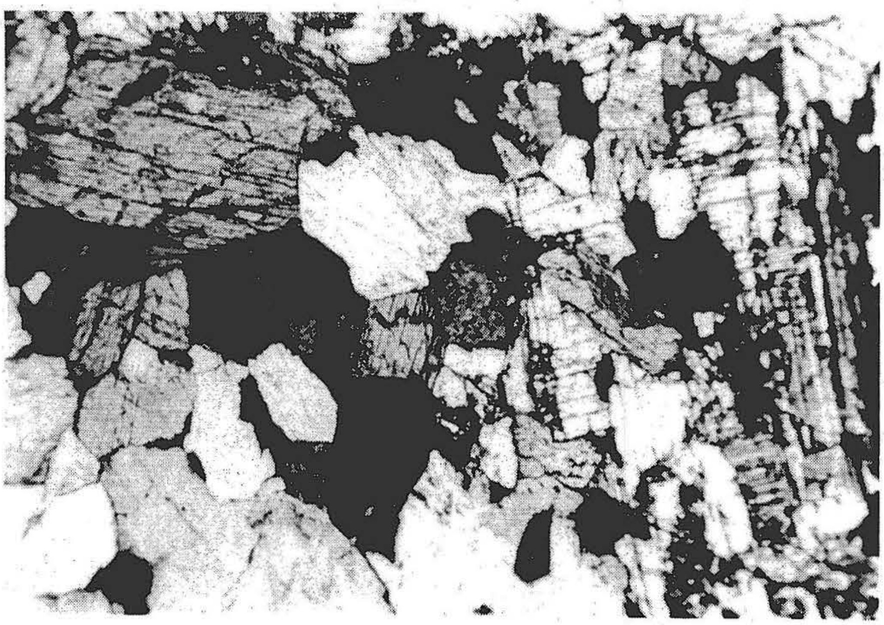
Petrography

Hybridized rocks that have undergone the most extensive modifications show loss of relict gabbroic textures and develop ment of granoblastic texture with poikiloblastic hornblende (Fig. 10). These hybridized rocks grade into gabbroic rocks that show effects of hybridization but retain relict textures and primary igneous mineralogy. Nearly all samples display varying degrees of cataclasis reflected by undulatory quartz, bent feldspar laths, and slight granulation and recrystallization.

Mineral constituents are similar to assemblages in meta-gabbroic rocks that have not undergone hybridization except that biotite and chlorite are increased and the anorthite content of plagioclase is decreased in the hybrid phases. Hornblende and plagioclase form the two predominant mineral phases, and accessory minerals include biotite, chlorite, epidote, sphene, quartz, apatite, scapolite, zircon, magnetite, ilmenite, and pyrite.

Hornblende occurs as anhedral to subhedral grains that are commonly poikiloblastic with quartz, epidote, and sphene inclusions. Grains that contain numerous magnetite inclusions may have a dusty appearance. Many larger grains are recrystallized to decussate aggregates. Hornblende has a number of pleochroic schemes, the most common being:

Fig. 10. Photomicrograph of hybridized metagabbro showing granoblastic texture. Sample 22-493, crossed nicols, X 27.5.



X = pale green Y = green Z = greenish brown

X = pale green Y = green Z = dark green

X = greenish brown Y = brownish green Z = dark green

Many hornblende grains have a light green, nearly colorless core rimmed by much darker hornblende, this zonation may reflect a more calcic core. Hornblende is commonly mantled by pale green actinolite-tremolite in less altered samples, and is variably altered to biotite and chlorite in more intensely altered samples.

Plagioclase is characteristically more sodic than in meta-gabbroic rocks that have not undergone hybridization. Andesine is the prominent variety of plagioclase and anorthite contents range as low as An_{35}. Plagioclase occurs as subhedral to anhedral crystals that are commonly well twinned and normally zoned. Plagioclase of intensely hybridized rock generally appears to be very fresh and normally zoned, whereas less hybridized plagioclase is highly sericited and/or saussuritized, although higher anorthite contents are retained. Several samples show alteration of plagioclase to small granules of scapolite.

Biotite is the most common accessory mineral and is found replacing hornblende in highly hybridized rocks. Biotite shows several pleochroic schemes, the most common being:

Table 5. Modal analyses (volume percent) of hybridized metagabbro.

Sample number	22-452	22-453b	22-454	M-455	22-496	22-556
Plagioclase	5.5	34.0	36.2	46.8	34.4	20.0
An content	(44)	(35)	(37)	(36)	(54)	(35)
Clinopyroxene	--	--	--	--	--	--
Hornblende plus actinolite-tremolite	53.2	49.5	52.8	40.7	56.1	57.5
Apatite	trace	trace	0.5	trace	trace	trace
Magnetite	5.5	trace	0.5	0.5	3.0	0.5
Ilmenite	trace	trace	trace	trace	trace	trace
Sphene	trace	trace	0.5	trace	--	trace
Biotite	2.0	--	2.0	4.5	4.0	3.0
Chlorite	--	1.5	2.0	--	trace	--
Muscovite	--	0.5	--	--	--	--
Sericite	24.3	8.0	1.0	1.0	2.0	3.5
Epidote	9.0	5.5	4.5	2.5	0.5	15.5
Clinozoisite	--	--	--	--	--	--
Scapolite	--	--	--	--	--	--
Zircon	--	trace	--	trace	--	trace
Pyrite	0.5	trace	trace	--	trace	--
Hematite	trace	trace	trace	trace	trace	trace
Allanite	--	--	--	--	--	--
Calcite	--	1.0	--	4.0	trace	--
Quartz	--	1.0	--	4.0	trace	--

X = yellow $\quad$ Y≃Z = reddish brown

X = light yellow $\quad$ Y≃Z = medium brown

Light yellow to light green flakes of chlorite were found as alteration products of biotite and hornblende.

Quartz is most abundant in samples showing the most intense hybridization effects and it occurs as small interstitial grains and small rounded inclusions in hornblende.

Sphene forms anhedral grains with epidote and hornblende, and occurs in granular aggregates surrounding ilmenite.

Apatite occurs as tiny anhedral grains poikilitically enclosed in plagioclase and as larger grains up to 1.5 mm long.

Epidote is found in nearly all hybridized samples and forms poikilitic inclusions in hornblende, as a complete to partial replacement of plagioclase, and in tiny veinlets. Epidote ranges from nearly colorless to bright yellow.

Late Stage Metagabbro

General Features

A coarse grained leucocratic metagabbro constitutes a late stage phase in the central part of the mafic complex (Plate 2). Exposure of this metagabbro is restricted to a few small areas in section 31.

Late stage metagabbro is predominantly a medium grained massive leucocratic rock that is locally melanocratic. It ranges

Table 6. Modal analyses (volume percent) for late stage metagabbro.

Sample number	22-360	22-463	22-478	22-494
Plagioclase	82.2	51.6	45.6	38.3
An content	(69)	(64)	(38)	(55)
Hornblende plus actinolite-tremolite	7.0	16.5	28.0	41.6
Apatite	--	trace	0.2	0.5
Magnetite	0.7	0.4	trace	1.1
Ilmenite	--	--	--	trace
Pleonaste	--	--	--	trace
Sphene	trace	trace	0.4	trace
Biotite	trace	--	3.1	0.7
Chlorite	0.9	--	0.2	0.2
Muscovite	1.1	--	2.4	--
Sericite	3.2	11.9	10.7	7.8
Epidote	4.9	13.7	5.7	5.8
Rutile	--	trace	--	trace
Zircon	--	--	trace	trace
Hematite	--	--	--	trace
Allanite	trace	--	--	--
Calcite	--	trace	--	trace
Clay products	--	5.9	1.7	--

from green to gray and weathers to sub-rounded bouldery outcrops. No layering or other primary structural features were observed, but evidence for forcible intrusion along joint planes in finer grained metagabbro was seen in section 31.

Leucocratic late stage metagabbro is distinguished in the field from other phases of metagabbro by a coarser grained equigranular texture, and a predominantly leucocratic composition. The late stage metagabbro has short, stubby, equant plagioclase crystals as opposed to the smaller lath-like plagioclase crystals found in the more melanocratic metagabbros of the district.

Cross-cutting relations with surrounding metagabbro and limited aerial extent of the late stage metagabbro indicate that it is a relatively minor late pulse of mafic magma that intruded the layered gabbroic sequence. The term "late stage metagabbro" is used as an informal term in this report to distinguish this later phase from the widespread layered metagabbros that are considered to have crystallized from a single intrusive event.

Lack of exposure and close similarity of late stage metagabbro with surrounding metagabbroic phases renders subdivision of the phases impractical at the present map scale. Consequently, over-print symbols are used to distinguish areas of predominantly late stage metagabbro from those of earlier metagabbro.

Petrography

In thin section, late-stage metagabbro is hypidiomorphic to allotriomorphic granular, and exhibits varying degrees of cataclasis. Late stage metagabbro is mineralogically similar to the finer grained metagabbro that it intrudes. It is composed principally of plagioclase and hornblende with accessory biotite, quartz, sphene, apatite, zircon, ilmenite, magnetite, allanite, rutile, and pleonaste. Secondary minerals include sericite, clays, calcite, hematite, quartz, epidote, and muscovite.

Hornblende displays a variety of pleochroic schemes, the most common being:

X = brownish green	Y = green	Z = dark green
X = pale brown	Y = greenish brown	Z = dark green

Pleochroism varies within single crystals and many grains have light bluish green to green cores with darker more strongly pleochroic rims. Zonal variation in pleochroism may reflect more calcic(?) cores. Other samples show partial alteration of hornblende to aggregate rims of fibrous actinolite-tremolite. Relict schiller and diallage structures are preserved locally, and reflect a pyroxene parentage. Secondary magnetite granules commonly riddle cores of amphibole grains. Texturally, amphibole fills angular interstices between plagioclase grains, forming a weak sub-ophitic texture. Many of the amphibole grains are poikilitic with inclusions of apatite, quartz, opaques and sphene. Amphiboles commonly are variably altered to tan and deep-reddish brown biotite.

Plagioclase (An_{39}-An_{69}) is generally medium to coarse grained and occurs as short, stubby, euhedral to anhedral tabular crystals. The plagioclase crystals commonly display albite, carlsbad and pericline twins and show normal zonation. Many grains are extensively sericitized and/or saussuritized.

Two generations of quartz are present. Larger primary anhedral crystals occur interstitial to plagioclase, and smaller rounded anhedral grains that are common along amphibole grain boundaries and intergrown with amphibole, probably formed during the breakdown of pyroxenes.

Other accessory minerals include granular sphene rimming and intergrown with ilmenite, clusters of large anhedral apatite, and large, strongly pleochroic, deep reddish brown to deep brown allanite.

Metapyroxenite

General Features

Metapyroxenite is found throughout the Mullen Creek Mafic Complex, and has been recognized by Reuhr (1961), Ramirez (1971) and McCallum (per. commun., 1977). It occurs both as discrete lenses and layers in the rhythmically layered gabbroic units and as small pods of metapyroxenite apparently not associated with layering. Lenses rarely exceed 10 mm in thickness and one meter in length whereas continuous layers measuring up to one meter in thickness were traced intermittently for approximately 0.4 km. Pod-like bodies range from small elliptical masses three to four meters in length up to masses measuring approximately 20 by 60 meters. A plot of all metapyroxenite pods in the study area indicates a random distribution. No structural patterns were observed to explain the seemingly chaotic occurrences.

Contact relations of metapyroxenite pods with the surrounding metagabbro are generally obscured by the deeply weathered nature of these rocks, and no continuous outcrops with contact relations were observed. However, isolated contact relationships suggest that metapyroxenite grades into coarse grained metagabbro which in turn grades into medium grained metagabbro. Of considerable interest is the ubiquitous presence of metadiabase near metapyroxenite bodies. This relationship is especially prevalent in the eastern part of the study area, but because of limited exposures, no contacts have been observed. In his work north of the study area, Ramirez (1971, p. 10) also noted the absence of clearly defined contact relationships.

The metapyroxenite weathers to a rough, coarse, warty surface that is characteristic of this lithologic unit. Weathered surfaces are dark green to dark gray, whereas fresh surfaces are dark greenish gray to light gray.

Petrography

In thin section, metapyroxenite shows a relict allotriomorphic to hypidiomorphic texture, and contains rare large poikilitic grains of secondary amphibole after pyroxene. Major mineral constituents include amphibole, talc, chlorite, serpentine, and magnetite, with accessory biotite, muscovite, sphene, ilmenite, epidote, apatite, hematite, pyrite, pyrrhotite(?), sericite, plagioclase, and rutile (Table 7).

Amphibole ranges from dark hornblende with a pleochroic formula of Z = pale brown, Y = greenish and Z = dark green, to light green to colorless actinolite-tremolite. Actinolite-tremolite commonly rims darker hornblende. Amphiboles may be recrystallized to fine-grained decussate aggregates, that in turn have been variably altered to tan, greenish brown, and reddish brown biotite, pale green to light yellow chlorite, and aggregates of talc. Small magnetite granules, generated from the breakdown of original pyroxenes, occur throughout the amphibole grains and are commonly concentrated in the colorless cores.

Table 7. Modal analyses (volume percent) for metapyroxenite.

Sample number	22-195	22-203	22-256	22-400	22-495	22-508
Plagioclase	7.3	--	4.2	trace	--	--
An content	(64)	--	ND	ND	--	--
Clinopyroxene	--	--	--	--	2.0	--
Hornblende plus actinolite-tremolite	86.5	56.3	71.5	67.5	64.7	72.2
Biotite	0.8	trace	0.3	--	--	--
Chlorite	3.7	29.1	20.6	27.3	29.2	25.5
Magnetite	trace	0.8	trace	0.8	3.9	1.7
Ilmenite	0.1	--	--	trace	trace	--
Sphene	trace	--	trace	trace	trace	trace
Epidote	trace	--	trace	1.8	--	--
Apatite	0.3	--	trace	trace	0.2	--
Muscovite	0.5	--	--	--	--	--
Pyrite	--	trace	trace	--	--	--
Pyrrhotite	--	--	trace	--	--	--
Hematite	trace	trace	trace	trace	trace	trace
Rutile	--	--	--	--	--	trace
Sericite	--	--	7.4	--	--	--
Allanite	trace	--	--	--	--	--

ND denotes composition not determinable.

Plagioclase occurs as a minor mineral constituent in some metapyroxenites (Table 7). Plagioclase ranges from subhedral to anhedral grains in up to 1.5 mm lengths. These grains are commonly altered to sericite and epidote, thus composition determinations are difficult to impossible. A few grains retain relict normal zoning.

Ilmenite occurs as small discrete granules and as skeletal dendritic crystals. Small granules of sphene sometimes rim the ilmenite.

Apatite is subhedral to euhedral and occurs as minute equant grains or elongate crystals measuring 0.1 to 1.0 mm.

In addition to secondary magnetite after pyroxene, larger anhedral grains are also commonly present. Other opaque minerals include small cubes of pyrite and rare pyrrhotite (?).

Metadiabase

General Features

Metadiabase was observed throughout the study area, and is especially common in the western half of the district. Complex cross-cutting relationships characterize the metadiabase (e.g. metadiabase was observed cross-cutting metagabbro and being cross-cut by metagabbro). A fine grained chill margin was observed in several outcrops, indicating intrusion into the gabbro host. In all cases, contact relationships indicate that both mafic phases were plastic during intrusion (i.e. all contacts are irregular and show plastic deformation). Cross-cutting relations were not observed between metadiabase and other mafic phases because of poor exposure.

Metadiabase is dark gray to dark greenish gray in weathered surfaces, and dark greenish gray to bluish gray on fresh surfaces. Outcrops generally weather to sharp angular blocks defined by closely spaced joints.

Metadiabase is mineralogically similar to metagabbro although texturally it characteristically retains a fine grained ophitic fabric that is readily recognizable in the field. The close similarity of metadiabase with fine-grained hybrid phases of metagabbro makes it difficult to discern metadiabase in areas of hybridization. Hybridization of metadiabase was also observed and this is reflected by development of macroscopically recognizable biotite, reddish coloration of plagioclase, and decreased anorthite content in plagioclase. Weakly hybridized metadiabase generally retains a weak relict ophitic texture which can be recognized in close inspection.

Petrography

Metadiabase closely resembles finer-grained phases of metagabbro both mineralogically and texturally. Metadiabase is generally characterized by a well preserved ophitic to subophitic texture, elongate plagioclase laths, the presence of minor amounts of primary (?) quartz, and a more sodic plagioclase than occurs in metagabbro. Large relict poikilitic grains of hornblende can be distinguished easily in hand sample.

Metadiabase is composed primarily of hornblende and plagioclase, with lesser amounts of actinolite-tremolite, epidote, biotite, and quartz, and accessory amounts of chlorite, apatite, sphene, magnetite, pyrite, relict clinopyroxene, rutile, sericite, zircon, allanite, and scapolite (Table 8).

Hornblende occurs in a variety of pleochroic schemes, the most common being:

X = brown	Y = light green	Z = blue-green
X = yellowish-green	Y = green	Z = blue-green

Light pale green to colorless actinolite-tremolite is generally present, replacing hornblende. Amphibole grains are commonly crowded with inclusions of iron oxides, quartz and apatite. Symplectic intergrowths of hornblende and quartz were noted, and with increasing quartz content, hornblende forms sponge-like grains enveloping quartz. Schiller structure and relict diallage is preserved in some samples. Where there is little evidence of cataclasis, hornblende occurs as large relict poikilitic grains up to 7.0 mm in diameter (Figure 11), some of which contain relict cores of clinopyroxene. Where effects of cataclasis are prominent, poikilitic grains have been recrystallized to finer grained decussate aggregates. It was noted that hornblende crystals that

Fig. 11. Relict poikilitic texture in metadiabase. Plagioclase grains are set in an optically continuous grain of hornblende. Sample 22-212, crossed nicols, X 79.

have not undergone extensive recrystallization commonly are crowded with iron oxide inclusions, whereas recrystallized grains have fewer iron oxide inclusions.

Plagioclase ranges from stumpy anhedral grains to subhedral laths. It is generally normally zoned with rims consisting of clear albite (?). Laths are generally randomly oriented and show varying degrees of saussuritization and sericitization, sericite, hydro-muscovite(?), and granular to prismatic epidote and clinozoisite are present locally. The more calcic cores commonly have a dusty appearance caused by inclusions of granular and rod-like iron oxides.

Biotite was found in nearly every sample studied (Table 8), and all appears to be an alteration product of hornblende. Biotite occurs as anhedral flakes in various reddish brown to bluish green pleochroic schemes. Metamict halos surrounding inclusions of zircon were observed in several thin sections. Light green chlorite with anomolous blue birefringence occurs as a local alteration product of biotite, and, more rarely, as an alteration product derived directly from hornblende.

Primary (?) quartz is present as irregular grains interstitial to plagioclase in approximately one-half of the thin sections studied. Secondary quartz occurs as smaller, rounded to irregular grains in hornblende, and is apparently derived from the breakdown of

Table 8. Modal analyses (volume percent) for metadiabase.

Sample number	22-61	22-77	22-123	22-282	22-477a	22-507
Plagioclase	38.6	28.6	42.6	27.3	19.4	36.9
An content	(50)	(46)	(58)	(68)	(45)	(51)
Hornblende plus actinolite-tremolite	51.7	56.1	35.9	55.1	61.3	53.1
Clinopyroxene	--	--	--	trace	--	--
Biotite	6.2	9.0	10.2	8.9	--	0.4
Apatite	trace	0.5	0.6	0.2	0.6	0.4
Magnetite	0.6	0.5	trace	0.2	trace	3.0
Ilmenite	--	--	--	--	--	trace
Pyrite	--	--	--	--	--	0.4
Hematite	--	--	--	--	--	0,3
Sphene	trace	--	trace	trace	trace	0.1
Rutile	--	--	--	trace	--	--
Chlorite	--	--	--	6.0	0.9	--
Sericite	1.2	1.1	1.5	2.5	9.5	3.2
Epidote	trace	3.4	4.7	1.2	7.7	0.7
Quartz	2.3	2.0	5.0	trace	0.6	0.6
Zircon	trace	trace	trace	--	--	--
Allanite	trace	trace	--	trace	--	--
Scapolite	--	--	--	--	--	1.0

pyroxenes. Quartz in samples having undergone cataclasis shows increased undulatory extinction and recrystallization.

Allanite occurs as trace amounts in nearly all samples studied. Skeletal grains, rods, and almond shaped allanite crystals may attain lengths of 0.5 mm.

Opaque minerals include magnetite, ilmenite, and pyrite. Magnetite occurs as large irregular anhedral grains, and as small granular inclusions in hornblende. Pyrite grains are quite small, rarely exceeding 0.5 mm, and generally have partially oxidized rims.

Other accessory minerals include granular sphene, apatite and scapolite. Sphene generally occurs as small granules, sometimes mantling ilmenite, but larger grains exceeding 2.0 mm in length were observed. Apatite is present as tiny anhedral to subhedral crystals. Scapolite occurs in small irregular patches as an alteration product of plagioclase and as tiny veinlets cutting plagioclase crystals.

Metabasalt Dikes

General Features

Narrow metabasalt dikes are found throughout the study area (Plate 2) and some may be traced intermittently for over two miles (3 km). With the exception of three dikes, all trend approximately N60°E and are nearly vertical. Although mineralogically and texturally similar, the dikes represent at least two stages of emplacement, both pre-dating and post-dating the Horse Creek granodiorite. Younger felsic intrusives cross-cut both generations of mafic dikes.

The metabasalt dikes generally display a fine grained ophitic texture which is readily recognizable in the field. Dikes range from three to twenty-two feet (1 to 6.5 meters) in thickness, and form discontinuous outcrops with slight positive relief. Outcrops are characteristically dark greenish gray to dark olive green and weather to tough angular fragments. Fine grained chill borders were recognized along some dike boundaries.

A metabasalt dike in sections 35 and 36, west of the North Platte River, is slightly more porphyritic than nearby dikes. The porphyritic nature of this dike gives the rocks a mottled appearance that is strikingly similar to hybrid metagabbro. There were no observed cross-cutting relationships between this dike and other dike rocks.

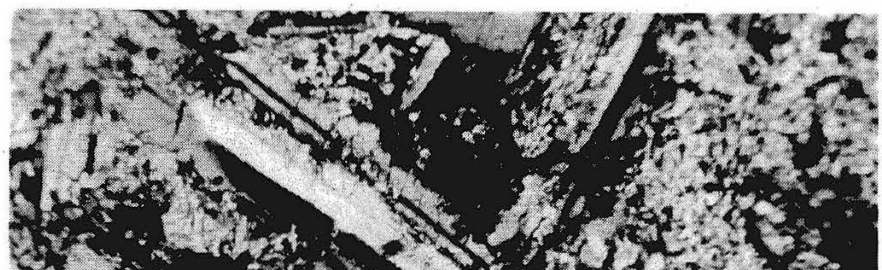
Petrography

Metabasalt dike samples are generally fine grained, holocrystalline, and range from porphyritic to equigranular. The meta-igneous dikes are composed predominantly of hornblende and plagioclase, with lesser amounts of chlorite and opaque minerals along with accessory amounts of sericite, epidote, sphene, biotite, apatite, quartz, rutile and muscovite.

Hornblende may have variable pleochroic schemes, but it is generally a blue-green uralitic variety that essentially shows the scheme X = greenish yellow, Y = green, and Z = blue-green. Colorless to light green actinolite-tremolite commonly rims many hornblende grains. Hornblende occurs in fine-grained decussate aggregates and as large relict poikilitic crystals after pyroxene. Schiller structures may be preserved, and inclusions of iron oxides, quartz, and epidote are common. In two samples, colorless to pale green actinolite-tremolite have partially replaced plagioclase with needle-like crystals that project into plagioclase, giving it a ragged appearance.

Plagioclase occurs as anhedral to subhedral crystals, ophitically to subophitically enclosed by amphibole. Two generations may be present; calcic phenocrysts (An_{56-71}) up to 4.0 mm in length and more sodic groundmass crystals (An_{39-58}). Rare euhedral phenocrysts up to 1.2 cm long were observed in the field. Groundmass plagioclase laths rarely exceed 1.0 mm in length. All plagioclase crystals are generally well twinned, especially in more calcic members. Crystals are generally zoned normally although oscillatory zoning may predominate locally. Albite (?) rims are not uncommon, and occur as thin clear overgrowths on well twinned grains. Although plagioclase crystals are generally randomly oriented, several samples show a weakly developed bostonitic fabric (Fig. 12).

Fig. 12. Relict bostonitic fabric preserved in metabasalt dike sample. Sample 22-456, crossed nicols, X 79.



Plagioclase typically shows incipient alteration to sericite and epidote. Secondary products commonly are restricted to calcic cores which may show a dusty appearance caused by tiny inclusions of iron oxides (?).

The porphyritic dike west of the North Platte River is similar mineralogically (Table 9, sample 22-424), but has stumpy anhedral phenocrysts of plagioclase that are intergrown glomeroporphyritically.

Biotite occurs as deep reddish brown to light reddish brown anhedral flakes altered from amphibole. Chlorite forms large feathery clots, generally formed after biotite.

Epidote, and less commonly clinozoisite, occur after plagioclase. Epidote also is present mantling magnetite grains.

Other accessory minerals include skeletal ilmenite in hornblende, pyrite with partially oxidized rims, sphene, apatite, quartz, leucoxene, rutile and muscovite.

Felsic Rocks

General Statement

Two distinct episodes of felsic intrusive activity are identified in the study area. These events are represented by the following units: (1) Horse Creek granodiorite and (2) Younger Felsic intrusives.

Table 9. Modal analyses (volume percent) for metabasalt dikes.

Sample number	22-47	22-290	22-371	22-424	22-488	22-493A
Plagioclase	27.5	23.3	30.4	40.1	25.4	30.3
An content*	(55)	(54)	(51)	(71-54)	(64-58)	(57-39)
Hornblende plus actinolite-tremolite	61.1	72.5	68.3	52.9	71.4	60.1
Apatite	trace	--	trace	trace	trace	trace
Magnetite	--	1.0	1.3	3.2	1.5	2.0
Pyrite	--	--	--	--	trace	trace
Sphene	--	trace	--	--	trace	trace
Biotite	3.2	0.4	--	0.2	1.4	3.9
Chlorite	5.5	1.3	trace	--	--	0.6
Muscovite	--	--	--	trace	--	--
Sericite	0.8	1.4	--	2.7	trace	1.9
Epidote	trace	0.1	--	0.6	trace	0.3
Quartz	--	--	--	--	--	0.6
Rutile	--	--	--	--	trace	--

*First number is An content of phenocrysts, second number is groundmass. Single number refers to samples with a single generation of plagioclase.

The felsic units are distinguished in the field by the following criteria:

(1) Horse Creek granodiorite; distinguished from other felsic units on the basis of a fine to medium grained equigranular texture, the presence of only minor amounts of muscovite, weak to moderate foliation and irregular contacts with mafic units. Hybridized mafic rocks commonly border granodiorite bodies.

(2) Younger Felsic intrusives; range in composition from alkali granite to granodiorite, are coarser grained and more massive than foliated granodiorite and commonly have small randomly distributed clots of biotite. Occurrences range from irregular bodies to small elliptical shaped masses that are approximately three to five times longer than their width. Included in this group are a series of coarse grained pegmatitic phases and biotite-epidote quartz monzonite intrusives in the western part of the study area. Pegmatites are thought to correlate with the conformable type of pegmatites described by Houston (1961). Hybridization of surrounding mafic rocks is sporadic, but the emplacement of Younger Felsic phases has definitely contributed to the local development of hybrid mafic phases.

As with mafic rocks in the region, there are gradations in composition and texture between the different felsic units and distinctions between units is sometimes difficult.

Age relations between the various felsic units are largely unknown as very few cross-cutting relationships could be observed. Younger felsic units were observed cutting Horse Creek granodiorite and biotite-epidote quartz monzonite. No cross-cutting relations were observed between pegmatitic phases and other felsic units or between biotite-epidote quartz monzonite and Horse Creek granodiorite. According to Houston and others (1968), the majority of cross-cutting and conformable pegmatites were introduced at approximately the time of formation of granite and quartz monzonite in the region.

Horse Creek Granodiorite

General Features

Horse Creek granodiorite underlies the eastern part of the study area in sections 7, 8, 17, 18, 19, and 20 of T14N, R80W. The granodiorite is part of a large irregular sill-like felsic intrusion. Smaller granodiorite bodies along the eastern margin of the mafic complex and in the east central part of the study area are believed to be satellites of this main granodiorite body (Plate 2). The structural nature of the granodiorite in the study area is difficult to evaluate because of limited exposures. McCallum (per. commun., 1977) has mapped the entirety of the main granodiorite body, and suggests that it is a synanticlinal sill with a predominantly shallow plunge to the northwest (Plate 1). Limited attitudes near the granodiorite-mafic complex contact indicate that the sill conformably (?) overlies the mafic body, but because of refolding, it now plunges steeply beneath the metaigneous mafic complex (Plate 1). Horse Creek granodiorite intrudes quartzofeldspathic and hornblende gneiss east and south of the study area, and large xenoliths and lenses of gneiss occur near the granodiorite-mafic complex contact (see description of hornblende-andesine-quartz gneiss). Contacts with gneissic xenoliths are commonly gradational and indicate a high degree of assimilation and/or replacement of the gneissic members. Small xenoliths of gneiss are particularly abundant east of the Golden Key Mine (Plate 2).

Horse Creek granodiorite is characteristically medium to fine grained, light gray to pink, and usually shows a weak to moderate primary foliation imparted by the alignment of biotite and lesser amounts of muscovite. Small pegmatitic phases are present locally. The unit has undergone extensive cataclasis, and wispy layers of biotite wrapping around felsic porphyroclasts impart a weak to strong secondary foliation that commonly obliterates the original fabric.

No contacts were observed between the Horse Creek granodiorite sill and mafic rocks, although host units are hybridized and silicified near covered granodiorite-mafic rock contacts. Intrusive breccias and mafic xenoliths commonly occur along margins of smaller bodies of Horse Creek granodiorite. Contacts between granodiorite and Younger Felsic units are also seldom seen and where observed, the Younger Felsic units cut the granodiorite.

Petrography

The Horse Creek granodiorite displays a hypidiomorphic granular texture with variable degrees of cataclasis. Mortar texture is prevalent in many samples, and strained quartz and potash feldspar, along with strained and bent plagioclase, and potash feldspar are the principal constituents (Table 10), and are accompanied by lesser amounts of muscovite, biotite, and accessory epidote, clinozoisite, sphene, magnetite, ilmenite, leucoxene, sericite, clay, and allanite. A triangular diagram showing modal compositions is shown in Figure 13.

Anhedral orthoclase is the predominant potash feldspar in rocks showing little or no deformation, but microcline content increases with increased cataclasis. Orthoclase is typically perthitic with flame-like intergrowths of albite.

Plagioclase (An_{26-41}) is characteristically poorly twinned and has thin rims of clear untwinned albite (?) mantling the normally zoned grains. With increased cataclasis, albite twinning is obliterated and degree of granulation increases along grain boundaries. Saussuritization and/or sericitization is ubiquitous. Various clays, sericite,

Table 10. Modal analysis (volume percent) for Horse Creek granodiorite.

Sample number	22-97	22-98	22-122	22-182	22-235	22-238	22-328	22-450	22-476	22-483
Quartz	30.8	29.4	28.9	33.0	31.6	26.0	32.1	32.5	26.7	28.3
K-feldspar	19.6	21.2	10.7	17.6	13.5	6.3	14.6	22.4	16.2	11.5
Plagioclase	39.0	36.6	41.8	37.1	44.3	43.6	40.9	34.6	35.3	46.6
An content	(26)	(26)	(37)	(37)	(28)	(41)	(34)	(34)	(31)	(27)
Hornblende plus actinolite-tremolite	trace	--	--	--	--	--	--	--	--	--
Biotite	7.3	6.3	12.8	7.8	6.4	18.2	7.7	2.8	11.8	11.5
Apatite	trace	trace	trace	trace	trace	trace	trace	--	trace	trace
Zircon	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace
Sphene	trace	trace	1.0	trace	--	0.6	0.4	--	trace	0.4
Rutile	--	--	--	--	--	--	--	--	--	trace
Allanite	--	--	--	--	--	--	trace	trace	trace	--
Magnetite	0.6	2.4	0.5	0.2	--	2.2	1.1	trace	1.1	0.4
Garnet	--	--	--	--	--	--	--	--	--	--
Muscovite	0.3	1.6	1.3	1.9	3.0	0.4	1.9	1.6	0.4	1.0
Chlorite	trace	trace	--	--	trace	--	--	0.7	0.6	trace
Sericite	trace	trace	--	trace	trace	--	trace	2.4	6.9	trace
Epidote	2.4	2.6	3.0	2.4	1.2	2.7	1.3	3.1	1.0	0.4
Leucoxene	--	--	--	--	--	trace	--	--	--	trace

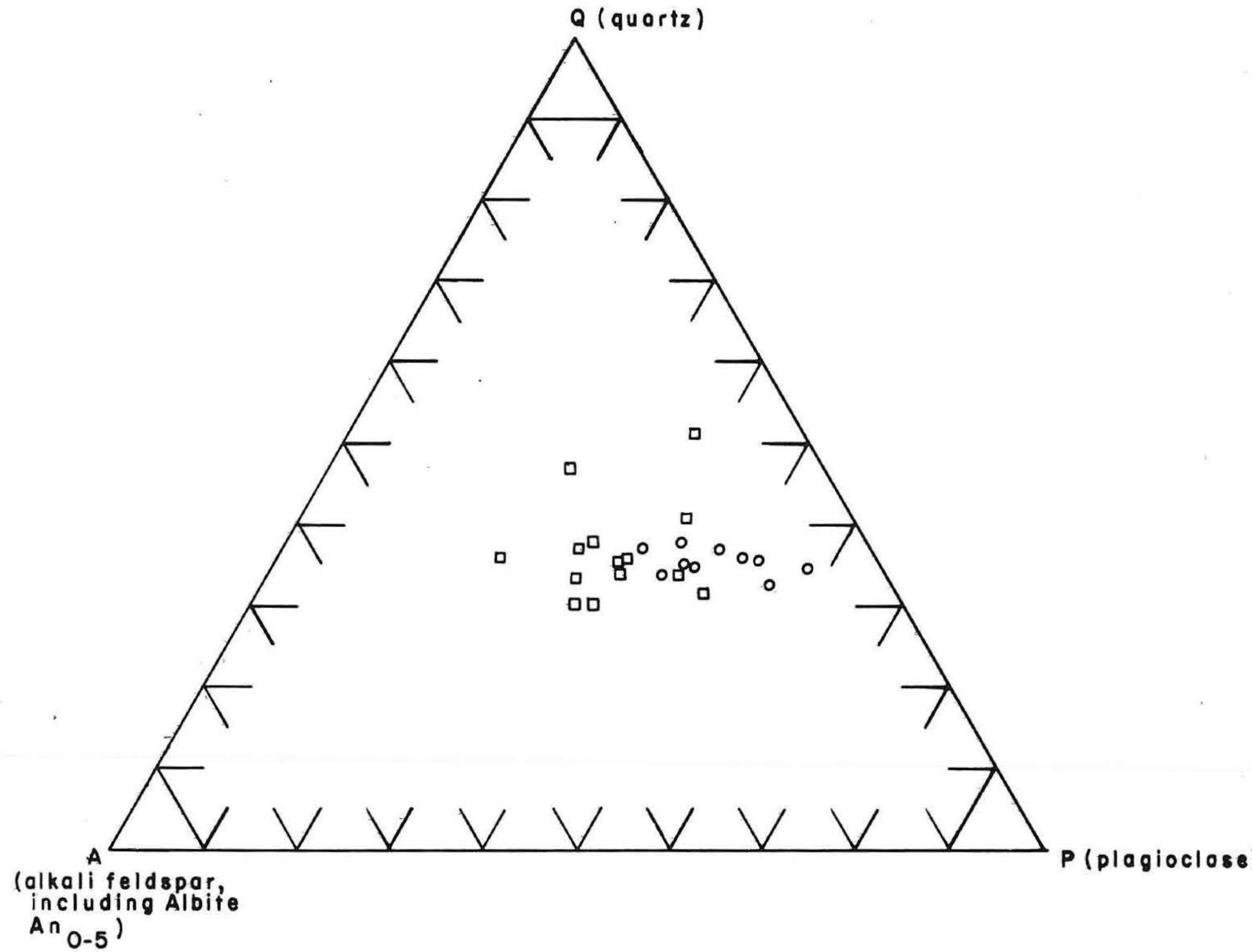


Fig. 13. Triangular diagram showing model compositions of felsic rocks in the study area. Squares represent Younger Felsics and circles show Horse Creek granodiorite compositions.

epidote, clinozoisite, and hydro-muscovite (?) pervade the calcic cores of altered grains.

Quartz displays undulatory extinction in all samples studied. Most porphyroclasts of quartz have recrystallized to fine grained aggregates. In more severely sheared phases, quartz forms small lenses of recrystallized grains with moderately developed triple point grain boundaries.

Biotite occurs as anhedral flakes that impart a weak to moderate foliation. The most common pleochroic schemes are: X = light brown, Y≃Z = greenish-brown, and X = yellowish brown, Y≃Z = reddish brown. Many biotite flakes have deep red lamellae of hematite. Alteration of biotite to light green chlorite was observed in several samples.

Other accessory minerals include euhedral to anhedral granules of epidote and clinozoisite, granular sphene rimming ilmenite, magnetite, and allanite (up to 0.3 mm and commonly rimmed by epidote).

Accompanying increased cataclasis are increases in development of perthite, cataclastically induced formation of microcline, strained and recrystallized quartz, and alignment of biotite and muscovite, and alteration of plagioclase.

Younger Felsic Intrusives

General Features

Numerous small highly irregular bodies and small dikes of felsic igneous rocks occur throughout the study area. Similar felsic rocks mapped by Ramirez (1971) north of the study area have been termed Younger Felsics. Comparable rocks south of the study area and in the southwest part of the study area were mapped by Ruehr (1961) as granite gneisses. Pegmatitic phases west of the North Platte River have been included in this unit and are thought to represent rocks correlative with Big Creek Pegmatites (Houston, 1961).

Although the majority of younger felsic igneous rocks are confined to large irregular masses, many of the bodies are small and lenticular. Lenticular bodies preferrentially strike in a northeasterly direction (Plate 2). The largest younger felsic bodies are quite irregular and emplacement control is uncertain. However, a number of younger felsic bodies appear to have been emplaced along pre-existing faults, and some have been sheared during subsequent episodes of reactivation. Pegmatitic phases in the western part of the study area are dike-like and generally strike approximately N60°E. Emplacement of these phases appears to be predominantly joint controlled.

Medium to coarse grained quartz monzonite comprises the bulk of this unit although granodiorite and lesser amounts of granite are present (Table 11). Several occurrences of foliated biotite-epidote

Table 11. Modal analyses (volume percent) for younger felsic intrusives.

Sample number	22-243	22-298	22-337	22-356	22-404	22-415	22-431	22-447	22-467	22-490	22-501	22-503	22-510	22-561
Quartz	29.1	31.4	35.8	30.8	32.3	29.5	30.0	43.6	42.4	48.6	32.2	34.5	32.0	35.2
K-feldspar	34.0	24.3	30.7	20.5	33.1	32.5	20.0	26.0	10.8	0.7	26.1	38.8	27.0	28.1
Plagioclase	33.8	33.0	31.5	39.6	32.5	36.1	44.8	24.5	31.5	47.8	34.1	23.6	36.1	30.9
An content	(38)	(34)	(34)	(31)	(33)	(26)	(32)	(34)	(29)	(28)	(31)	(27)	(27)	(33)
Biotite	1.6	5.7	0.2	4.3	trace	0.3	0.6	5.2	12.9	trace	0.7	0.4	4.0	1.6
Apatite	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace
Zircon	--	trace	trace	trace	trace	trace	--	trace	trace	trace	trace	trace	trace	trace
Sphene	0.2	0.2	trace	trace	trace	--	0.2	0.2	trace	trace	trace	trace	trace	trace
Rutile	--	--	--	--	--	--	--	--	--	--	trace	--	trace	trace
Allanite	--	trace	trace	trace	--	trace	--	trace	--	--	--	trace	--	--
Magnetite	0.6	0.9	0.8	0.6	0.1	0.1	trace	0.3	0.4	0.5	0.3	0.9	0.4	trace
Muscovite	0.3	2.7	0.8	2.6	1.5	1.5	4.4	0.2	1.8	1.2	4.6	1.2	0.5	2.2
Chlorite	trace	--	trace	--	trace	trace	--	--	trace	trace	0.7	0.6	trace	0.8
Sericite	trace	trace	trace	--	trace	trace	trace	trace	trace	0.5	trace	--	--	trace
Epidote	0.3	1.7	trace	1.6	0.4	trace	--	0.2	trace	0.7	1.1	trace	trace	1.2
Leucoxene	trace	trace	--	--	--	--	trace	--	--	--	--	--	--	--

quartz monzonite were observed in section 32. Aplitic and coarse grained pegmatitic phases are present locally. Outcrops are more resistant than the surrounding mafic country rock and range from rounded bouldery blocks to tombstone-shaped slabs that have developed in more strongly foliated and jointed phases. Fresh surfaces range from red to pinkish-white to gray , and various shades of white, buff and orange prevail locally. In hand sample, younger felsic rocks are characterized by a medium to coarse grained texture with small clots of biotite and muscovite. Although most of the younger felsic rocks are non-foliated, weak to moderate foliations of predominantly cataclastic origin are present locally.

Contact relationships with mafic rocks are generally sharp and intrusive breccias and inclusions of mafic rock in younger felsics were noted at a number of localities. Contact effects of younger felsic intrusives on the mafic country rock are quite extensive and widespread hybridization is prevalent immediately adjacent to many of the felsic bodies. Where younger felsic rocks reflect a high degree of assimilation of the host mafic units, distinction between Horse Creek granodiorite and younger felsic phases is difficult.

Petrography

Younger felsic intrusives are characterized by allotrimorphic to hypidiomorphic granular textures and exhibit varying degrees of cataclasis. Porphyritic textures prevail locally. Cataclastic effects range from strained quartz and slightly bent mica platelets to well developed mortar texture accompanied by bent, cracked, and strained porphyroclasts of potash feldspar and plagioclase.

Principal mineral constituents are quartz, plagioclase, and potash feldspar (Table 11). Predominant accessory minerals include biotite, muscovite, epidote, sphene, and magnetite with traces of allanite, hornblende, sericite, rutile, leucoxene, apatite, and zircon (Table 1). Figure 13 shows variation in modal compositions.

Potash feldspar occurs as anhedral to subhedral crystals of orthoclase and microcline, microcline being the predominant phase in samples having undergone more extensive cataclasis. Individual grains of potash feldspar range up to 3.0 mm and grain boundaries are commonly granulated. Porphyroclasts (1-3 mm) set in a fine-grained granulated matrix are locally abundant. Potash feldspar is generally perthitic with fine to coarse bead and string type intergrowths of albite. Some inclusions of rounded quartz grains and dusty plagioclase were noted. Myrmekitic intergrowths between potash feldspar and plagioclase are also common.

Plagioclase (An_{26-38}) occurs as subhedral to anhedral crystals, and prominent lath shaped grains are restricted to more calcic varieties. Plagioclase crystals are normally zoned, the outer zones consisting of clear untwinned albite. Large plagioclase grains generally show some degree of granulation, and several samples show large relict outlines of grains that apparently were crushed and the finer grained aggregates were recrystallized to untwinned albite. Antiperthite was noted, and partial replacement by microcline is common where skeletal plagioclase crystals are surrounded by microcline. Saussuritization and/or sericitization is widespread, and coarse grained sericite and clays have developed in the more calcic cores of the normally zoned crystals.

Two generations of quartz are present in the younger felsic rocks. Older grains are larger and show undulatory extinction, whereas younger grains are small and embay and replace other minerals. Quartz occurs as anhedral strained crystals in less deformed samples, and is granulated and recrystallized in train-like aggregates in intensely deformed samples.

Biotite occurs as anhedral ragged flakes with muscovite, chlorite, epidote, and magnetite in small isolated clot-like aggregates. Biotite ranges from deep reddish brown to deep green, the most noted pleochroic formulas being: X = yellowish green, $Y \simeq Z$ = dark green, and X = yellow, $Y \simeq Z$ = brown. Much of the biotite has altered to green chlorite which may include small lenses of dark granular sphene.

Strongly pleochroic epidote may be observed rimming magnetite. Rare clinozoisite is a product of the breakdown of plagioclase.

Minor accessory minerals include small subhedral to euhedral apatite, zircon, magnetite, hematite, and yellowish brown to deeply pleochroic reddish brown allanite. Allanite is commonly rimmed by epidote.

QUATERNARY DEPOSITS

General Statement

Quaternary deposits in the area consist predominantly of alluvial and colluvial mixtures in stream drainages. Small talus slope deposits in the western part of the study area have been included with the colluvium map unit.

Alluvium

Alluvial clays, sands, gravels, and cobble and/or boulders occupy most stream valleys. Areas of moderate to low relief commonly have peat rich bog deposits associated with alluvium and these have been included with the alluvium map unit.

STRUCTURE

General Features

The Medicine Bow Mountains have been subjected to several major episodes of deformation (Houston and others, 1968, p. 101), and at least three periods of unrelated deformation have been suggested for the area north of the study area (McCallum, 1964, p. 143).

Geologic mapping by the author and results of geologic mapping by McCallum (per. commun., 1977) of the eastern part of the Mullen Creek mafic complex and adjacent areas suggest that the mafic complex has been subjected to at least two major folding episodes along with multiple episodes of faulting and shearing. The structural history of the area has in large part been established on the basis of primary features found within the layered mafic sequence (e.g., rhythmic layering, igneous lamination, traceable lithologic units and compositional trends).

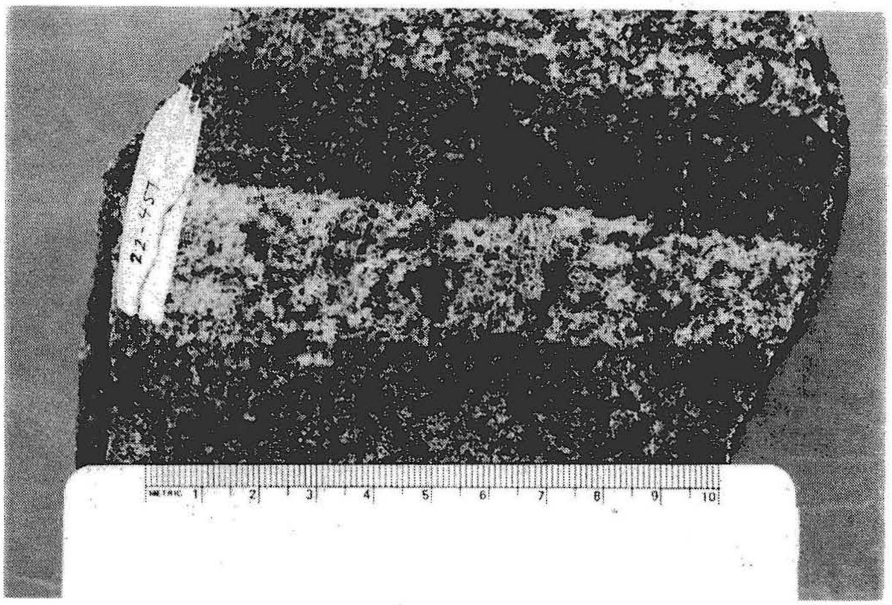
Primary Structures within the Layered Mafic Sequence

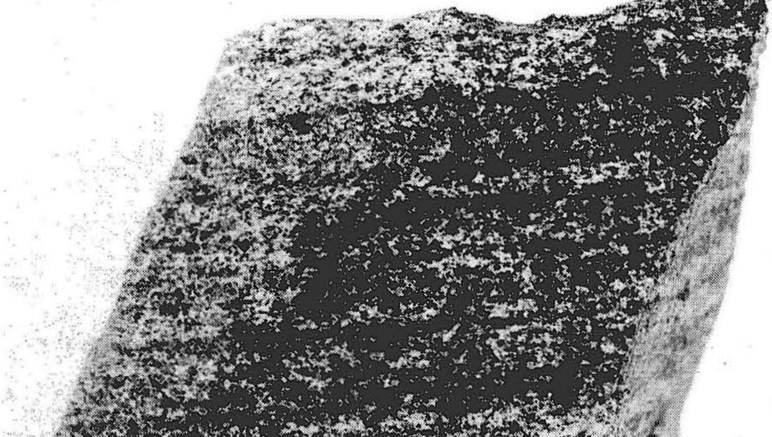
Numerous structural features associated with the development of a layered mafic sequence were observed in the study area and they appear to be similar to those described by Hess (1960), Wager and Brown (1968), and Morse (1967). Those features include: igneous lamination, rhythmic layering, cross-bedding, and a single scour channel. Mechanisms that account for the development of these features are believed to have been operative during crystallization of the layered mafic sequence and are discussed in more detail under petrogenesis. Identification of these features in the study area and especially in the previously unmapped western portion of the mafic complex has led to better documentation of the complex as a metamorphosed layered mafic intrusion as first suggested by McCallum (written commun., 1970) and Ramirez (1971, pp. 130-131).

Igneous lamination, the arrangement of platy minerals in a parallel manner, was observed at a number of localities throughout the mafic complex. Because of pervasive high grade metamorphism, this feature is preserved only in the arrangement of lath-like plagioclase crystals. Localities where igneous lamination is best observed are in rhythmically layered anorthositic gabbros and anorthosites in the vicinity of Jays Roost, in sec. 7, T14N, R80W, and in comparable units in the western portion of the area principally in sec. 35, T14N, R81W (Fig. 14). The weak to strong lamination of these rocks is best seen microscopically. An area where igneous lamination is well developed in rocks that do not display rhythmic layering is in the S½ of sec. 25. At this locality, strongly laminated gabbros occur within massive gabbros.

Fig. 14. Strong rhythmic layering in metaleucograbbro sequence west of the North Platte River, Sec. 35, T14N-R81W, centimeter scale.

Fig. 15. Layering in metagabbroic sequence, Sec. 35, T14N-R18W, centimeter scale.


22-457
METRIC 1 2 3 4 5 6 7 8 9 10

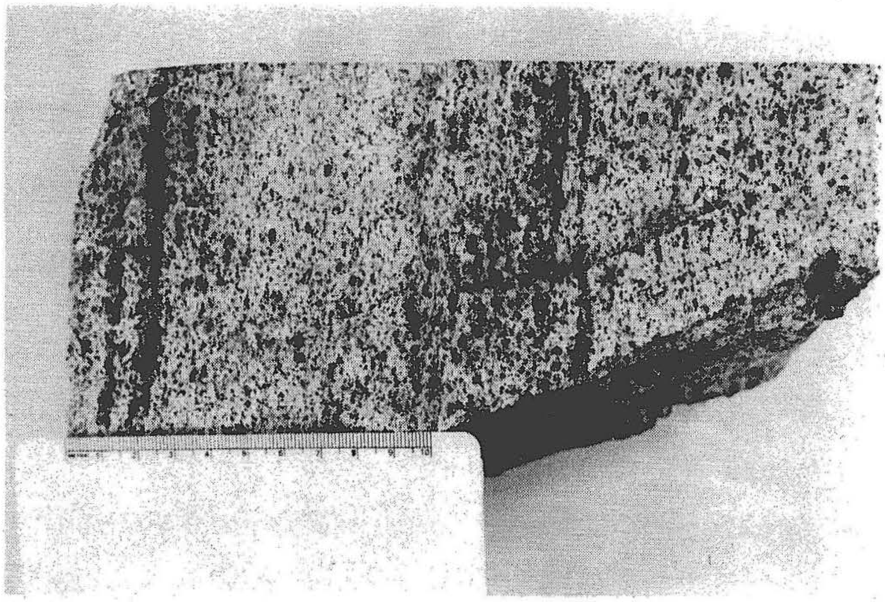


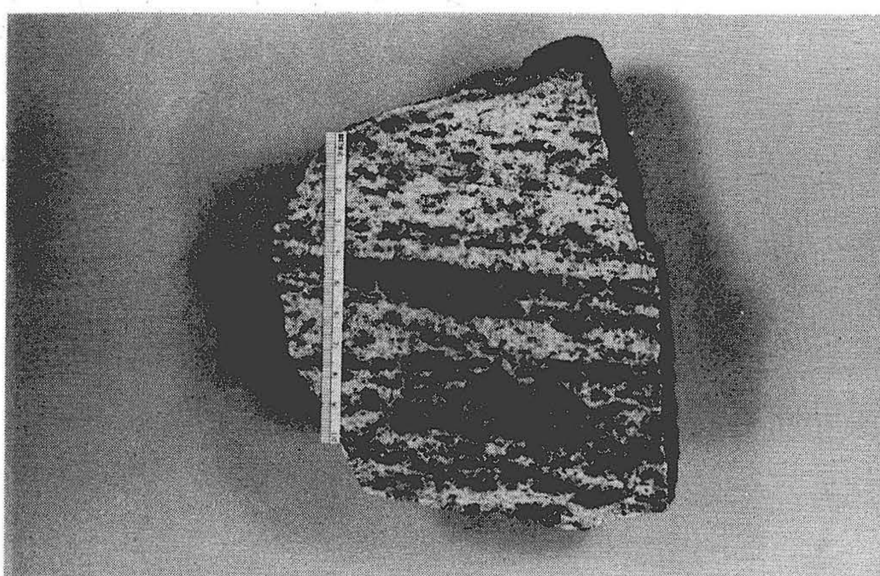
Rhythmic layering was observed at a number of localities and appears to be best preserved in the vicinity of Jays Roost and in sec. 35 west of the Platte River. Figures 14 and 15 show examples of rhythmic layering that reflect well developed stratification and distinct banding. Layering is defined by alternating concentrations of leucocratic and melanocratic rock, and these layers rarely exceed 10 centimeters in thickness. Larger scale rhythmic layering may be present; however, the poorly exposed nature of most mafic complex units permits examination of layering in only small, isolated outcrops and in float blocks. Although similar layering may occur (or may have occurred) in pyroxene and olivine-rich rocks, poor exposure, lack of color contrast, and obliteration of much of the primary mineral assemblage by metamorphism precludes the easy identification of all but leucocratic layers. The lateral extent of individual layers or lenses in strongly rhythmically layered rocks is unknown. As seen in Figures 16 and 17, layering in the Jays Roost area appears to be discontinuous (i.e., individual layers commonly pinch, swell, and bifurcate). The lenticular layering and thinning of layers along strike may be a consequence of current action and reworking of crystals as in sedimentary environments.

Gravity stratification as described by Hess (1960, p. 127) was observed in a number of outcrops, and was distinguished by the apparent grading upward of pyroxene (now amphibole) into more

Fig. 16. Layering in metaleucogabbroic rocks in the Jays Roost area, Sec. 24, T14N-R80W, centimeter scale.

Fig. 17. Layering in metaleucogabbroic sequence in Sec. 24, T14N-R80W. Note bifurcation in hornblende-rich layers, centimeter scale.





leucocratic zones. This feature was seen primarily in the rhythmically layered rocks in the western part of the study area.

Cross-bedding has been observed by McCallum (per. commun., 1977) at several localities in the mafic complex. The best examples of cross-bedding were found in the western portion of the mafic complex in the west central 1/2 of section 35, T14N-R81W and the NE$\frac{1}{4}$ of section 25, T14N-R81W. The presence of cross-bedding is strongly inferred in several outcrops in the Jays Roost area.

A single scour channel was observed in a large slump block in section 35, T14N-R81W, west of the Platte River in an area where rhythmically layered rocks are found. The scour channel is thought to represent erosional scour by strong, localized bottom currents.

Foliation in Felsic Rocks

Foliations in felsic intrusive units are exhibited locally in the Horse Creek granodiorite and in younger felsic rocks. Primary igneous foliations are present in both felsic units, however, cataclastic foliations predominant locally and mask earlier features.

Primary foliations are developed by the alignment of biotite and secondary chlorite and muscovite. Cataclastic foliations are characterized by segregation and alignment of mineral phases and by small lenses and elongate knots of crushed grains.

Because of poor exposure and the massive appearance of some of the Horse Creek granodiorite, foliation data are limited. The low number of data points precludes formulation of a meaningful structural analysis of these units.

Joints

Joints are present in all rocks in the study area, but they are particularly abundant in mafic units. Attitudes were recorded for 73 representative joint sets. Although as many as nine clearly defined joint sets were observed in a single outcrop, trends of only major sets were recorded as a complete structural analysis of jointing was considered beyond the scope of this project. Poles normal to joint surfaces are plotted on a Lambert azimuthal equal-area net using the standard percent area method (Billings, 1954, pp. 111-114) (Fig. 18). Although 73 attitudes are insufficient for a significant structural analysis, Figure 18 indicates dominant joint trends of N30°W, N80°W, and N60°E, all dipping steeply to the east. The joint trend of N60°E closely approximates the strike direction for mafic dikes and elongate felsic bodies in the area.

Origin for the joint sets is difficult to ascertain considering the small number of data points. However, different joint sets apparently originated under stresses that may indicate differences in ages and origin between different sets. Evidence for this conclusion includes the following: certain joint sets are annealed with

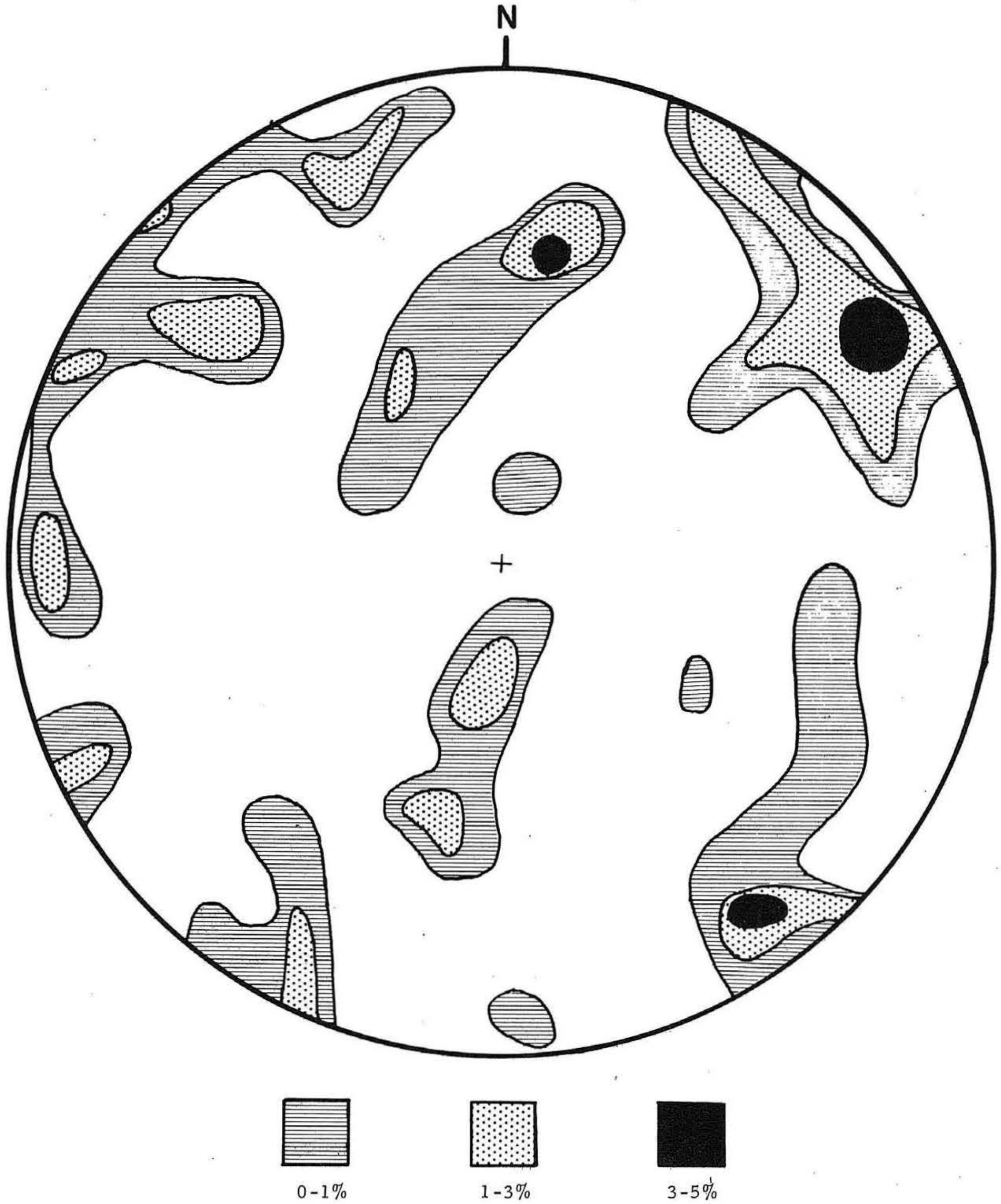


Fig. 18. Pole-plot diagram (contoured at % per 1% area) of joint attitudes. A total of 73 joint attitudes are shown.

epidote whereas others are barren, slickenslides are abundant on certain selected joint sets, and some joint sets displace others.

Closely spaced joint planes annealed with epidote are particularly abundant in the northern part of the area. These show a slight raised relief on outcrop surfaces and are commonly mistaken for layering which is very similar in appearance.

Shear Zones

Although shear zones structurally dominate the central portion of the Medicine Bow Mountains and variable degrees of cataclasis are reflected in nearly all rocks of the area, only a few shear zones were of sufficient size to map as discrete structures.

The shear zones generally consist of thin mylonitized layers that grade outward into rocks that megascopically show no appreciable deformation. Several of the mapped shear zones are lensatic, forming discrete pods and lenses of sheared rock with no apparent displacement. Much of the shearing has apparently taken place along zones of deformation that form anastomosing shears that are predominantly in the millimeter to centimeter thickness range.

The predominant trend of shears in the study area is northeast and east, sub-paralleling the Mullen Creek-Nash Fork shear zone. These shear zones are thought to be subsidiary to the shear zones to the north and all are believed to have formed during the major deformational event that generated the Mullen Creek-Nash Fork shear zone.

McCallum (1964, p. 144) indicates that the major shear zones north of the study area are believed to have developed during an early stage of kinetic metamorphism that accompanied and followed regional metamorphism. However, as noted by McCallum (1974, p. 473), the cataclastic history of the region appears to be quite complex and tectonites of the Mullen Creek-Nash Fork shear zone are products of multiple deformation events that range from high grade amphibolite series to low grade greenschist facies, to late stage brittle shears that produced fault gouge.

Faults

Numerous faults were observed in the study area but these undoubtedly represent only a small number of those actually present. Only those faults that could be readily determined and traced are included on the geologic map (Plate 2)

Field criteria used to determine faults are:

(1) The presence of brecciated and/or granulated rocks, especially in a preferred topographic alignment.

(2) Displacement of dikes, and

(3) Occurrence of fault annealing minerals: massive quartz, intensely epidotized rock, calcite and opaline chalcedony.

Many faults are exposed in prospect pits which greatly facilitate defining fault traces. The straight courses of most fault traces suggest that high angle relationships prevail. In most cases, magnitude and direction of displacement could not be determined. It was recognized, however, that two periods of faulting are expressed in the area by: (1) an early east-northeast trending set, and (2) later northwest trending faults that locally cross-cut the northeast trending set (Plate 2).

In many faults, annealing minerals are brecciated, suggesting reactivation along a pre-existing fault zone.

Structure of the Mullen Creek Mafic Complex

Structural data on primary rhythmic layering, igneous lamination, and a zone of predominantly metaleucogabbro that is tentatively traced from east to west, along with general compositional trends indicate that the Mullen Creek mafic complex and surrounding rocks have undergone at least two major episodes of folding. The mafic complex has been folded anticlinally about a slightly overturned axis plunging steeply to the northwest (Donnelly and McCallum, 1977) (Plate 1). Refolding is reflected by a shallow, westerly plunging, synanticlinal fold along the east margin of the mafic complex (Plate 1). This later episode of folding is well expressed in the Horse Creek granodiorite and adjacent quartz-biotite-andesine gneiss northwest of the Keystone quartz diorite pluton (Houston and others, 1968, p. 125, Plates 1 and 4) (Plate 1). The extension of this fold to the west is inferred by shallow dipping layering in the central portion of the mafic complex.

The overturned nature of the eastern limb of the anticline is reflected by compositional trends within the mafic sequence. Plate 1 shows a schematic geologic map of the mafic complex showing division of the mafic rocks into three zones. Zones I and III are predominantly metagabbro with similar modal mineralogy, whereas zone II is predominantly metaleucogabbro. Whole rock geochemistry on samples from each zone indicate that the bulk content of Na, Ti, V, Zr, P, and the Fe/Mg ratio increases and Ni decreases from zone I to zone III (Figs. 20 and 21). A more complete chemical description is given in a later section. These trends, if consistent with those of other more thoroughly studied layered mafic intrusions (Wager et al., 1967, p. 153-183; Allard, 1970, p. 491), indicated that zone III is the top of the layered sequence. Attitudes on layered units indicate that the eastern limb must be overturned.

Geologic mapping by McCallum (per. commun., 1977) in the Albany $7\frac{1}{2}$ minute quadrangle has verified that the Horse Creek granodiorite is sill-like and is folded into a shallow, westerly plunging synanticline which extends westward into the mafic complex (Plate 1). Primary foliations recorded by McCallum along the western border of the granodiorite sill infer that the sill plunges sharply beneath the mafic complex (Plate 1). Extremely poor

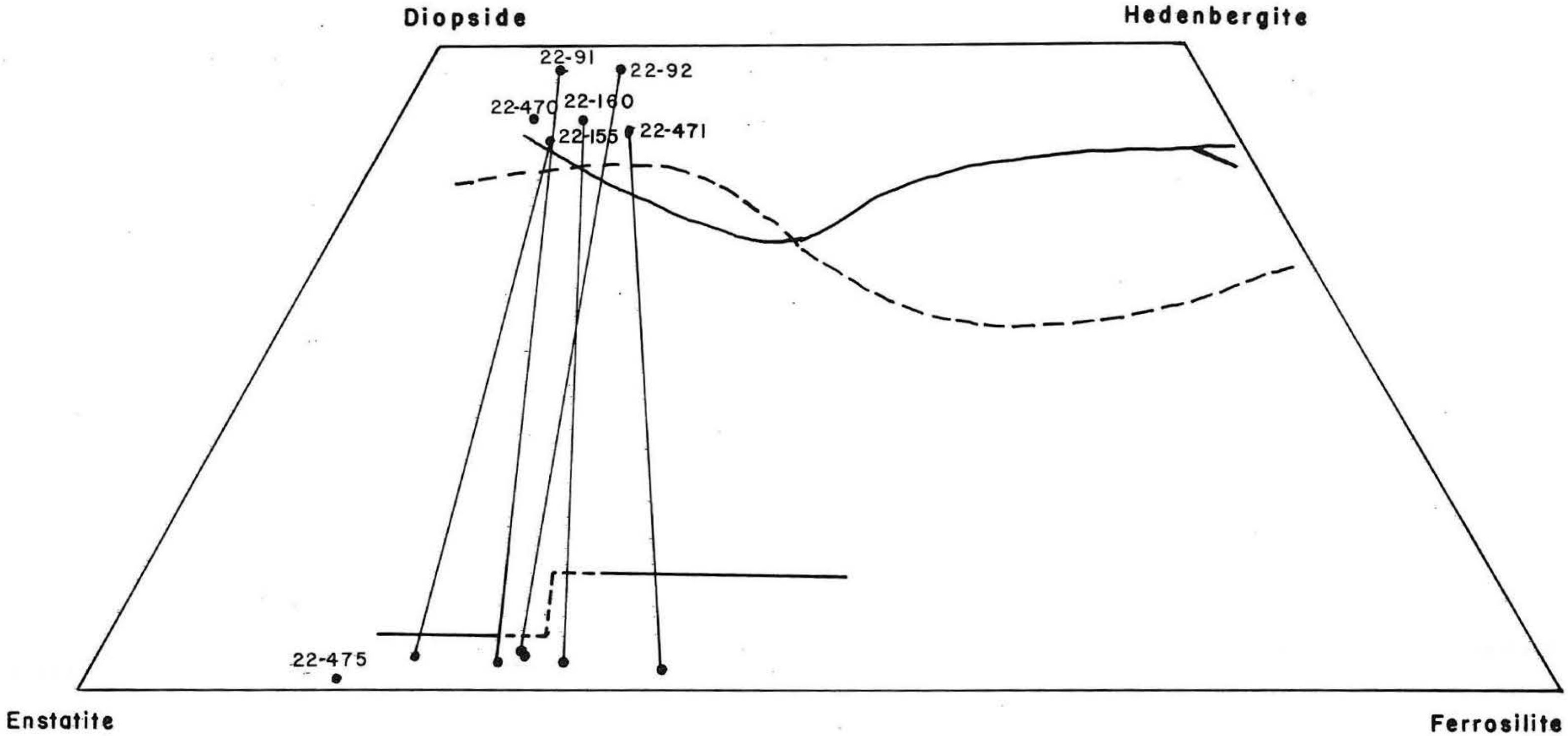


Fig. 19. Electron microprobe analyses of calcium-rich and calcium-poor pyroxenes. Solid lines show crystallization trend for pyroxenes from the Skaergaard Intrusion (Wager and Brown, 1968, p. 39). Dashed line reflects crystallization trend for clinopyroxenes in common mafic magmas after Hess (1941). Numbers refer to sample numbers.

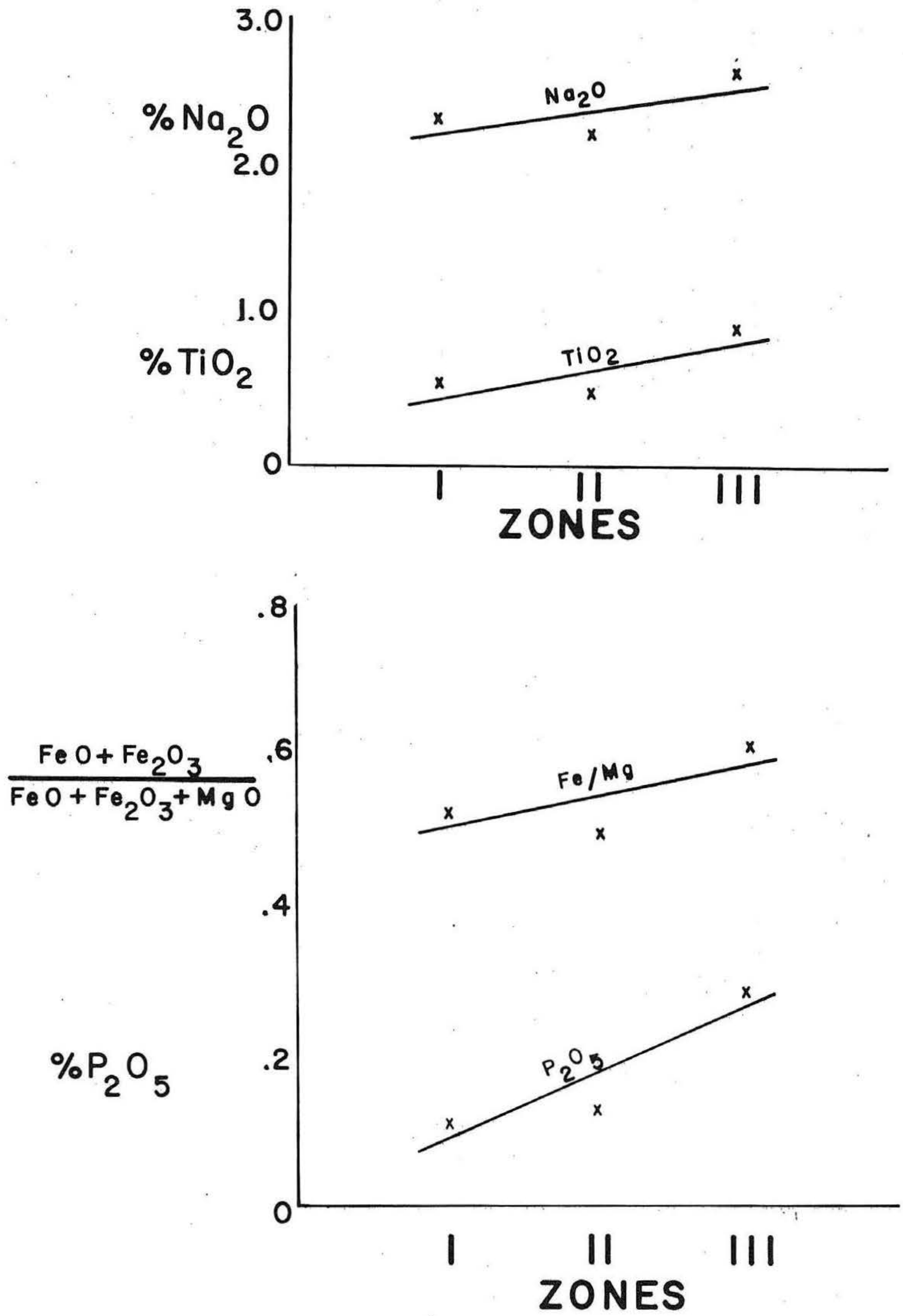


Fig. 20. Plots of weight percent P_2O_5, Na_2O, T_iO_2, and the iron to magnesium ratio vs. zones outlined in Plate 1. Points reflect the mean of 7 samples from zone I, 11 from zone II, and 5 from zone III.

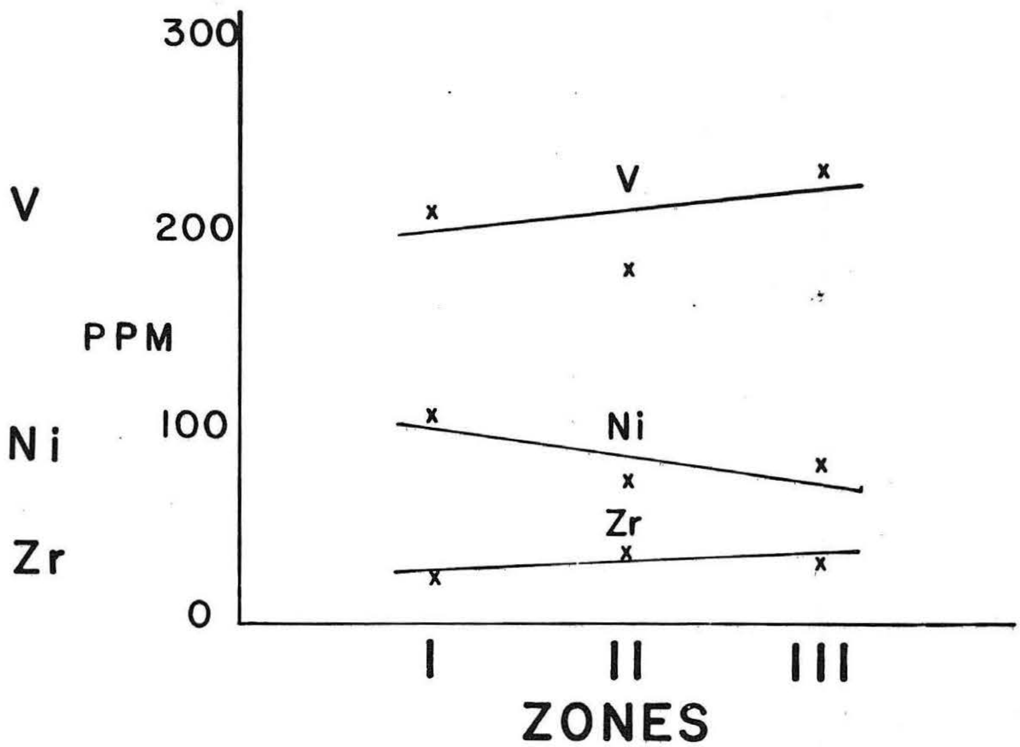


Fig. 21. Plots of V, Ni, and Zr vs. zones outlined in Plate 1. Points reflect mean of 7 analyzed samples from zone I, 11 from zone II and 5 from zone III.

exposure along the Horse Creek granodiorite-mafic complex contact precludes a definitive structural interpretation; however, sparse foliation data recorded by the author support McCallum's structural interpretation. The extension of the synanticlinal fold into the central part of the complex is reflected by rare attitudes on layering (Plate 2). Refolding of the central and eastern portion of the mafic complex explains in part the apparent excessive thickness of the mafic rock succession exposed in the Mullen Creek mafic complex.

The documentation of two major episodes of folding in the Mullen Creek complex and evidence for an earlier deformational event that resulted in northeast trending structures in bordering gneissic units supports the thesis that rocks south of the Mullen Creek-Nash Fork shear zone have been subjected to at least three episodes of folding (Houston and others, 1968, p. 123).

PETROGENESIS

Introductory Statement

Complex cross-cutting relationships between mafic and felsic rocks in the Mullen Creek mafic complex indicate multiple intrusions of mafic and felsic magma. Detailed field mapping in the study area together with geologic mapping of the Keystone Quadrangle by McCallum (per. commun., 1977) and Ramirez (1971) has established the existence of at least one major mafic intrusive event that provided a layered mafic sequence that was subsequently intruded by numerous mafic and felsic magmas. Although much of the original mineralogy of the mafic rocks has been obliterated by regional amphibolite facies metamorphism, felsic phases show only the effects of late kinetic metamorphism.

Origin of the Layered Sequence

Mineralogic Evidence of Fractionation and Parent Magma Type

The lack of chilled border rocks has precluded the availability of chemical analyses on phases that closely approximate the parent magma of the layered sequence. However, the presence of sparse olivine and relict calcium-poor and calcium-rich pyroxenes suggest that the parent magma was a basaltic magma with tholeiitic rather than alkalic affinities.

The rare occurrences of relict orthopyroxenes and olivine prevented a systematic evaluation of these minerals throughout a given zone or unit. Analyses were obtained for mineral phases collected from scattered locations over the study area and they therefore cannot be used to infer crystallization paths of pyroxenes with regard to "stratigraphic" position within the layered sequence. Analytical results are given in Tables 2 and 3 in the Appendix. Clinopyroxenes in analyzed samples are considered to represent intercumulate phases whereas orthypyroxenes are interpreted as cumulate phases. Thus, the pyroxene pairs do not define an equilibrium assemblage. Tie lines have been included in Figure 19 only to illustrate the progressive iron enrichment of the pyroxene pairs.

Figure 19 illustrates the calcium-deficient nature of ferriferous orthopyroxene. The low calcium content and apparent lack of exsolution lamellae in orthopyroxenes suggest that the ferriferous orthopyroxenes first crystallized as hypersthene rather than pigeonite. Although rocks from many layered mafic intrusions show an inversion of hypersthene to pigeonite at approximately En_{70} (Wager and Brown, 1967, p. 39), orthopyroxenes in the study area do not suggest the presence of inverted pigeonite. Wager and Brown (1967, p. 436) note that orthopyroxenes in the Kaerven Intrusion in East Greenland exist as primary hypersthene as ferriferous as En_{54}, whereas in the Skaergaard, Bushveld, and Stillwater intrusions, pigeonite is the calcium-poor phase at compositions more ferriferous than En_{70}. Wager and Brown (1967, p. 444) also note that in the Insch Intrusion, Aberdeenshire Northeast Scotland, orthopyroxenes from En_{84}-En_{56} are primary enstatite. Ferriferous orthopyroxenes within the range En_{55}-En_{32} have apparently inverted from pigeonite and ferropigeonite. According to Wager and Brown (1967, p. 436), the persistence of ferriferous hypersthene crystallizing as the primary phase in the Kaerven and Insch intrusions may result from slightly higher water content that would depress the pyroxene crystallization temperature in relation to the subsolidus inversion temperatures (Bowen and Schairer, 1935), and thus extend the field of hypersthene crystallization. A similar mechanism may be responsible for the persistence of ferriferous hypersthene in the study area.

The least altered major mineral component, plagioclase, is perhaps the best indicator of the primary composition and changes in composition in the mafic rock sequence. Ramirez (1971, p. 109) suggests that the anorthite content in plagioclase increases from west to east in the northern portion of the mafic complex. No such association was observed by the author, but systematic evaluations of plagioclase compositions across well-defined sequences of layers were beyond the scope of this project. The irregular compositions of samples collected in the study area, even where in close spatial association, suggest that a closely spaced sampling density must be employed for future studies.

As previously indicated, zoning in plagioclase is normal, reverse, and oscillatory, although normal zoning is most common. Ferguson and Wright (1970) describe reversed zoning in plagioclase from samples in the Bushveld intrusion. Their interpretation of this feature is consistent with that of Wager and Brown (1967, p. 387) who regard reversed zoning as follows:

(1) (increased) "...pressures exerted in the locally-confined pore spaces may result in the pore liquid crystallizing a relatively calcic plagioclase," and

(2) "An increase in the partial pressure of water in the melt, resulting in reaction of the outer zone of the plagioclase crystal with liquid, producing a more calcic rim."

As demonstrated by Yoder et al. (1957), an increase in P_{H_2O} on the anorthite-albite system will lower the liquidus and solidus, resulting in a more calcic plagioclase crystallizing.

Oscillatory zoning may also reflect variation in the partial pressure of water in the melt, but in this situation, the changes are repeated or cyclic.

Genesis of Cumulate and Ophitic Texture

Cumulate textures were identified in a number of thin sections and Ramirez (1971, p. 111) suggests the presence of cumulate textures north of the study area. Recognition of cumulate phases is difficult and evidence is in part indirect. Distinction of this texture can generally be drawn with consideration of textural relationships (i.e., crystal zonation and grain boundary relationships) combined with field observations of layering and primary depositional features (i.e., rhythmic layering and igneous lamination).

Cumulate texture is regarded as the result of gravity settling and subsequent growth of crystal nuclei on the floor of the magma chamber. The processes of deposition, accumulation, and growth of slowly crystallizing minerals from a melt, and evaluation of cumulate nomenclature have been discussed by many workers (e.g., Wager, 1960, pp. 73-85; Wager, 1963; and Jackson, 1967, pp. 21-24). The terminology proposed by Wager et al. (1960) are used in this report.

Cumulate mineral phases identified in the Mullen Creek mafic complex include plagioclase, olivine, and orthopyroxene. Although pyroxene and olivine are preserved as rare relict grains, plagioclase has survived with little modification and provides the best evidence for a cumulate origin. Those rocks that best display cumulate fabric lie within leucocratic zones (Plates 1 and 2). Within these zones, plagioclase appears to be the primary cumulate phase. Type of plagioclase cumulate growth varies dramatically from sample to sample in these zones. Cumulate crystals show strong, predominantly normal zoning, suggesting enlargement of grains by trapped pore liquid. Products of this process are referred to as orthocumulates. Locally, however, the near absence of zoning suggests adcumulate growth, which results in plagioclase mesocumulates. The predominance of orthocumulates suggests fast bottom accumulation during formation of the leucocratic zones, accompanied by intermittent(?) slow accumulation which allowed time for the development of mesocumulates (Wager et al., 1963, p. 79).

Evidence such as igneous lamination, plagioclase in rhythmically layered units, and relict cumulate textures indicates that plagioclase acted as a cumulate phase and suggests that the plagioclase phenocrysts had a specific gravity greater than that of the surrounding liquid during settling. A calculation of the compositions and densities of the successive liquids during crystallization indicates that plagioclase will <u>tend</u> to float in a "dry" magma but <u>will</u> float only if the magma has a high water content (Bottinga and Weill, 1970, p. 180). Bottinga and Weill (1970), emphasize that variation of density of the liquid with composition is quite significant. Thus, compositional variation and water content play a critical role in those systems where plagioclase settling can be demonstrated.

Mafic rocks that do not indicate a cumulate origin most commonly have a sub-ophitic to ophitic fabric. Development of ophitic texture has long been a subject of interest to petrologists and several unsatisfactory explanations have been given by various workers (e.g., Hess, 1960, p. 114; Walker, 1969, p. 157; Wager, 1961). Carmichael, et al. (1974, p. 24, p. 167-168), in a review of ophitic texture, suggests that the development of this fabric is a consequence of the differences in melting entropies of diopside and anorthite. The nucleation and growth rates of the species are proportional and inversely proportional respectively to the entropy of melting. Thus, a mafic magma with a slow or intermediate cooling rate would generate more feldspar nuclei but faster growing olivine or pyroxene would enclose or partially enclose the slower growing plagioclase. Magnetite and ilmenite have been observed enclosing plagioclase in some thin sections (Fig. 9), and they are similar to their pyroxene counterparts with regard to their greater entropy of fusion (Carmichael, et al., 1974).

Genesis of Structures Within the Layered Sequence

Various gravitational features have been observed in the mafic complex rocks and evidence of reworking of settled crystals is moderately abundant.

The development of igneous lamination, rhythmic layering, cross-bedding, and at least one scour channel are attributed to motion in the magma during crystallization. It is reasonable to assume that motion induced by convection was operative during at least part of the crystallization history. This has been inferred by Bartlett (1969) based on theoretical considerations and by the intuitive reasoning of Jackson (1961, p. 96).

Bartlett (1969) has shown that conditions necessary for convection are obeyed by igneous intrusions greater than 15 meters in thickness with viscosities up to 10^8 poise. Basalt viscosities are shown by Shaw (1972) to be on the order of 10^2 to 10^3 poise. The presence of adcumulus growth of plagioclase in the metaleucocratic and anorthositic rocks is further evidence of motion, as adcumulate growth requires renewal of magma near the floor by flow, otherwise diffusion distances become impossibly large (Morse, 1969, p. 67).

A review of the various proposed mechanisms for the development of rhythmic layering indicates that most workers favor convectional motion in the magma with accompanying gravitational differentiation.

Hess (1960) in a study of the rhythmic layering in the Stillwater Complex demonstrated that an upward component of liquid motion is the most effective mechanism for separating different mineral phases and he concluded that intermittent upward currents near the floor were primarily responsible for the formation of rhythmic layering.

Wager (1963) and Wager and Brown (1967) suggest that a cooling layer of magma adjacent to the roof and walls intermittently descends as a column in a convection cell. The crystal laden magma then spreads over the floor of the magma chamber and crystals settle at different rates. Wager (1963) credits the effect of supercooling and the relative nucleation rates of different minerals as a contributing factor in the development of rhythmic layering. Subsequent work by Goode (1976) suggests that small scale layering is produced by repeated bursts of discontinuous nucleation followed by differential gravitational settling of the different cumulate mineral phases.

Effects of currents and differing rates of convecting currents are also proposed as an aid to the winnowing of lighter grains and to the generation of differing settling rates as suggested by Wager (1963), Wager and Brown (1967), and Morse (1969).

Igneous lamination, often accompanying layering, was considered by Grout (1918, p. 453, 456-457), in his studies of gabbroic rocks in the Duluth Complex of Minnesota, to be due to deposition of tabular minerals from a convecting magma. More recent explanations of igneous lamination in mafic rocks are in agreement with Grout (Wager and Brown, 1967, p. 102; Morse, 1969, p. 67).

Jackson (1961) in a study of layering in the Ultramafic zone of the Stillwater Complex suggests successive units were formed by the bottom accumulation of crystals separating from successive, relatively thin layers of magma adjacent to the floor. Loss of heat from the floor would permit crystals to form and sink to the floor until the latent heat of crystallization had raised the temperature locally, to prevent further crystallization. After sinking of suspended crystals, this now hotter magma would have a lower density than the overlying magma and a convective overturn would occur. This process would then be repeated to form the next ultramafic unit.

Other mechanisms include periodic fluctuation in the water vapor pressure (Ferguson and Puldertaft, 1963; Yoder, 1954), and abrupt changes in temperature and/or pressure (McDonald, 1967).

Where macro-rhythmic units show reversals in the chemical variation layering, it is believed to be caused by a major influx of new magma. Successive injections of parental magma are believed to be responsible for the development of macro-rhythmic units in the Rhum complex where no overall cryptic layering could be detected (Brown, 1956, p. 44-45), and in development of macro-rhythmic units in the Bushveld marked by a strong reversal in cryptic variation (Wager and Brown, 1967, p. 619).

Clearly, one or several of these mechanisms may be operative at any given time in the crystallization history of a layered mafic complex, and this in part explains the similarities and dissimilarities between complexes making each unique.

Conditions operative in the Mullen Creek mafic complex are still uncertain considering that in addition to the fact that portions of the complex remain unmapped, exposures suitable for examination of structural features are uncommon, and primary mineral assemblages have been extensively modified by metamorphism. Based on the structures observed, however, it is apparent that currents were active periodically at the depositional surface and this motion was probably convectional in origin. Most of the features described have been observed in a zone of rocks that is significantly more leucocratic than those rocks above and below and it is possible that two mechanisms are responsible for the formation of primary structural features in the more leucocratic unit. The predominance of current produced structures in the more leucocratic zones is in agreement with observations on similar sequences that show comparable features (Emslie, 1975; Goode, 1976b). Goode (1976b) suggests that this may reflect the increased viscosity during crystallization of more anorthositic sequences which would increase potential particle mobility and lead to easier redistribution and erosion of settled crystals. The restriction of small scale rhythmic layering to more leucocratic zones may be due to repeated bursts of discontinuous nucleation with differential gravitational settling of pyroxene relative to plagioclase. The prevalent massive unlayered sequences (i.e., metagabbro) may be the result of continuous nucleation irrespective of differential gravitational settling. Evidence of fresh influxes of magma during the crystallization sequence is uncertain especially so considering the limited number of geochemical analyses and unknown extent of cryptic variation.

Differences in habits of small scale layering (i.e., discontinuous lenticular layers as opposed to more even continuous layering) and localized erosional and depositional features are thought to be the result of differences in currents. Lenticular layering in the Jays Roost area suggests the presence of strong localized currents. The presence of igneous lamination and more continuous rhythmic layering may indicate broad gentle currents. A similar classification of currents has been suggested by Hess (1960) and Wager (1963). Localized reworking of settled crystals such as scour channels and cross-bedding are considered a result of vigorous, unidirectional localized currents of convectional origin (Wager and Brown, 1967; Goode, 1976b).

The mechanism of formation of metapyroxenite pods is unknown. The gradiational contacts of some pods with metagabbroic rocks suggests local accumulation of mafic phases during crystallization as suggested by Ramirez (1971, p. 110) for pods to the north. Other instances of pyroxenite pods, described by Morse (1969, pp. 52-55), are thought to represent either foundered blocks of gneissic or sedimentary country rock that have been completely assimilated, or contamination at the magma-roof interface resulting in a possible growth of a local shell of orthopyroxene that eventually foundered. The numerous and chaotic distribution of metapyroxenite pods throughout the complex suggests that pods did not form as the result of foundered blocks from the roof of the intrusion. Although assimilation of foundered gneissic blocks cannot be ruled out, there is no evidence that the pods form a disequilibrium assemblage.

Geochemistry of Layered Mafic Rocks

During field investigations, thirty-four rock samples were selected for whole rock analysis (McCallum and others, 1979). Of these, twenty-six samples represent the various mafic phases and eight analyses of felsic rocks were made. The lack of analyses from the central part of the complex is a reflection of more intense felsic intrusive hybridization in that area (Plate 2). Because of restrictions on the number of analyses that could be run, hybrid phases were excluded. Although the analyses from this study and those made available by M. E. McCallum (McCallum and Mussard, 1979a), represent an insufficient number of samples to accurately define many trends, there does appear to be a consistent fractionation trend in bulk chemistry with inferred stratigraphic height. Work currently in progress (D. E. Mussard, Colorado State University, per. commun., 1977; Mussard and McCallum, 1977; McCallum and

and Mussard, 1979a,b) may reflect additional trends within the various units in the complex and trends between the Mullen Creek mafic complex and the Lake Owens complex.

A spatial distribution plot of the major oxides was prepared and from this initial study there does not apear to be a consistent variation in the oxides with regard to location in the complex. Sample compositions show a strong variation from one another even if taken in close proximity. This variation is also reflected in mineralogy and modal composition. As previously noted, comparison of plagioclase and pyroxene compositions of those samples taken close to one another show very diverse compositions.. Since the limited number of whole rock analyses do not show any apparent trends with relation to position in the complex, samples have been treated with respect to position of zones. Plate 1 illustrates the position of three zones that have been drawn to reflect field observations of principal areas of lithologies. Zones I and III are predominantly metagabbroic in composition, generally massive in appearance, and contain rare layering. Zone II is primarily metaleucogabbro with compositions ranging from anorthosite to metapyroxenite. This zone is the site of the most layering and "sedimentary-type" features. Plots of the major oxides and selected trace elements in respective zones were prepared, but because of their erratic distribution of values they are not included in this report. However, average values of selected oxides and trace elements within each zone do reflect interesting variations. These variations are illustrated in Figures 20 and 21. From these curves it is evident that from zone I to III, (zone III being the inferred top of the complex), there is a trend of increasing TiO_2, Na_2O, P_2O_5, Fe/Mg ratio, V and Zr and a decrease in Ni between the two principal metagabbroic units. The more leucocratic unit is deficient in V, Ni, TiO_2 and Na_2O and shows a lower Fe/Mg ratio. The apparent depressed values in the leucocratic zone can be explained by mineral composition and modal mineralogy. The apparent decrease in the Fe/Mg ratio in zone II probably reflects the decreased amount of iron oxides crystallizing at that stage of crystallization. The increase in the Fe/Mg ratio from zone I to III is a result of iron enrichment of the ferromagnesium minerals with fractionation. The decrease in vanadium and titanium appears to vary sympathetically with the crystallization of titanomagnetite which is most abundant in the metagabbroic phases (Table 3). The sympathetic relationship of vanadium with iron and titanium reflects the substitution of vanadium for ferric iron. Sodium shows a general increase between the two metagabbroic zones and this is best explained by enrichment of sodic plagioclase with fractionation. The decreased values of sodium in zone II are thought to represent a greater proportion of adcumulus growth of plagioclase (i.e., enlargement of the cumulus crystal by material of the same composition) in this leucocratic zone, and less modal pyroxene. Phosphorus shows an enrichment during fractionation in all three zones, being the most pronounced near the inferred stratigraphic top of the complex. The apparent strong enrichment in zone III may be due to the development of apatite as a cumulus(?) phase in that zone. The tendency for phosphorus to become strongly enriched in the late differentiate is pronounced in the Skaergaard intrusive (Wager and Brown, 1967, p. 171, Pl. X). Zirconium shows a fairly consistent increase from zone I to zone III which is consistent with other observations (Wager and Brown, 1967, p. 195). Zirconium is thought to be held predominantly in zircon, which was observed in trace amounts in most rocks studied. The apparent steady decrease of nickel is thought to represent nickel's early removal in olivine, pyroxenes, and iron-oxides. The apparent variations in bulk chemistry of the rocks are consistent with chemical changes documented in other layered mafic intrusions (Wager, 1960, pp. 364-368, and Wager and Brown, 1967, pp. 150-204), and are thought to reflect fractionation during crystallization.

The apparent erratic geochemical values within individual zones may be explained by the presence of numerous cyclic units that overlap portions of the crystallization sequence which, on a larger scale, define an overall fractionation sequence (i.e., numerous (?) reversals in the cryptic layering). Three explanations may be given for the presence of this cyclic variation; (1)

a fresh influx of magma of similar composition, as proposed by Brown (1956, pp. 44-45) to account for cryptic variations in the Rhum intrusive, (2) a basal layer of magma undergoing crystallization periodically joining with an overlying convection cell that supplies a fresh influx of magma to the stagnant basal layer (Jackson, 1961), and (3) changing water vapor pressures which have been shown to raise and lower the liquidus and solidus of the various silicate mineral phases. Although there are insufficient geochemical and mineralogical analyses to determine the extent of cyclic variation and which explanation may best explain the variations, a limited number of plagioclase grains displaying oscillatory zoning were noted implying changing P_{H_2O} conditions. Chemical and mineralogic variations within zones I and III may suggest crystallization from a basal layer where there is limited evidence of bottom currents.

Further evidence of fractionation and the chemical variability from each zone may be seen in the AFM diagram in Figure 22, and the CaO-K_2O-Na_2O diagram in Figure 23. Figure 22 also includes the computed liquid trend of fractionation for the Skaergaard intrusion (Wager and Brown, 1967, p. 238) and the Stillwater "liquid trend" prepared by Hess (1960), p. 166, Pl. 11-c). Although Carmichael (1974, pp. 476-479) raises some serious questions concerning the validity of the Skaergaard trend, it is included here to

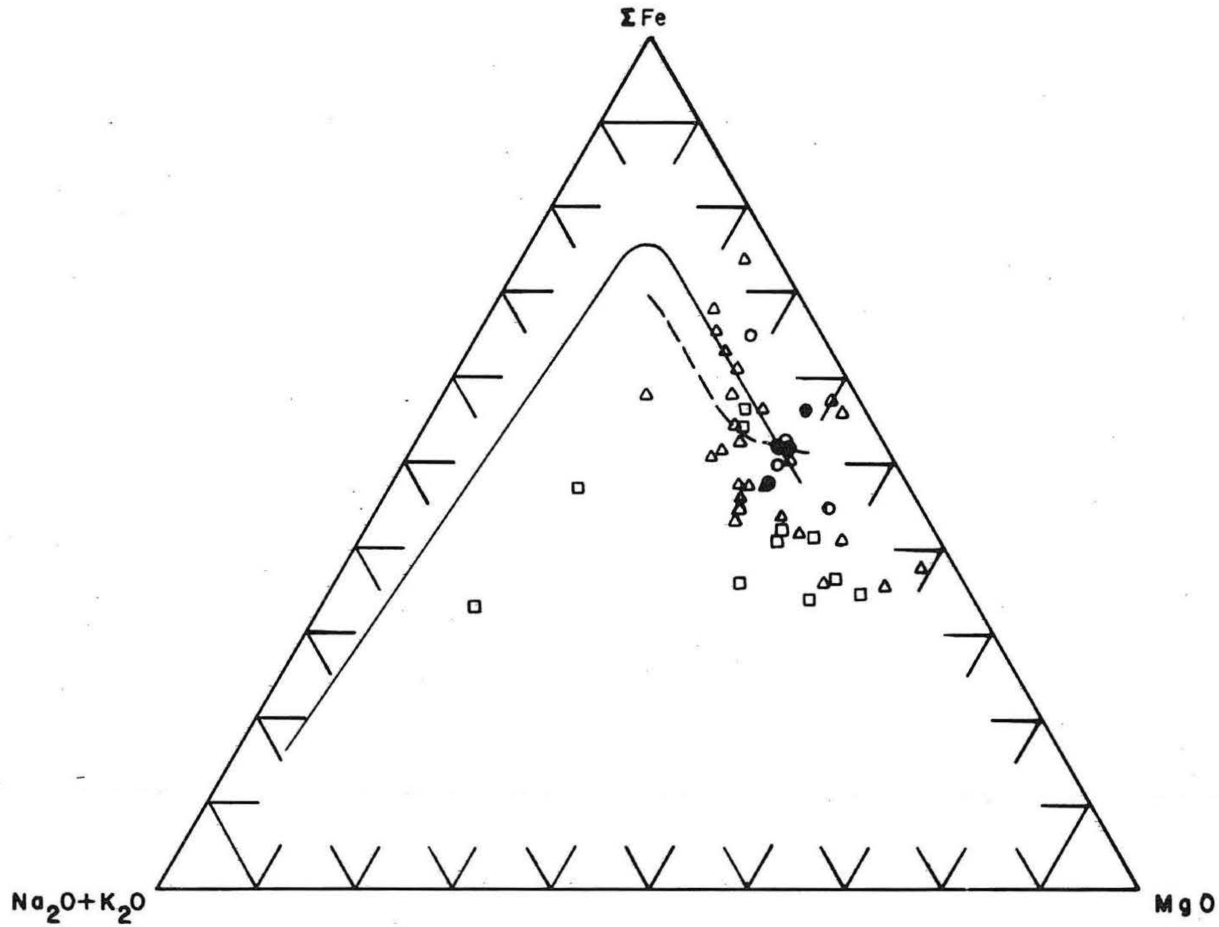


Fig. 22. AFM diagram showing distribution of mafic rock phases from the Mullen Creek mafic complex. Data from McCallum and others (1979). Mafic phases represented by triangles, metagabbro; squares, anorthosites and metaleucogabbro; open circles metabasalt, and; solid circles, metadiabase. Dashed line is the Stillwater "liquid trend" of Hess (1960). Solid line shows fractionation trend of the Skaergaard pluton (Wager and Brown, 1968).

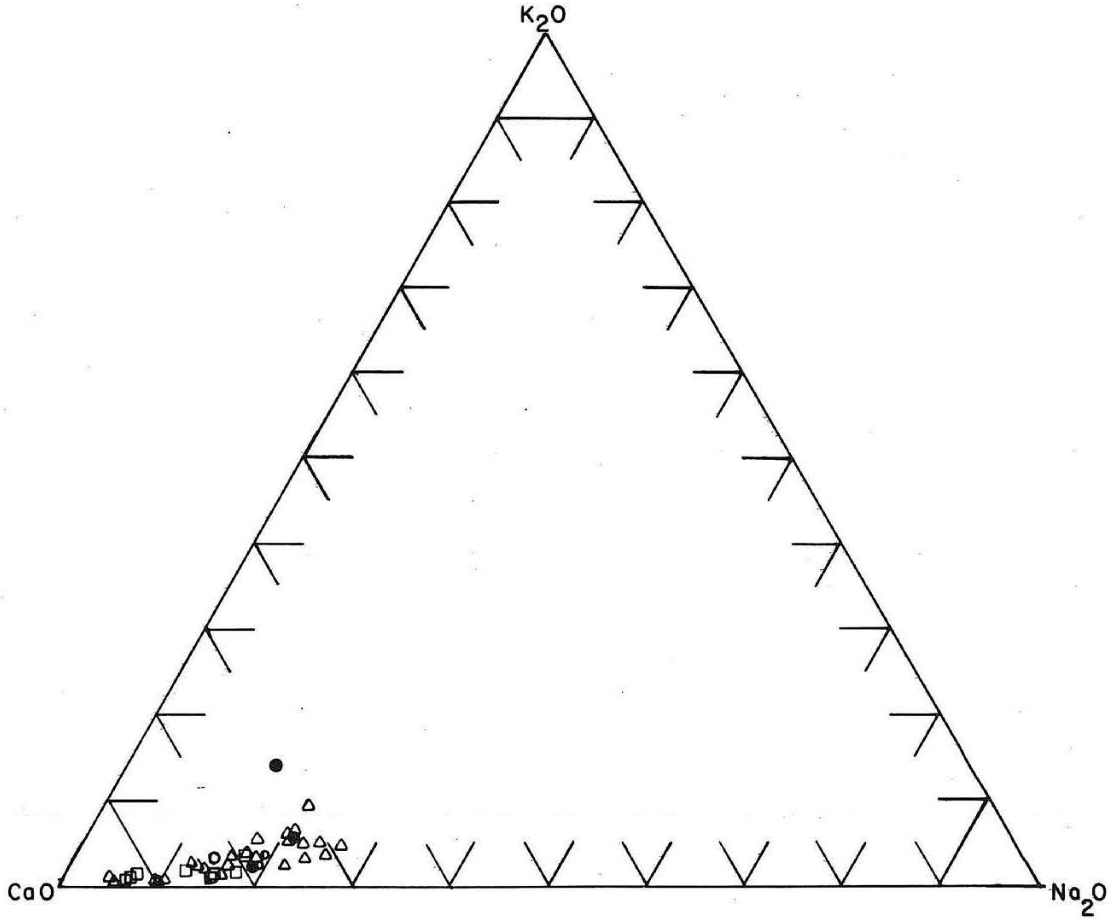


Fig. 23. CaO-K_2O-Na_2O triangular diagram showing distribution of mafic rock phases from the Mullen Creek mafic complex (McCallum and others, 1979). Mafic phases represented by triangles, metagabbro; squares, anorthosite and metaleucogabbro; open circles, metabasalt dikes and; solid circles, metadiabase.

show an assumption of how fractionation of tholeiitic magma at low oxygen fugacity is likely to occur.

It is evident from Figure 22, that the metagabbroic phases show a partial fractionation trend towards an increasing iron-rich end member. The wide scatter of leucocratic phases, collected predominantly in zone II (Plate 2), is further evidence that periodic fluctuations or cyclic variations are present. The reason that more extreme fractionated mafic phases are not shown may be because the structural top of the intrusive has not been sampled and investigated as thoroughly as underlying phases, or because extremely fractionated mafic phases may not be exposed in the study area.

Figure 23 further illustrates variation of the alkalies. There appears to be a general trend of increased FeO-Na_2O with fractionation. The erratic K_2O rich point reflects a metadiabase sample that is partially hybridized.

These geochemical data, combined with mineralogical and structural data, suggest the Mullen Creek mafic complex shows bulk chemical fractionation trends that indicate fractionation of a tholeiitic magma that was at times undergoing convectional motion. Variation in bulk chemistry between zones is interpreted as changes in modal mineralogy and crystal chemistry during fractionation. Repeated(?) cyclic reversals appear to be present in the mafic sequence suggesting changing conditions during crystallization, or conceivably, fresh influxes of magma during crystallization.

Origin of the Metadiabase

Intrusions of diabasic rocks into the gabbroic sequence have presented many puzzling field relationships. Metadiabase-metagabbro contacts are ill-defined and show evidence that the diabase was intruded into a hot, plastic gabbroic sequence. This in part explains the irregular and sometimes conflicting cutting relationships between the two units.

Limited geochemical analyses of metadiabase (Appendix, Table 5) show a strong clustering of points in the (Na_2O+K_2O)-FeO-MgO diagram presented in Figure 22. This point cluster is intermediate between the more fractionated gabbroic phases, suggesting that the diabase is the product of a single intrusive episode that showed little fractionation, if not several intrusions of mafic magma of similar composition. Additional chemical analyses are needed before a final interpretation may be made.

It is interesting to note that the location of the major portion of the metadiabase is in the vicinity of the inferred NW-trending anticlinal axis (Plate 1). This may suggest that the bulk of the diabasic intrusive activity occurred along a zone of weakness induced by folding of the still hot gabbroic sequence. Additional geologic mapping to the north may give further insight into the origin and intrusive nature of the metadiabase.

Origin of Metabasalt Dikes

The numerous metabasalt dikes that reflect two generations of dike emplacement provide additional evidence for repeated periods of basaltic magma activity in the region (McCallum, 1964, p. 96; Houston and others, 1968, p. 44, 84).

Two generations of plagioclase, normally zoned calcic phenocrysts set in a fine grained groundmass containing more sodic plagioclase, were noted in numerous samples (Table 9). Processes that can produce the observed equilibrium relationship between phenocryst and host liquid may be either filter pressing or flow-differentiation (Simkin, 1967; Komar, 1972). An additional mechanism for the observed relationship of phenocryst rich and phenocryst poor dikes may be the result of tapping different levels of an underlying magma chamber undergoing differentiation and crystallization (Macdonald, 1972).

The development of crude glomeroporphyritic texture, or synneusis, was observed in those dikes exhibiting two generations of feldspar. Development of this fabric implies a drifting together and attachment of crystals freely suspended in a fluid medium (Vance and Gilreath, 1967; Vance, 1969).

Origin of the Felsic Rocks

As noted earlier in this report in the review of felsic units, limited field and geochemical relationships have made it difficult to distinguish individual phases and even the number and relationships between felsic events is questionable. Work currently in progress by D. E. Mussard and M. E. McCallum (Colorado State University) may provide insight into this problem.

Modal compositions of the felsic rocks in the study area are shown in a triangular diagram in Figure 24 with modal analyses from similar units north of the study area made by Ramirez (1971). From the diagram it is evident that the field of composition for younger felsics is more granitic in composition than that of Horse Creek granodiorite. The greater variation in composition in the younger felsics is due partially to the assimilation of mafic rocks during emplacement and the sampling of aplitic and/or pegmatitic phases. The wide range of compositions for younger felsics may also reflect different ages and phases of emplacement.

The position and conformable nature of the Horse Creek granodiorite sill (Plate I and II) suggest that this unit may be a late stage differentiate of the mafic complex. Preliminary work on major and trace element geochemistry suggests a similar relationship (D. E. Mussard, per. commun., 1977), although additional field work and analyses are necessary to make a conclusive interpretation. The numerous smaller granodiorite intrusives mapped as Horse Creek granodiorite (Plate II) are thought to represent satellitic phases of the larger Horse Creek granodiorite sill.

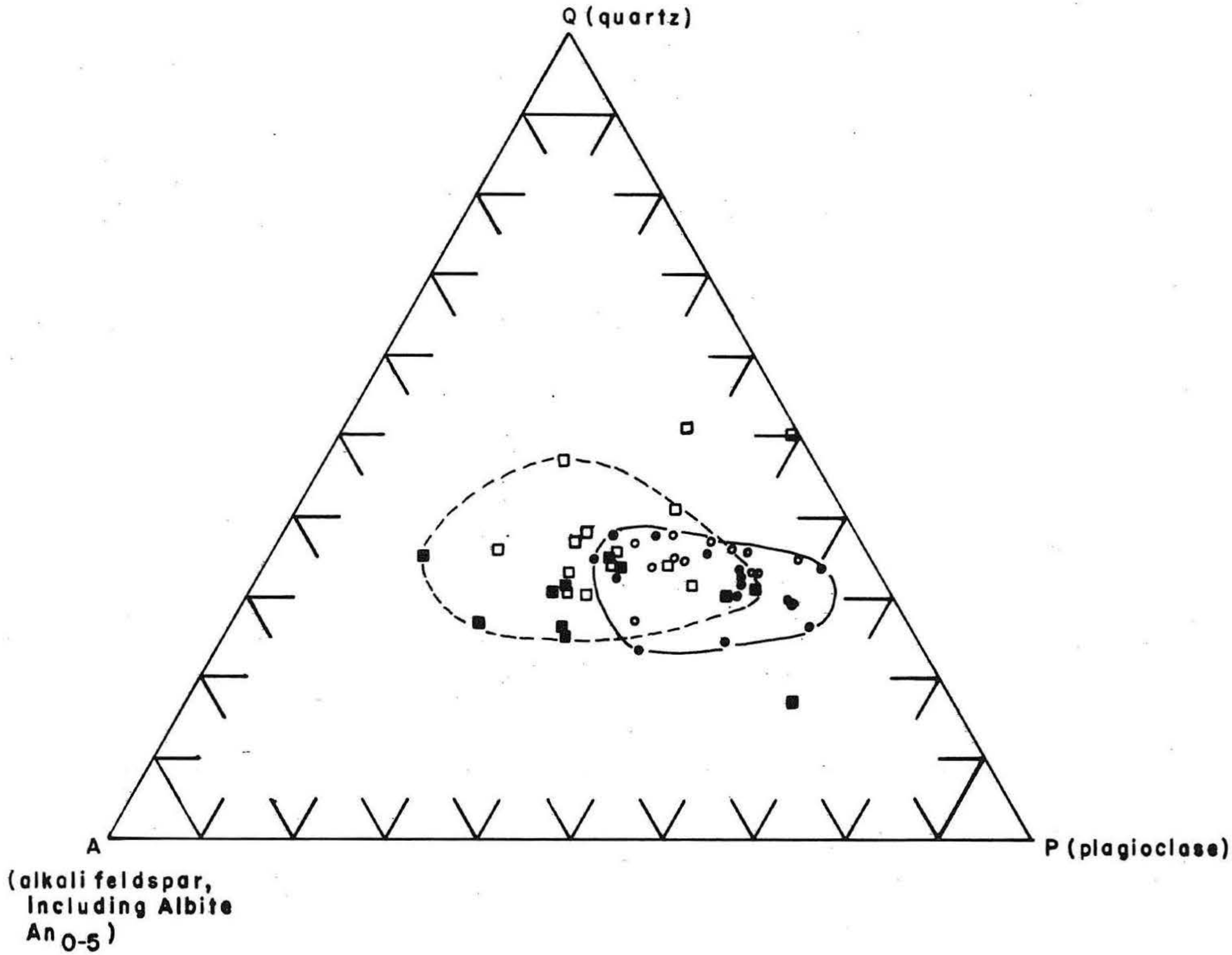


Fig. 24. Triangular diagram displaying modal composition of felsic rocks in the study area and adjacent areas. Solid symbols represent felsic rocks north of the study area (Ramirez, 1971). Open symbols represent rocks from study area. Dashed line encloses predominant field of Younger Felsic intrusives. Solid line outlines field of Horse Creek granodiorite.

Because of the wide range of compositions and limited exposed field relationships, the younger felsic unit may include different phases of felsic rock that represent different ages of emplacement. Numerous small pegmatitic bodies exposed in the western part of the study area resemble the conformable type of pegmatite described by Houston (1961) in the Big Creek area as opposed to the zoned rare-earth bearing cross-cutting type also found in that area. However, as noted by Houston (1961), gradations between the conformable and cross-cutting types exist and distinctions between the two are sometimes arbitrary. Although these pegmatitic phases may not be genetically equivalent to the younger felsic bodies, Houston (1968, p. 81) suggests that these phases were introduced at approximately the time of formation of the younger felsic bodies.

It is interesting to note that the bulk of the younger felsic intrusions lie along the inferred NW fold axis (Plate I and II), as is the case with the metadiabase. Emplacement along a zone of weakness in the folded mafic sequence is suggested. The relatively unmetamorphosed nature of these rocks and slight cataclastic overprint infer a late syn- or post-kinetic time of emplacement following an earlier kinetic event recorded in the mafic sequence.

METAMORPHISM

The complex geologic history of the Precambrian rocks in the study area and immediate vicinity carries a connotation of similar complex history of metamorphism. All rocks in the study area show variable degrees of regional and kinetic metamorphism induced by multiple events.

Gneissic rocks, which served as hosts for mafic and felsic intrusions have been metamorphosed to the amphibolite facies. These rocks are characterized by a typical assemblage of hornblende-andesine-quartz-epidote-sphene. Calcareous rocks are modified to calcite-diopside-epidote-garnet-quartz assemblages. The gneissic rocks were metamorphosed during an early metamorphic event preceding intrusion of the mafic complex. Further south in Colorado, similar rocks are intruded by granite as old as $1.700 \pm$ m.y. (Peterman and Hedge, 1968) and within the mafic complex, age dates on felsic units of $1,760 \pm 60$ (Hills, pers. commun., 1977) set a minimum age for emplacement of the layered gabbroic sequence.

Mafic rocks in the Mullen Creek mafic complex are predominantly metamorphosed to amphibolite grade. Within the complex, mafic rocks show variable degrees of metamorphism ranging from only slightly altered rocks with preserved mineral assemblages and textures to orthoamphibolite. There does not appear to be progressive metamorphism between the two extremes, rather, there appears to be isolated areas of only slightly metamorphosed mafic rock in otherwise amphibolite facies terrain. Poldervaart (1953) indicates that rocks of basaltic composition may follow several different trends during metamorphism: diabase-greenschist, diabase-amphibolite, and diabase-granulite. Poldervaart (1953) suggests that these different trends commonly develop in the same terrain even when rocks were of similar composition. Allard (1970, p. 490) notes that in the Dore Lake mafic complex of Quebec, fresh unmetamorphosed mafic rocks grade into their greenschist facies equivalents within short distances. Allard (1970) explains the controls of this selective metamorphism as rock permeability and availability of water along structural displacements. This may in part explain the variation in metamorphic grade in the study area; higher metamorphic grade may have occurred in areas subjected to greater stress. This may be shown by the absence of crushed and granulated crystals in mafic rock retaining their primary mineralogy. Retrogressive greenschist grade metamorphism, superposed on higher grade metamorphic rocks, is shown by the development of biotite-chlorite-epidote assemblages. This retrograde event is thought to have occurred during a deformational event subsequent to an earlier regional amphibolite grade event, possibly analogous to a later period of kinetic metamorphism at lower amphibolite-upper greenschist grade suggested by McCallum (1964, p. 95; 1974, pp. 473-474, 476) for rocks north of the study area. Age dating by Hills et al. (1968) suggests, a regional metamorphic event may have occurred during a major thermal episode between 1,600 - 1,455 m.y. ago.

Intrusion of younger felsic phases, possibly during the waning stages of a regional or kinetic event was accompanied by contact and metasomatic modifications of the metagabbro host. The development of bleached amphiboles, saussuritization, and seritization is especially pronounced in hybrid rocks, indicating the effects of hydrothermal solutions and metasomatism. The presence of scapolite in metagabbro may be interpreted as having formed with introduction of the felsic phases, or during an earlier regional thermal event. Scapolite is reported to form in a broad range of pressure and temperature conditions during metamorphism coupled with pegmatitic, pneumatolytic, or hydrothermal activity (Shaw, 1960, p. 284).

MINERALIZATION

Mineralization observed in the study area is restricted to narrow quartz veins with modest amounts of copper and gold. Mineralized veins occur predominately in northwesterly trending faults and shear zones that are subsequently displaced by barren northly trending faults. Several mineralized faults show multiple periods of displacement, indicated by brecciated and granulated vein rock annealed with calcite and chalcedony. Vein mineralogy consists of quartz-carbonate (siderite, calcite, and ankerite)-pyrite-arsenopyrite$\pm$tourmaline (schorl) $\pm$gold. Supergene covellite, malachite, and limonites are common.

Numerous samples were taken for assay from prospect pits, mine dumps, and gossans. Results of these analyses (McCallum and others, 1979) are given in Appendix, Table 4. Sample locations are shown on Plate 2.

Anomalous gold values and visible gold occur at the Golden Key Mine and two unnamed prospects in Sec. 30, T14N, R79W.

The Golden Key mine, which is located in Sec. 10, T14N, R79W, is a small gold-bearing pyritic quartz vein in a northwest trending fault. Prospecting along the vein consists of two shallow shafts and several prospect pits. The quartz vein contains pyrite, chalcopyrite, limonites after carbonates and small amounts of gold. Loucks

(1976, p. 163) reports that gold occurs mainly as disseminated grains in quartz and as leaves along microfractures.

Prospects in Sec. 30, T14N, R79W, consist of several shafts and prospect pits along at least two different vein systems. One shaft, situated northwest of the Boat Creek Road, is a shallow shaft intersecting a 0.1-0.15 meter wide vein in younger felsic rocks. The quartz vein contains arsenopyrite, chalcopyrite, limonite, rhombohedral casts of limonite after carbonates, and traces of free gold. A shaft immediately adjacent to the road is sunk in metagabbro. Similar vein material was observed, however, no gold was found. Immediately northwest of this shaft along the same fault, prospect pits have uncovered quartz vein material with chalcopyrite, arsenopyrite, limonite after carbonates, and traces of free gold in limonite.

Numerous other prospect pits were examined and sampled during this investigation. However, all are similar in mineralogy to those described above and all are apparently barren.

Loucks (1976), in an extensive study of vein mineralization in an area east and slightly overlapping with the writer's study area, found numerous vein occurrences similar to those described. In nearly all cases, Loucks (1976) reports that those veins carrying anomalous amounts of gold, copper, and platinum group elements are intimately associated with mafic metaigneous rocks. Although no veins were found to contain anomalous amounts of platinum in the study area, a large number of prospects and abandoned mines in the district are reported to contain anomalous amounts of these metals (Loucks, 1976; McCallum and Orback, 1968; McCallum and others, 1976), and at least one, the Rambler Mine, has shown platinum production (McCallum and others, 1976). Loucks (1976) concludes that mafic rocks are the principal source of metals in these hydrothermal deposits and that the metals were leached following the buildup of H_2O and CO_2 derived from metamorphic pore fluids and fluid inclusions that were liberated during regional cataclasis and metamorphism. Hydrothermal solutions migrated along shear zones and faults and collected in lower pressure dilation structures. For a thorough treatment of processes of vein formation and descriptions of mineralized vein occurrences in the district, the reader is referred to Loucks (1976) and McCallum and others (1976).

Although no magmatic ore deposits associated with the layered gabbroic sequence are known in the Mullen Creek mafic complex, deposits in similar terrains are known throughout the world. Metals associated with these deposits include chromite, platinum, vanadiferous magnetite, copper, and nickel (e.g., Vermaack, 1976; Jackson, 1961, 1963; and Allard, 1976). The intensive tectonic overprint on the Mullen Creek mafic complex, coupled with its lack of accessibility and poor exposure prevented its layered identity to be realized until first recognized by McCallum in 1969 in early work in the Keystone quadrangle and finally documented in this report. These factors have hindered a systematic search of these metals in the complex and may make it an attractive target for further exploration.

GEOLOGIC HISTORY

Reconstruction of the geologic history of the study area remains partly conjectural due to the limited areal extent of the area studied. It has been demonstrated in this report that numerous mafic and felsic intrusive episodes have taken place in the Mullen Creek mafic complex as well as multiple metamorphic and deformational events. Reconstruction of Precambrian rock chronology is always difficult in complex terrains, thus the following is an approximate chronologic order of events recorded in rocks within the study area.

1. Development of the hornblende-andesine-quartz gneiss and quartzofeldspathic gneisses which served as host for later introduction of mafic and felsic magma. Origin of the gneisses is partly speculative, but they are thought to represent rocks of original igneous and sedimentary parentage that now show similar mineralogic and textural features (Houston et al., 1968, p. 65). No age dates are available for these rocks, but a limited number of samples with rubidium to strontium ratios suitable for study from the southwestern corner of the Medicine Bow Mountains did not retain evidence of the 2.4 b.y. event recorded north of the Mullen Creek-Nash Fork shear zone in similar rocks (Hills et al., 1968; Hills and Armstrong, 1974). However, the samples did not fit an isocron, and no definitive

age dates are available for the gneissic units in the southern Medicine Bow Mountains.

2. Intrusion of basaltic magma in the area now occupied by the Mullen Creek metaigneous mafic complex. Numerous periods of basaltic magma emplacement have been demonstrated in this study, and they have resulted in a varied metagabbroic-metadiabasic-metabasaltic rock assemblage. Gravitational differentiation of a major pulse(s) of mafic activity gave rise to the main body of layered gabbroic rock described in this report. This was followed by numerous basaltic events forming what is now late-stage metagabbro. In the east and northeast corner of the complex, felsic rocks are dated at 1760 $\pm$ 60 m.y. (Hills, per. commun., 1975) setting a minimum age for intrusion of the gabbro.

3. Two episodes of folding are thought to have occurred before basaltic dike emplacement and possibly contemporaneous with or preceding intrusion of diabase. Emplacement of Horse Creek granodiorite occurred prior to folding as shown by its folded and refolded nature.

4. Regional metamorphism following emplacement of the mafic bodies generated amphibolite grade metamorphism that characterizes most mafic rock in the complex.

5. Emplacement of younger felsic intrusives, possibly during the waning stages of regional metamorphism, was the last igneous

event recorded in the study area. These rocks may correlate in age with the approximately 1,700 m.y. old Boulder Creek plutons in northern Colorado (Mussard and McCallum, 1977).

6. Kinetic metamorphism at lower amphibolite-upper greenschist grade gave rise to shearing and granulation found in many mafic rocks, in the Horse Creek granodiorite, and locally in younger felsic intrusions. Shear zones north of the study area were apparently activated and reactivated during this time (McCallum, 1974). Hills et al. (1968) notes one or more periods of metamorphism in the Medicine Bow Mountains between 1,600 and 1,455 ± 40 m.y. ago that may coincide with this period of metamorphism.

7. Reactivation of faulting along pre-existing shear zones and faults appears to have taken place during the Laramide orogeny accompanied by localized vein mineralization.

8. Tertiary sedimentation, deformation, and erosion, documented northeast of the study area by Knight (1953) and McCallum (1964, p. 126-133, 1968), was active during this period even though no Tertiary sediments are preserved in the study area.

9. Erosion apparently dominated much if not all of Quaternary time in the area.

CONCLUSIONS

Geologic mapping by this writer and others in the Mullen Creek mafic complex has distinguished five mafic phases and three felsic phases in the study area. Inadequate exposure has limited observable relationships between the units and hindered the reconstruction of the chronologic order of some events. However, it now appears that the main body of the complex represents a folded and metamorphosed gabbroic mass that underwent gravitational differentiation from a tholeiitic basaltic magma. Structural and textural features suggest convection was operative during at least part of the cooling history. Limited geochemical data suggests cryptic variation is present in this stratified sequence and local reversals and cyclic fluctuations are present. Comparison of the bulk chemistry between zones indicates there is increasing phosphorus, sodium, titanium, zirconium, iron to magnesium ratio, and decreasing nickel in the bulk chemistry of similar units with increasing stratigraphic height. Subsequent basaltic activity gave rise to diabase, a late stage gabbro, and two episodes of basalt dikes, one of which post dates emplacement of the Horse Creek granodiorite. The conformable nature of the granodiorite suggests it may represent a final felsic differentiate of the stratified gabbroic sequence.

Two episodes of folding occurred early in the history of the complex. Fold patterns are thought to have structurally influenced emplacement of younger felsic intrusives. Partial mapping of the complex suggests that it is folded anticlinally with a slightly overturned axis plunging steeply to the northwest. Refolding of the complex resulted in a shallow, westerly plunging synanticlinal fold expressed along the east margin of the complex and is inferred to the western portion of the complex, explaining the apparent great thickness of the stratified sequence.

Regional metamorphism at amphibolite grade has effected the entire mafic complex although isolated segments remain relatively unchanged. Younger felsic intrusive phases may have been emplaced during the waning stages of this metamorphic event. Extensive hybridization of host metagabbro accompanied younger felsic intrusive activity with development of rocks with a metadiorite composition. A late kinetic metamorphic event at lower amphibolite-upper greenschist grade produced both tectonites and localized retrograde metamorphism at greenschist grade.

Gold mineralization, the only mineralization found in the study area, occurs in narrow quartz-carbonate veins occupying northwest trending faults. Gold and sulfide mineralization is thought to be a result of liberation of H_2O, CO_2, and the various metals during regional cataclasis and metamorphism. Brecciated faults and vein material and offset of earlier faults by northeast trending faults attest to reactivation and displacement during the Laramide orogeny.

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APPENDIX

Table 1. Microprobe analyses of olivines. Number in parenthesis following sample number refers to number of grains probed in sample. Samples marked with asterisk are included in this report for comparative purposes only.

Sample number	22-91(5)	22-155(4)	22-160(3)	22-403(2)	*22-470(4)	*22-475(2)
SiO_2	39.76	39.61	38.71	38.92	39.84	40.63
TiO_2	--	--	--	--	--	--
Al_2O_3	--	--	0.01	--	0.10	0.12
FeO	22.49	22.44	29.56	19.53	24.48	18.82
MgO	40.25	39.47	34.10	43.26	38.64	45.64
CaO	--	--	--	--	--	--
Cr_2O_3	0.02	--	0.03	--	0.01	--
MnO	0.41	--	0.29	0.09	0.31	0.21
Total	102.93	101.52	102.70	101.80	103.18	105.42
<u>Atomic Proporations for 6 Oxygen Atoms</u>						
Si	1.002	1.011	1.010	0.981	1.008	0.982
Ti	--	--	--	--	--	--
Al	--	--	--	--	0.003	0.004
Fe	0.474	0.479	0.645	0.411	0.514	0.381
Mg	1.512	1.501	1.326	1.625	1.458	1.645
Ca	--	--	--	--	--	--
Cr	--	--	0.001	--	0.001	--
Mn	0.009	--	0.006	0.020	0.007	0.004
<u>Atomic Percentage</u>						
Fe	76.14	75.80	67.40	79.72	73.90	80.95
Mg	23.86	24.20	32.60	20.28	26.1	19.05

Table 2. Microprobe analyses of orthopyroxenes. Number in parenthesis following sample number refers to number of grains probed in sample.

Sample number	22-91(2)	22-92(2)	22-155(1)	22-160(2)	22-403(1)	22-470(2)	22-471(3)	22-475(3)
SiO_2	52.15	53.36	53.96	50.95	54.46	53.26	51.97	54.58
Al_2O_3	1.58	1.72	1.58	1.94	1.23	1.53	1.11	2.32
MgO	25.81	25.68	28.48	24.09	31.60	26.48	21.71	30.84
CaO	0.94	1.21	1.25	1.01	0.11	1.25	0.85	0.80
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21
FeO	17.36	19.09	13.65	20.30	12.51	13.81	24.65	11.33
TiO_2	0.32	0.40	0.54	0.23	0.21	0.36	0.42	0.05
K_2O	0.08	0.00	0.08	0.04	0.00	0.09	0.00	0.00
MnO	0.44	0.30	0.34	0.22	0.32	0.37	0.71	0.26
Total	98.68	101.76	99.89	98.78	100.45	97.15	101.42	100.39
Atomic Proportions for 6 Oxygen Atoms								
Si	1.932	1.927	1.938	1.912	1.929	1.963	1.936	1.925
Al	0.069	0.073	0.067	0.085	0.051	0.067	0.049	0.097
Mg	1.425	1.383	1.525	1.348	1.669	1.455	1.206	1.622
Ca	0.037	0.046	0.048	0.041	0.004	0.049	0.034	0.030
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014
Fe	0.537	0.576	0.410	0.638	0.371	0.438	0.768	0.337
Ti	0.009	0.011	0.015	0.006	0.006	0.010	0.012	0.001
K	0.003	0.000	0.004	0.002	0.000	0.004	0.000	0.000
Mn	0.014	0.009	0.010	0.007	0.010	0.012	0.022	0.008
Atomic Percentage								
Ca	1.84	2.31	2.71	2.02	0.20	2.51	1.67	0.25
Mg	70.75	68.63	75.40	66.04	81.40	74.46	59.41	82.16
Fe	27.41	29.06	21.88	31.94	18.40	23.03	38.92	17.59

Table 3. Microprobe analyses of clinopyroxenes. Number in parenthesis following sample number refers to number of grains probed in sample.

Sample number	22-91(2)	22-92(2)	22-155(2)	22-160(1)	22-470(2)	22-471(3)
SiO_2	52.59	51.93	49.38	50.56	42.91	51.21
Al_2O_3	1.21	2.75	3.21	2.17	11.10	2.41
MgO	14.63	15.23	15.60	14.73	15.70	14.47
CaO	22.00	22.06	20.12	20.96	21.96	21.58
Na_2O	0.51	0.43	0.40	0.25	2.00	0.25
FeO	5.74	7.19	6.56	7.84	5.63	10.10
TiO_2	0.36	0.55	0.56	0.44	1.49	0.62
K_2O	0.11	0.00	0.08	0.09	0.33	0.00
MnO	0.11	0.27	0.19	0.16	0.09	0.34
Total	97.26	100.41	96.10	97.20	100.31	100.98
Atomic Proportions for 6 Oxygen Atoms						
Si	1.977	1.917	1.898	1.932	1.609	1.905
Al	0.050	0.120	0.145	0.098	0.490	0.105
Mg	0.820	0.839	0.892	0.839	0.877	0.802
Ca	0.927	0.872	0.829	0.858	0.846	0.860
Na	0.037	0.931	0.030	0.019	0.109	0.017
Fe	0.181	0.222	0.211	0.250	0.177	0.314
Ti	0.011	0.015	0.016	0.013	0.042	0.017
K	0.005	0.000	0.004	0.005	0.016	0.000
Mn	0.003	0.008	0.006	0.005	0.003	0.011
Atomic Percentage						
Ca	48.02	48.27	42.75	43.95	44.47	43.28
Mg	42.48	38.43	46.05	42.98	46.10	40.36
Fe	9.50	13.29	11.19	13.06	9.46	16.36

Table 4. Analyses of selected mineralized vein samples and rock samples. All values in ppm. Au, Pd, and Pt by fire assay-emission spectrography. Co, Cr, Mo, Ni, Pb, Zn, and As by semiquantitative D.C. arc spectroscopy. Analysis techniques and analysts (all of the U.S. Geological Survey) are given in McCallum and others (1979). Abbreviations: ND (.002) = not detected at detection limit of .002 ppm. L = detected but below determination limits, and G = greater than the value shown.

Sample number and description		Pt	Pd	Au	Ag	Co	Cr	Cu	Mo	Ni	Pb	Zn	As
22-1A	Vein material	.012	.008	G(10)	--	200	10	300	N	100	1000	1000	5000
22-1B	Vein material	.005	.012	.80	--	10	10	300	20	30	L	L	5000
22-1C	Vein material	N	.003	G(10)	--	100	N	300	15	100	50	500	5000
22-1D	Vein material	.009	.014	G(10)	--	100	10	500	10	70	10	300	2000
22-2A	Vein material	N(.004)	.008	1.0	--	200	10	300	N	200	N	N	L
22-2B	Vein material	.005	.005	G(10)	--	70	10	1000	N	50	100	500	2000
22-2C	Vein material	.007	.012	5.0	--	30	10	500	20	50	N	L	5000
22-2D	Vein material	N(.004)	N(.002)	G(20)	--	100	N	200	N	30	200	500	3000
22-5	Metagabbro	N(.002)	.008	--	N	50	500	50	N	150	N	N	N
22-66	Metagabbro	.011	.002	--	N	70	300	70	N	150	N	N	N
22-75A	Vein material	N(.002)	.002	3.0	--	10	N	500	30	20	N	N	N
22-75B	Vein material	N(.002)	.001	1.0	--	10	N	2000	N	20	N	N	N
22-77	Metadiabase	.008	.007	--	N	70	200	150	N	200	L	N	N
22-86B	Metagabbro	N(.002)	.001	--	N	50	300	150	N	100	L	N	N
22-91	Metagabbro	.002	.007	--	N	70	200	70	N	700	L	N	N
22-97	Granodiorite	--	--	N	N	5	L	L	N	10	20	N	N
22-122	Granodiorite	--	--	N	N	10	L	L	N	7	15	N	N
22-137	Metagabbro	.030	.016	.01	--	20	150	1500	L	70	N	N	N
22-150	Metagabbro	.002	.001	--	N	50	300	70	N	150	N	N	N
22-160	Metaleucogabbro	N(.002)	.009	.025	--	100	150	1500	10	200	N	N	N
22-182	Granodiorite	--	--	N	N	5	L	10	N	20	15	N	N
22-185	Metagabbro	.006	.006	.002	--	50	100	200	N	70	N	N	N
22-190	Younger felsic	--	--	N	N	5	L	10	N	5	20	N	N
22-199	Metagabbro	N(.002)	.002	--	N	30	500	30	N	100	L	N	N
22-203	Metapyroxenite	N(.002)	N(.001)	--	N	70	500	70	N	700	L	N	N
22-205	Metapyroxenite	N(.002)	N(.001)	.005	--	150	700	100	N	1500	N	N	N
22-208	Vein material	N(.002)	N(.001)	.7	--	10	N	70	N	15	N	N	N
22-212	Metadiabase	N(.002)	.003	.002	--	70	150	100	N	300	N	N	N
22-237	Metagabbro	.007	.004	.009	--	70	150	100	N	300	N	N	N
22-238	Younger felsic	--	--	N	N	10	L	10	N	5	10	N	N
22-243	Younger felsic	--	--	N	N	5	L	10	N	7	L	N	N

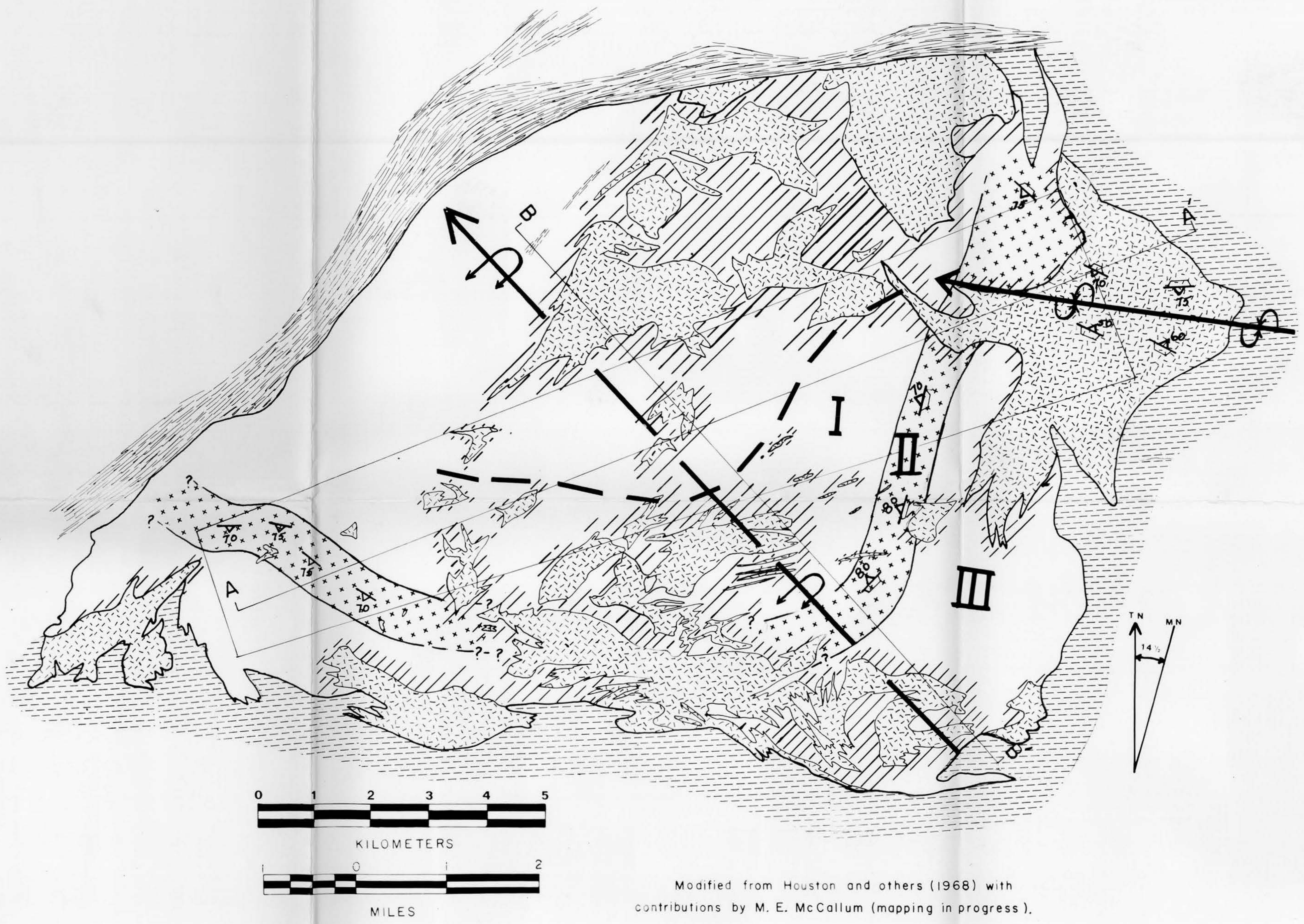
Table 4 (Continued).

Sample number and description	Pt	Pd	Au	Ag	Co	Cr	Cu	Mo	Ni	Pb	Zn	As
22-245 Metapyroxenite	N(.002)	N(.001)	.003	--	100	50	70	N	1500	N	L	N
22-251A Metaleucogabbro	N(.002)	.006	.002	--	50	200	70	N	150	N	N	N
22-251B Metaleucogabbro	.003	.005	--	N	50	500	20	N	100	L	N	N
22-255 Metagabbro	.007	.005	--	N	50	200	70	N	150	L	N	N
22-256 Metapyroxenite	N(.002)	N(.001)	--	N	70	300	50	N	200	L	N	N
22-262 Metagabbro	.007	.004	--	N	70	500	150	N	70	L	N	N
22-267 Metagabbro	N(.002)	.003	--	N	20	200	50	N	50	N	N	N
22-270 Metagabbro	.004	.001	--	N	20	150	50	N	70	L	N	N
22-274 Metagabbro	.003	N(.001)	.005	--	70	30	150	N	100	N	N	N
22-279 Metagabbro	.008	.006	.007	--	50	50	150	N	100	N	N	N
22-298 Granodiorite	--	--	N	N	5	L	5	N	10	10	N	N
22-301 Metapyroxenite	N(.004)	N(.002)	.008	--	100	1000	70	N	1000	N	L	N
22-315A Vein material	.003	.019	.17	--	100	20	200	N	200	N	N	N
22-315B Vein material	.008	.025	.250	--	500	50	500	L	500	N	N	N
22-318 Anorthosite	N(.002)	N(.001)	--	N	L	N	200	N	70	N	N	N
22-327 Metagabbro	N(.002)	.001	--	N	50	100	30	N	200	N	N	N
22-328 Granodiorite	--	--	N	N	5	10	20	N	10	15	N	N
22-334A Vein material	.005	.018	.160	--	300	10	1000	N	150	N	N	N
22-335 Metadiabase	.006	.004	--	N	70	10	150	N	50	N	N	N
22-337 Younger felsic	--	--	N	N	5	L	5	N	10	L	N	N
22-339 Metagabbro	N(.004)	N(.002)	.008	--	50	300	70	N	300	N	L	N
22-352 Metapyroxenite	N(.004)	N(.002)	.002	--	200	500	50	N	1000	N	L	N
22-356 Younger felsic	--	--	N	N	5	L	15	N	10	20	N	N
22-365 Metagabbro	N(.002)	N(.001)	.035	--	100	10	300	N	200	N	L	N
22-370 Metaleucogabbro	.002	.001	--	N	20	150	30	N	70	L	N	N
22-371 Metabasalt	N(.002)	N(.001)	--	N	100	30	70	N	200	N	N	N
22-376 Vein material	N(.002)	N(.001)	--	N	L	L	200	N	5	L	N	N
22-386A Vein material	N(.002)	.017	1.0	--	500	N	1500	200	100	N	N	N
22-386B Vein material	N(.004)	.014	2.0	--	50	N	20,800	150	30	N	N	N
22-386C Vein material	N(.002)	.014	.50	--	150	N	1500	700	50	N	N	N
22-386D Vein material	N(.002)	.006	.25	--	15	N	1000	700	10	N	N	N

Table 5. Whole rock analyses. All values in percent. Analysts (all of the U.S. Geological Survey) and techniques described by McCallum and others (1979). Sample description abbreviations used: YG=younger felsic intrusive, HCG=Horse Creek granodiorite, MG=metagabbro and metaleucogabbro, MD=metadiabase, MB=metabasalt, MP=metapyroxenite.

Sample number description	22-5 MG	22-47 MB	22-61 MD	22-77 MD	22-92 MG	22-98 HCG	22-123 MD	22-137 MG	22-155 MG	22-160 MG	22-235 HCG	22-238 HCG	22-240 MG	22-274 MG
SiO_2	49.8	47.0	50.5	52.0	50.4	69.1	54.3	47.2	46.3	42.3	71.0	67.5	49.9	52.0
TiO_2	0.26	0.56	0.60	0.63	0.58	0.34	0.69	0.12	0.26	0.71	0.18	0.64	0.83	0.89
Al_2O_3	23.7	17.0	16.0	16.3	15.0	14.3	16.5	26.4	16.2	16.0	14.3	14.4	15.4	14.9
Fe_2O_3	1.5	2.9	2.8	2.7	2.4	2.4	2.5	0.9	1.8	5.6	1.3	2.5	3.3	3.9
FeO	2.5	8.0	6.4	6.0	5.4	0.8	5.4	2.5	5.3	8.3	0.6	2.3	6.6	6.6
MnO	0.08	0.19	0.17	0.15	0.16	0.06	0.14	0.07	0.13	0.16	0.05	0.06	0.19	0.16
MgO	5.8	8.0	7.4	7.0	9.3	0.65	5.1	5.3	11.1	10.2	0.58	0.88	7.7	6.5
CaO	14.7	10.0	10.0	10.0	12.9	1.7	8.6	16.3	15.8	13.6	1.8	3.6	10.0	9.6
Na_2O	1.87	2.19	2.81	2.24	1.65	3.37	2.92	1.06	0.65	0.66	3.27	4.06	2.94	2.93
K_2O	0.20	0.45	0.89	0.88	0.36	4.90	1.15	0.09	0.14	0.06	4.31	1.97	0.98	0.65
P_2O_5	0.15	0.13	0.24	0.34	0.33	0.11	0.28	0.07	0.10	0.06	0.08	0.29	0.52	0.40
H_2O+	0.63	1.7	0.63	0.52	0.57	0.65	0.77	0.93	0.48	0.7	0.58	0.68	1.2	0.77
H_2O-	0.84	0.19	0.09	0.48	0.06	0.07	0.06	0.07	0.06	0.11	0.07	0.07	0.08	0.06
CO_2	0.03	0.01	0.02	0.02	0.01	0.01	0.01	0.04	0.03	0.06	0.02	0.01	0.01	0.01
Total	102.06	98.32	98.55	99.44	99.12	98.46	98.42	101.05	98.35	98.52	98.14	98.96	99.65	99.37

DIAGRAMMATIC GEOLOGIC MAP OF THE MULLEN CREEK MAFIC COMPLEX



Modified from Houston and others (1968) with contributions by M. E. McCallum (mapping in progress).

EXPLANATION

FELSIC INTRUSIVES

HYBRIDIZED MAFIC ROCKS

METALEUCOGABBRO

DOMINANTLY METAGABBRO

HORNBLENDE GNEISS

SHEAR ZONE

STRIKE AND DIP OF FOLIATION

STRIKE AND DIP OF OVERTURNED FOLIATION

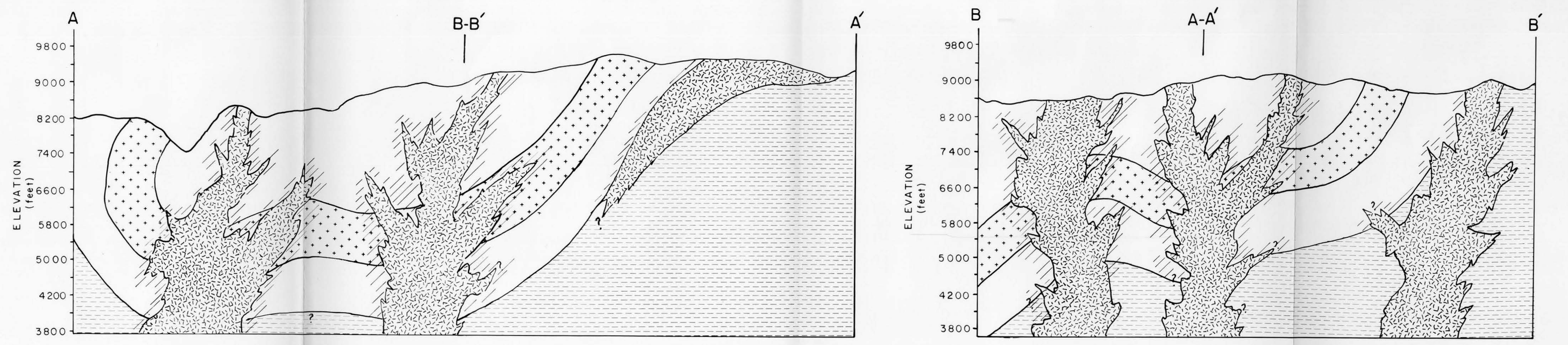
ASYMMETRIC ANTICLINE SHOWING DIRECTION OF PLUNGE AND DIP OF LIMBS

OVERTURNED SYNCLINE SHOWING DIRECTION OF PLUNGE

II ZONES DESCRIBED IN TEXT

STUDY AREA IN BOX INSET

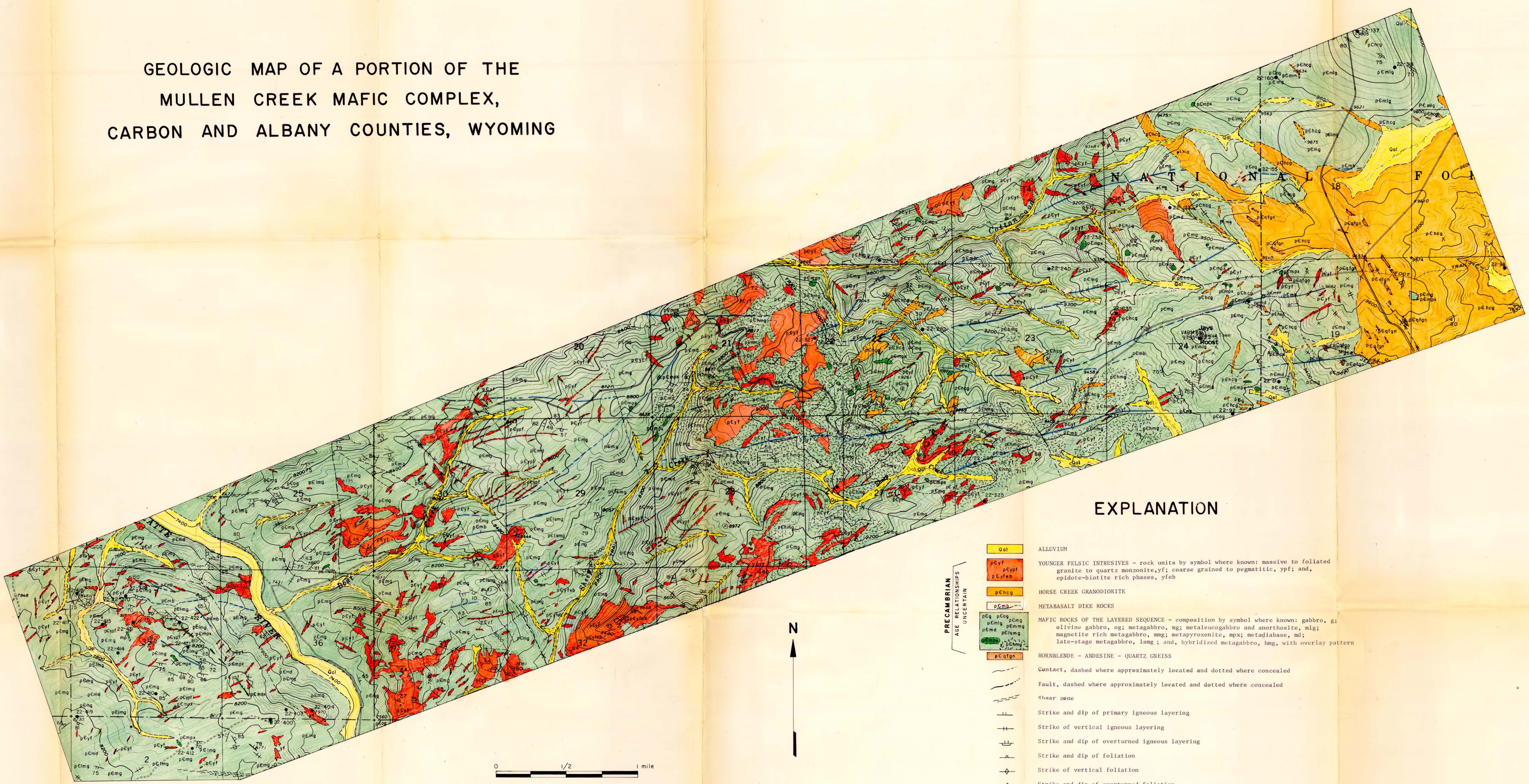
DIAGRAMMATIC CROSS SECTIONS



Drawn by Michael Donnelly, 1979.

PLATE I

GEOLOGIC MAP OF A PORTION OF THE MULLEN CREEK MAFIC COMPLEX, CARBON AND ALBANY COUNTIES, WYOMING



N

0 1/2 1 mile

0 1/2 1 kilometer

Geology by Michael Donnelly.
Geology mapped in 1974 and 1975.

EXPLANATION

PRECAMBRIAN — AGE RELATIONSHIPS UNCERTAIN

Qal — ALLUVIUM

pЄyf, pЄypf, pЄyfeb — YOUNGER FELSIC INTRUSIVES - rock units by symbol where known: massive to foliated granite to quartz monzonite, yf; coarse grained to pegmatitic, ypf; and, epidote-biotite rich phases, yfeb

pЄhcg — HORSE CREEK GRANODIORITE

pЄmb — METABASALT DIKE ROCKS

pЄg, pЄog, pЄmg, pЄmlg, pЄmmg, pЄmd, pЄlsmg, pЄmpx, pЄhmg — MAFIC ROCKS OF THE LAYERED SEQUENCE - composition by symbol where known: gabbro, g; olivine gabbro, og; metagabbro, mg; metaleucogabbro and anorthosite, mlg; magnetite rich metagabbro, mmg; metapyroxenite, mpx; metadiabase, md; late-stage metagabbro, lsmg ; and, hybridized metagabbro, hmg, with overlay pattern

pЄqfgn — HORNBLENDE - ANDESINE - QUARTZ GNEISS

Contact, dashed where approximately located and dotted where concealed

Fault, dashed where approximately located and dotted where concealed

Shear zone

Strike and dip of primary igneous layering

Strike of vertical igneous layering

Strike and dip of overturned igneous layering

Strike and dip of foliation

Strike of vertical foliation

Strike and dip of overturned foliation

Strike and dip of joints

Mine shaft

Prospect pit

Trench

● 22-75 Sample location and sample number

PLATE II