



Archean geology of a part of the northern Gallatin Range, southwest Montana
by Karen Anne May

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Earth Sciences

Montana State University

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Abstract:

The northern Gallatin Range in southwest Montana is predominantly composed of regionally metamorphosed Archean quartzofeldspathic gneisses with minor amounts of metabasites. This study characterizes the petrography, petrology, and structure of Archean rocks exposed in a part of the northern Gallatin Range to determine the Archean tectonic evolution of this part of southwest Montana. Metamorphism in the study area ranges from epidote-amphibolite to transitional granulite facies. These rocks are believed to have initially experienced a transitional granulite facies metamorphic event (M1) followed by epidote-amphibolite facies conditions (M2). Retrograde assemblages in the study area rocks may be indicative of a greenschist thermal event (M3?). A dominant N45E structural grain is expressed by foliation strikes and fold hinge line trends. Polyphase deformation is evident based on the identification of two fold generations. Isoclinal folds were produced during an earliest (M1) event. Coaxial open folds were subsequently produced during M2. The tectonic setting for study area rocks is best represented by an ensialic basin depositional environment that was subsequently deformed via A-type subduction processes.

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APPROVAL

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Waren Anne May

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December 18, 1985

To my parents, for twenty-nine years of patience and support.

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ERRATA

The following corrections should be noted:

The location abbreviations S-13 and S-14 found on the following pages should instead read S-12 and S-13, respectively:

page 48

page 51 (text only - figure caption on this page is correct).

page 55

page 84

This section label S-13 on table 7, page 91 should instead read S-43.

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ABSTRACT

The northern Gallatin Range in southwest Montana is predominantly composed of regionally metamorphosed Archean quartzofeldspathic gneisses with minor amounts of metabasites. This study characterizes the petrography, petrology, and structure of Archean rocks exposed in a part of the northern Gallatin Range to determine the Archean tectonic evolution of this part of southwest Montana. Metamorphism in the study area ranges from epidote-amphibolite to transitional granulite facies. These rocks are believed to have initially experienced a transitional granulite facies metamorphic event (M1) followed by epidote-amphibolite facies conditions (M2). Retrograde assemblages in the study area rocks may be indicative of a greenschist thermal event (M3?). A dominant N45E structural grain is expressed by foliation strikes and fold hinge line trends. Polyphase deformation is evident based on the identification of two fold generations. Isoclinal folds were produced during an earliest (M1) event. Coaxial open folds were subsequently produced during M2. The tectonic setting for study area rocks is best represented by an ensialic basin depositional environment that was subsequently deformed via A-type subduction processes.

INTRODUCTION

Foreword and Statement of Purpose

The northern Gallatin Range in southwest Montana lies in the northwestern part of the Wyoming Archean Province (Figure 1) and is predominantly composed of regionally metamorphosed Archean quartzofeldspathic gneisses with minor amounts of metabasites. The metamorphic grade of these rocks ranges from epidote-amphibolite to transitional granulite facies. The nature of protoliths and a tectonic setting for Archean rocks in southwest Montana is currently speculative and incompletely understood. As a result, our present state of knowledge of Archean evolution of continental crust in this area is limited. The study area is located near the transition from predominantly igneous and meta-igneous rocks in the Beartooth Range to the east and a predominantly metasupracrustal terrane in the ranges to the west (Figure 2, Mogk et al, in review). This study provides additional petrographic, petrologic, and structural detail for a part of the Archean rocks in this critical transition area. Mylonites, migmatites, and transitional granulites present in the study area provide details vital to an analysis of the Archean tectonic evolution of southwest Montana.

The objectives of this research are threefold: 1) to describe the lithologies and structures of the Archean basement rocks present in the study area, 2) to characterize their petrogenesis and subsequent

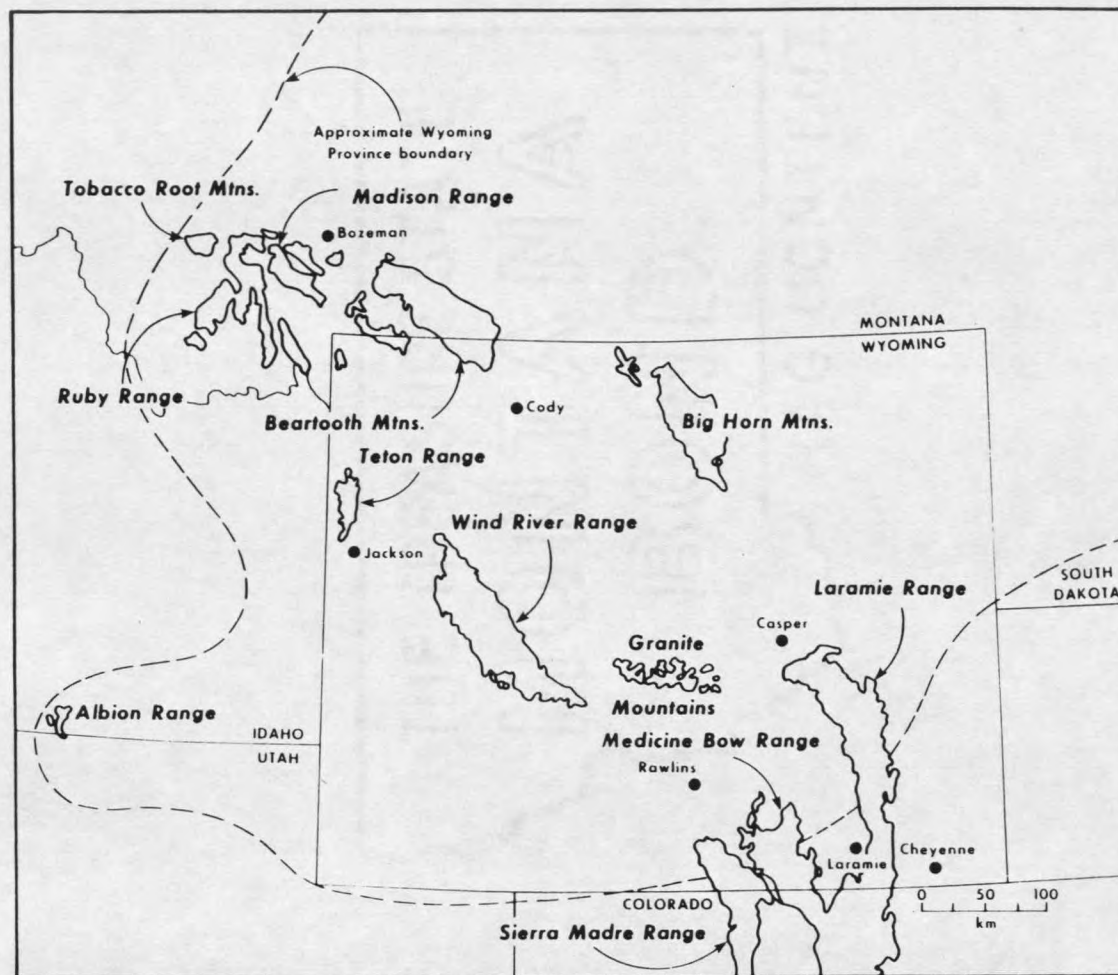


Figure 1. Wyoming Archean Province (after Condie, 1975).

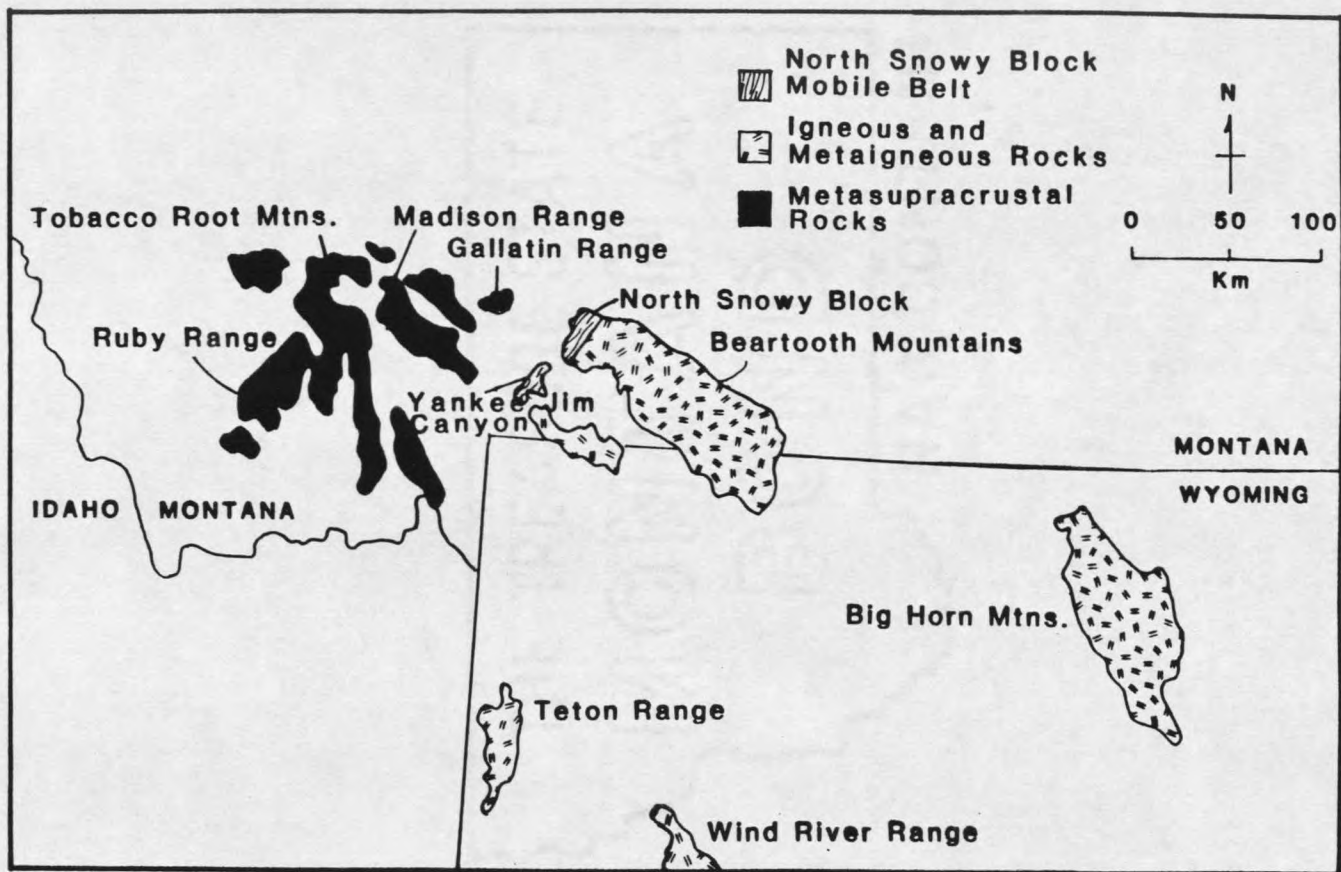


Figure 2. Index map of the northern portion of the Archean Wyoming Province. The North Snowy Block mobile belt serves as a local boundary, separating predominantly igneous and meta-igneous rocks to the east from predominantly metasupracrustal rocks to the west (from Mogk, et al, in review).

style of deformation, and 3) to place them in the context of a regional Archean setting and develop a tectonic interpretation.

Methods of Investigation

The summer field seasons of 1982 and 1983 were spent collecting rock specimens, structural data, and observations of field relationships. The sporadic nature of exposures did not warrant lithologic mapping of the study area. About 100 outcrops were observed, though most were too small or insufficiently exposed to yield valuable data. Four unique outcrops substantial enough in size were studied in detail as separate domainal units and are representative of lithologies and structures observed throughout the study area. These outcrops are highlighted throughout the text (locations of these major outcrops appear in Appendix A). One hundred and forty-seven rocks were collected and 57 thin sections representative of the major lithologic units and unique lithologies were prepared for detailed petrographic study. X-ray diffraction was used to identify the mineralogy of one rock. Structural data were plotted on stereonetts to aid in the analysis of structural elements.

Location and Access

The study area lies in the northern Gallatin Range about six miles south of Bozeman, Montana and is covered by the U.S.G.S. Bozeman 15-minute quadrangle (Figure 3). It is bounded by Hyalite Creek on the west, Sourdough Creek to the east, the Gallatin Valley to the north, the rest of the Gallatin Range to the south, and encompasses an

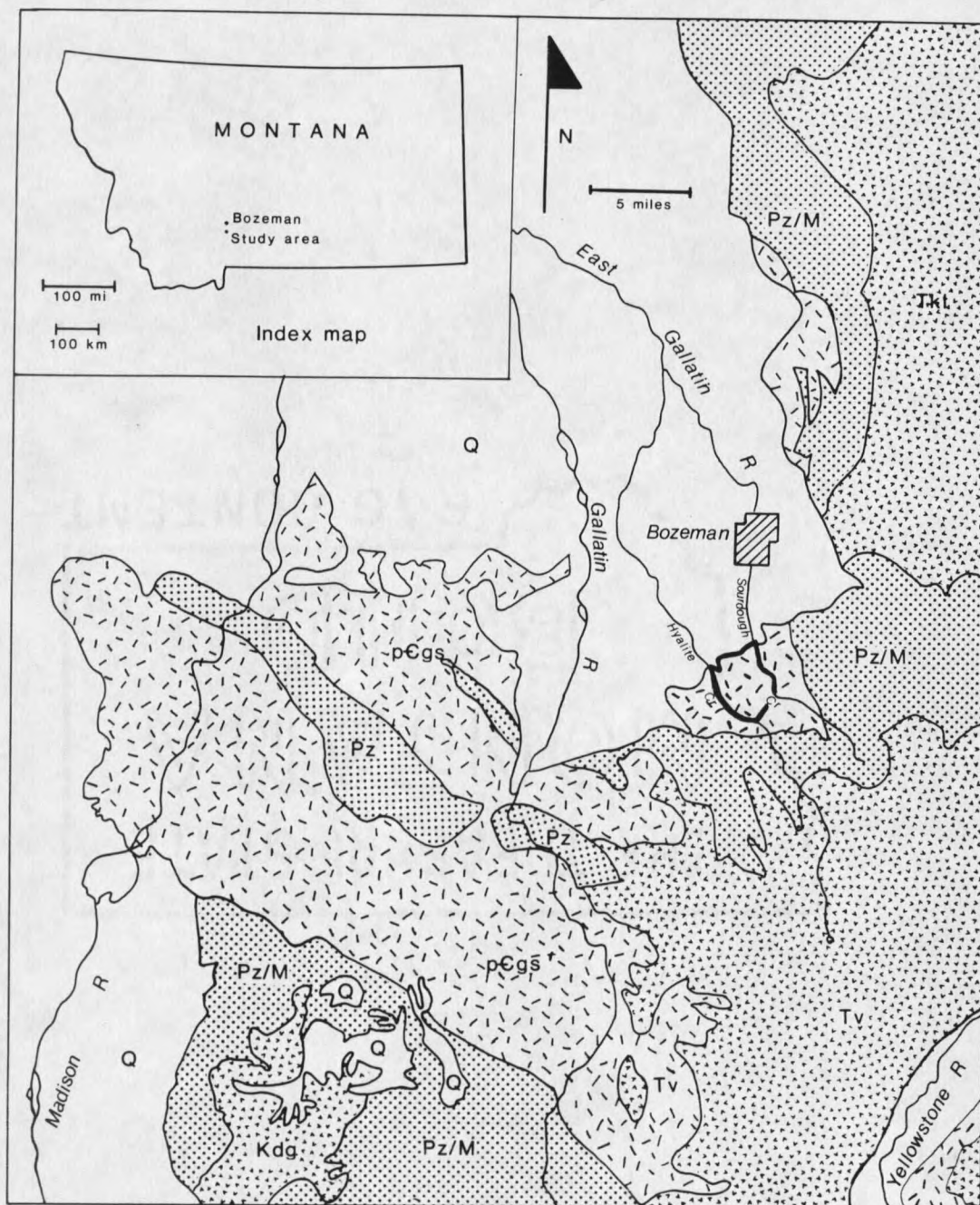


Figure 3. Generalized geologic and index map for study area (after Ross, et al, 1955). Lithologies are: Precambrian gneiss and schist (pCgs), Paleozoic and Mesozoic sedimentary units undifferentiated (Pz/M), Cretaceous diorite and gabbro (Kdg), Tertiary water-laid volcanic material (Tk1), Tertiary volcanics (Tv), and Quaternary alluvial deposits (Q). Heavy outline indicates study area.

area of about seven square miles. The area was chosen because of the presence of Archean rocks, proximity to Bozeman, and ease of access. Access to the study area was gained by permission of private landowners and through the use of Forest Service and public roads.

Previous Studies

A limited amount of information is available on Archean rocks exposed in the Gallatin Range. Master's theses from Montana State University have included cursory descriptions and limited mapping of the Archean rocks in this area (Mifflin, 1963; Weber, 1965; and Tysdal, 1966). A brief description of Archean lithologies to the southwest of the study area accompanies a map of the Garnet Mountain quadrangle (McMannis and Chadwick, 1964). Spencer and Kozak (1975) mapped and described a part of the Archean rocks of the Gallatin Range along the Gallatin River Canyon as well as the Spanish Peaks area in the northern Madison Range. Gilletti (1966, 1968) and James and Hedge (1980) have reported age dates from the Gallatin Canyon area.

REGIONAL GEOLOGIC SETTING

The Gallatin Range lies in the northwestern part of the Wyoming Archean Province (Figure 1; Condie, 1975). Two fundamentally distinct terrains exist within the Archean basement of this province (Figure 2). The North Snowy Block in the Beartooth Range locally defines the boundary between these two terrains (Mogk, et al, in review). To the east of this boundary the Beartooth Range and other exposures of Archean rocks are predominantly composed of late Archean andesites and granitoids with inclusions of older supracrustal rocks (Peterman, 1979; Henry, et al, 1982; Mueller, et al, 1985). The terrane west of the North Snowy Block predominantly consists of high-grade metasedimentary rocks (Spencer and Kozak, 1975; Garihan, 1979; Vitaliano, et al, 1979; Erslev, 1983). These rocks are composed of quartzofeldspathic gneisses and metabasites, as well as subordinate amounts of marbles, quartzites, sillimanite schists, and iron formations. Meta-igneous and ultramafic rocks are also locally present. The metamorphic grade throughout these exposures in the western terrane ranges from greenschist to granulite facies, with upper-amphibolite facies predominant (Spencer and Kozak, 1975; Garihan, 1979; Vitaliano, et al, 1979; Erslev, 1983). Two major generations of folding have been recognized (Spencer and Kozak, 1975; Garihan, 1979; Vitaliano, et al, 1979; Erslev, 1983). The first

deformation cycle produced isoclinal folds. These folds were subsequently deformed to produce large open folds.

James and Hedge (1980) reported Rb-Sr data from Archean rocks in southwest Montana yielding a 2.75 B.Y. age date for metamorphism in the area. Gilletti (1966, 1968) reported 1.6 B.Y. age dates from Archean exposures west of the Gallatin River, representing a regional thermal event that reset K-Ar isotopic clocks. A shear zone in the Portal Creek area of the Gallatin Range marks the transition zone that separates the 1.6 B.Y. terrane to the northwest from an older terrane (~2.7 B.Y.) to the southeast. At present no age dates younger than 2.1 B.Y. have been recognized southeast of the transition zone (Gilletti, 1966).

Unconformably overlying the Archean basement in the northern Gallatin Range are Paleozoic and Mesozoic sediments and Eocene volcanics (Figure 3; Chadwick, 1969). Archean terranes in southwest Montana have been exposed through Cenozoic block faulting.

PETROLOGY

Quartzofeldspathic Gneisses

The northern Gallatin Range is composed predominantly of quartzofeldspathic gneisses. The majority of these gneisses exhibit primary compositional layering on a centimeter-scale. These are stromatic migmatites, defined by McLellan (1983) as migmatites with a small-scale layered structure. A minor amount of quartzofeldspathic gneisses exhibit evidence of leucosome mobilization. These migmatites are discussed in a following section. With the exception of the presence of epidote and a minor amount of sillimanite, most of the quartzofeldspathic gneisses lack bulk chemical compositions necessary to give rise to index minerals. Forthcoming observations, however, suggest that the gneisses initially attained transitional granulite facies grade followed by an epidote-amphibolite facies overprint.

Field Occurrence

Quartzofeldspathic gneisses exhibit pervasive compositional layering of millimeter to centimeter-scale, alternating leucocratic, amphibole + biotite-rich, and hybrid layers with a salt and pepper appearance (dark mineral percentages are 1%, >10%, and 10%, respectively). Compositional layering is parallel to mineral foliation. Leucocratic units occur within the quartzofeldspathic gneisses as conformable millimeter to centimeter-scale lenses, coalescing porphyroblasts, and isolated intrafolial folds.

Mineralogy

Mineral assemblages of the quartzofeldspathic gneisses and quartzites are summarized in Table 1. Modal analyses of each thin section are listed in Appendix B. Compositions predominantly range from tonalitic to granitic and have been plotted on a Streckeisen diagram for reference (Figure 4). The dominant assemblage of the amphibolite facies overprint is quartz (qtz) + plagioclase (plag) +/- hornblende (hbl) +/- potassium feldspar (kspar) + biotite (bt) +/- garnet (gt). Accessory minerals include muscovite, epidote, sillimanite, iron-titanium oxide phases, zircon, apatite, and tourmaline. Retrograde phases include sericite, chlorite, muscovite, calcite, and white mica mats.

Titanium-rich biotite grains (reddish-brown pleochroism) are suggestive of high metamorphic grade (Guidotti, 1977). Perthite, antiperthite, and myrmekitic textures present in some thin sections are also permissive of transitional granulite facies conditions. Plagioclase compositions in the quartzofeldspathic gneisses range from An₂₆ (oligoclase) to An₄₇ (andesine). These compositions are compatible with assemblages from amphibolite to granulite facies. The range in composition could reflect more than one metamorphic grade. Zoning was not observed in plagioclase grains. The predominant amphibole present is common hornblende (ext. $\angle = 13^\circ-32^\circ$, Z=olive-green to blue-green, (-), 2V=80°-90°), although grunerite (grun), gedrite (ged), and cummingtonite (cumm) are present in isolated discrete occurrences. Clinopyroxenes are diopsidic (diop) to salitic (sal).

Table 1. Mineral assemblages of quartzofeldspathic gneisses and quartzites.

Note: Plagioclase compositions indicated where determinable.

Amphibole-Absent Assemblages

qtz + bt + plag (An₂₆) + kspar

qtz + bt + plag +/- kspar + gt

qtz + plag + kspar

qtz + bt + gt + plag

Amphibole-Bearing Assemblages

qtz + bt + gt + grun

qtz + bt + gt + plag (An₄₀) + hbl

qtz + bt + plag (An₃₄) + kspar + hbl

plag + ged

Pyroxene-Bearing Assemblages

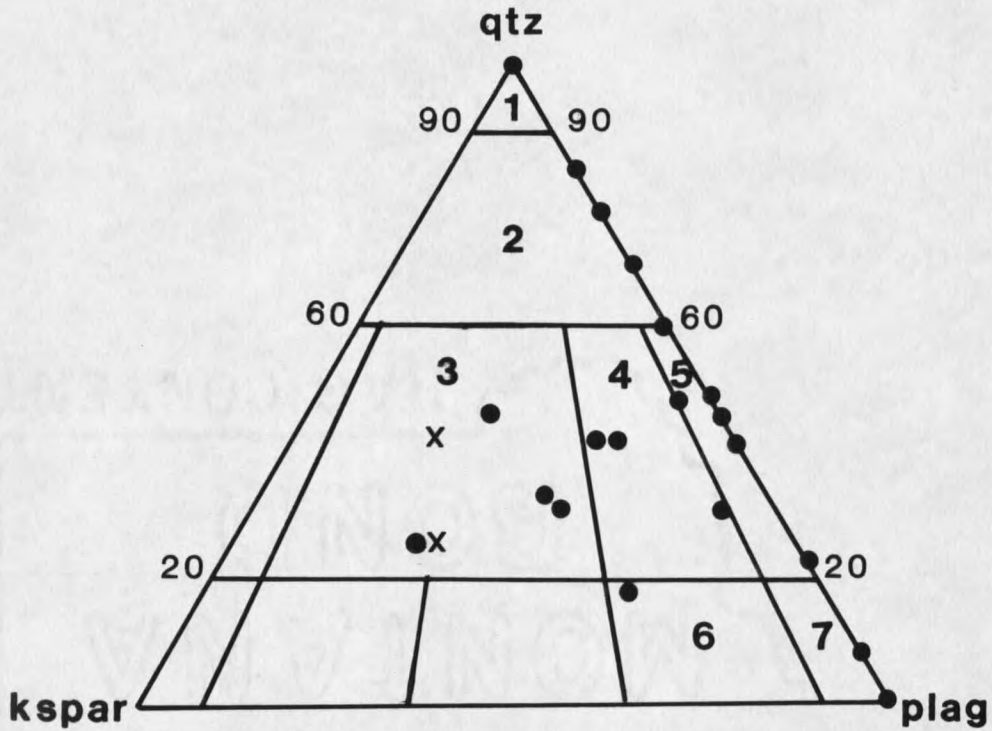
qtz + gt + plag (An₄₇) + hbl + salite

qtz + bt + plag + hbl + diop

Quartzites

qtz + bt + gt + cumm

qtz + bt + gt +/- plag

KEY

- = primary compositions
 X = mobilized migmatites

COMPOSITIONS

(from Streckeisen, 1973).

- 1- quartzolite (silexite)
 2- quartz-rich granitoids
 3- granite
 4- granodiorite
 5- tonalite
 6- quartz monzodiorite/
 quartz monzogabbro
 7- diorite/gabbro/anorthosite

Figure 4. Quartzofeldspathic gneiss compositions. Fields are for igneous rocks and are thus for reference only. Plots represent normalized modal abundances. Three hundred points were counted for each plot.

Retrograde Assemblages

In some thin sections hastingsitic hornblende (ext. $\chi = 12^\circ$, Z=greenish-blue, (-), $2V=60^\circ$) occurs as patches or rims on common hornblende grains. This occurrence is interpreted to reflect retrograde effects. Evidence of retrogression may reflect either a greenschist overprint or retrograde processes associated with the introduction of fluids along fracture zones. It is also possible that several retrograde events occurred (e.g. during the waning stages of the transitional granulite and/or epidote-amphibolite facies conditions or that a combination of causes imparted retrograde effects). Several other microscopic observations of retrograde effects follow. Some epidote grains have been observed to occur between biotite and hornblende grains as products of retrogression, characterized by the reaction: $hb1 + K^+ = bt + \text{clinozoisite}$. Biotite exhibits varying degrees of alteration to chlorite, muscovite, and iron-titanium oxide phases. Sagenitic textures are found rarely, defined as rutile needles arranged along the pseudo-hexagonal symmetry of biotite. Sericite occurs as a common alteration product of plagioclase.

Textures

Only one foliation surface has been identified within the quartzofeldspathic gneisses. It is defined by the alignment of biotite grains, nematoblastic amphiboles, columnar sillimanite, linear iron-titanium oxide grains, ovoid garnets, and some elongate quartz grains. Grain sizes range from fine-medium (1mm) to coarse (>3mm). Changes in grain size are present within individual conformable

layers. This may reflect either grain size differences that were present in the protolith or differential crystal growth during metamorphism. Varying degrees of textural equilibrium have been observed in thin section. Curved, serrated, embayed, and straight grain boundaries as well as triple junctions have all been observed. Granoblastic textures are locally present.

Deformational and Recrystallization Effects

Strain is microscopically evident in various forms throughout the quartzofeldspathic gneisses. Quartz grains exhibit varying degrees of strain. Recrystallization is common as well as evidence of strain in the form of subgrains, reductions in grain size, and undulose extinction similar to textures reported by Mitra, 1978, Vauchez, 1980, White, et al, 1980, and Tullis, et al, 1982). Ribbon textures have also been observed. Plagioclase ranges from well-recrystallized to some exhibiting recovery structures such as subgrains, undulose extinction, and incipient polygonization. Deformation twins are common. Plagioclase grains occur both as rounded porphyroblasts and as smaller neoblasts in the groundmass. Marked reduction in grain sizes in the matrix surrounding plagioclase porphyroblasts is present in some samples. Some biotite grains show evidence of strain through strongly undulose extinction, unequal pleochroism and birefringence, ragged form, or bent grains. Biotite is commonly synkinematic and occurs as foliated unstrained and well-recrystallized grains. Recrystallization processes outlasted deformational effects.

In summary, most of the quartzofeldspathic gneisses are of the epidote-amphibolite facies. However, it is believed that these gneisses originally attained transitional granulite facies grade based on the presence of granoblastic textures and mineral assemblages indicative of that grade. Based on forthcoming evidence from metabasites and the observation that no new structural elements are evident within the epidote-amphibolite facies rocks, it is believed that a transitional granulite facies oldest event was subsequently overprinted by epidote-amphibolite facies conditions.

Protolith

Due to the high grade of metamorphism attained and exposure to intense deformation, any relict sedimentary or igneous textures have been obliterated. All units are conformable and occur on a millimeter to centimeter-scale of layering. There are no discernable spatial relationships amongst the different quartzofeldspathic gneiss compositions (i.e. individual lithologies do not appear to be concentrated in certain areas). The range of study area quartzofeldspathic gneiss compositions has been plotted on a Streckeisen diagram for reference (Figure 4). Potassic segregations yield granitic compositions. Compositions of quartzofeldspathic banded gneisses predominantly range from tonalitic to granitic. Notable exceptions plot within the following fields on the Streckeisen diagram.

Quartz-rich Granitoid and Quartzolite Compositions. There are no known igneous rocks with compositions this quartz rich. Two of the rocks that plot in this area are mylonites composed of more than 75%

quartz. These rocks likely represent metamorphic equivalents of quartz-rich sandstones. One quartz-rich granitoid contains sillimanite, strongly indicative of a sedimentary origin.

Diorite/Gabbro/Anorthosite. Rocks plotting on Figure 4 with these compositions may represent primary compositions of dacite, diorite, or plagioclase arkose, or segregations resulting from metamorphic differentiation or anatexis.

Myers (1978) has suggested that uniformly banded gneisses in West Greenland resulted from extreme flattening of plutonic rocks that might have otherwise been overlooked as little deformed relict primary layering. Gneissic banding due to intense deformation of originally plutonic rocks and/or metamorphic differentiation has been demonstrated for several high-grade granitic gneiss units of widespread extent in West Greenland (e.g. McGregor, 1973; Bridgwater, et al, 1973). However, several observations of study area quartzofeldspathic gneisses do not support a plutonic origin:

1. A plutonic parent would yield rocks more mineralogically homogenous than those observed in the study area;
2. Biotite and hornblende are locally present in greater amounts than would be expected from a calc-alkaline igneous parent rock;
3. Igneous rocks lack typically pelitic minerals such as garnet and sillimanite. Both minerals are present in study area quartzofeldspathic gneisses; garnets are abundant.

In light of the absence of any readily observable indications of an igneous origin such as disconformable layering, relict igneous

textures, or complex oscillatory zoning in plagioclase grains, it is clear that trace element and other geochemical analyses must be implemented in order to resolve this problem.

Another possibility is that the tonalitic and granitic compositions represent a supracrustal sequence of predominantly sedimentary origin. Features within the quartzofeldspathic gneisses that are suggestive of a sedimentary origin include:

1. The presence of sillimanite;
2. The presence of quartzite units;
3. A concordance of units with schists and thin sheets of amphibolite;
4. A persistence of layering;
5. The presence of a gradual repetition of compositional layers most likely represents primary compositional layering as metamorphic differentiation is not expected to generate this pattern;
6. The presence of discontinuous quartzofeldspathic layers on a millimeter to centimeter-scale may represent primary interbedding of sedimentary units.

Some of the above criteria have been cited by numerous authors in postulating a sedimentary origin for the quartzofeldspathic gneisses in Archean exposures in southwest Montana (e.g. Cordua, 1973; Spencer and Kozak, 1975; Vitaliano, et al, 1979; Fountain and Desmarais, 1980; and Wilson, 1981). An outcrop along Hyalite Creek in the study area (H1) offers the strongest field evidence for a sedimentary origin of the gneisses. A minor amount of centimeter-scale schist units are

intimately and conformably interbedded with quartzofeldspathic gneisses and metabasite units. Layering in most of the quartzofeldspathic gneisses is thought to represent primary compositional layering, though it likely has been modified to some degree by transposition and/or metamorphic differentiation. Partial melting is suggested in migmatitic gneisses to be discussed in the next section.

One explanation for the distribution of compositions on the Streckeisen diagram (Figure 4) may be as follows. Tonalitic compositions for study area metasediments may reflect the North Snowy Block of the Beartooth Range as a source area. This is reasonable as trondhjemitic rocks there are of appropriate composition and age (~3.5 Ga, Mogk, 1984, and Mogk, et al, in review). Potassium-rich rocks of granitic composition (Mueller, et al, 1982) may reflect the later calc-alkaline rocks of the Beartooth Range as their source.

Though there is no unequivocal evidence of an origin, field observations, petrographic study, and corroborative evidence from previous studies of surrounding ranges most strongly support a predominantly sedimentary origin for quartzofeldspathic gneisses in the region. These rocks likely represent metagraywackes or meta-arkoses. Some amount of acid volcanoclastic sediments may also have contributed to the supracrustal pile that yielded gneisses of tonalitic composition.

Migmatites

Unique occurrences of migmatite are exhibited within the Leverich Creek outcrop (L-1). These migmatites differ from the predominantly stromatic migmatites of the study area in that leucosomes within the Leverich Creek migmatites have been mobilized, thus indicating superheated conditions with respect to the stromatic migmatites (Tracy and Robinson, 1983). Two occurrences of mobilized migmatites have been observed. No single mechanism can account for all of the observed features displayed by these migmatites. Their description and petrogenesis will be discussed separately.

The first occurrence of mobilized migmatite lies within a mafic gneiss characterized by the assemblage $qtz + gt + hbl + plag (An_{47}) + sal + epidote$. This rock unit is thought to be a mesosome, similar to that described by McLellan (1983) as an unmigmatized body occurring within a migmatitic suite. The leucosomes within this gneiss are characterized by the assemblage $qtz + plag (An_{30}) + microcline +/- bt$. Leucosomes occur as centimeter-scale layers, some ptigmatic in form. They are predominantly conformable with the surrounding gneiss but also occur as irregularly formed, centimeter-scale masses, still roughly conformable (Figure 5). The irregular form is likely due to high grade metamorphic conditions (Johannes and Gupta, 1982). Cross-cutting leucosome layers are rare and occur on a very local (centimeter) scale. The lack of strongly anisotropic patterns within the leucosomes is suggestive of a non-igneous origin (Yardley, 1978). It is also believed that this leucosome was not derived via metamorphic segregation as there is not a close relationship between its

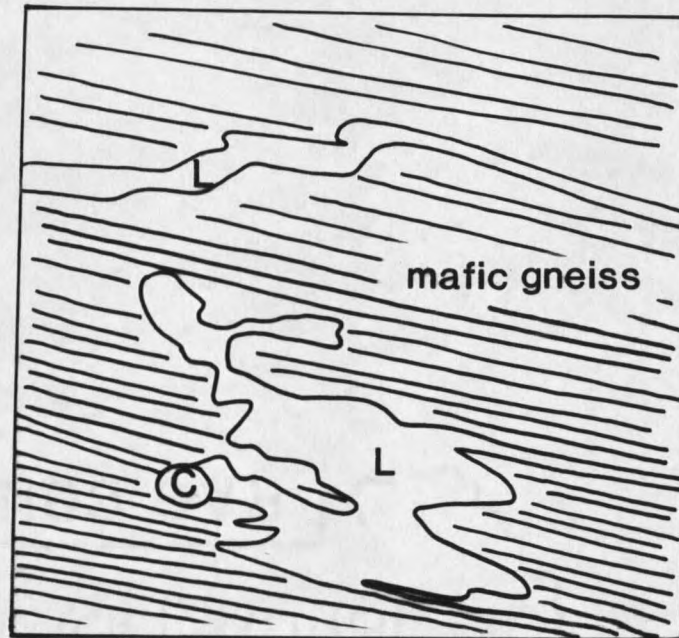


Figure 5. Mobilized leucosomes (L) within mafic gneiss (mesosome).
Lens cap (C) diameter = 5 cm.

plagioclase composition (An_{30}) and the plagioclase composition in the surrounding gneiss (An_{47}). Yardley, 1978, defines close anorthite compositions as those within a few percent of each other. Gneisses surrounding the leucosome at one time attained at least transitional granulite grade. This grade is compatible with anatexis as it has been suggested that there is a genetic relationship between partial melting and granulite facies conditions (e.g. Fyfe, 1973; Winkler, 1976). Since the leucosome plagioclase composition is significantly more albite-rich than the plagioclase of the mesosome, it is believed that in situ partial melting (Winkler, 1961, 1979; and Winkler and Von Platen, 1961) is the most reasonable origin for this migmatite. The mobilization of these leucosomes is indicative of high grade

metamorphic conditions. It is inferred by this author that partial melting took place at transitional granulite facies conditions.

The second occurrence of migmatite occurs as centimeter-scale, unconformable, non-directional leucosomes within metabasite units (Figure 6) that are discontinuous but conformable with surrounding gneisses. Leucosomes locally cross-cut the metabasite. Local tight to isoclinal folding of the leucosome occurs on a centimeter-scale. This migmatitic leucosome contains substantially more microcline than the previously described leucosomes. On this basis, the two are differentiated.



30 cm

Figure 6. Non-directional leucosome within metabasite unit.

The following observations imply that the leucocratic material was locally introduced from an external source on an outcrop scale:

1. Melanosome units are locally invaded and assimilated by leucocratic units. Some melanosomes appear to be rotated. It is possible that the leucosome represents a late hydrothermal deposit, infilling around the melanosome;
2. The mineral phases in the leucosome are not related to the mineralogy of the host rock;
3. Melanosomes that contain the migmatitic leucosome exhibit the following characteristics that imply alteration:
 - a. Hastingsitic patches within common hornblende grains;
 - b. A major amount of chlorite occurs as pseudomorphs after biotite and in places hornblende is replaced by chlorite;
 - c. Epidote occurs as a replacement of calcite with and without chlorite.

In addition, extensive plagioclase sericitization occurs throughout the leucosome, again indicating alteration. Extensive replacement of plagioclase by microcline has been observed throughout the leucosome. Similar observations have been reported in the Tobacco Root Range and are attributed to a potassic mobilization (Cordua, 1973). Hydrothermal alteration, perhaps resulting from external metasomatism, is strongly suggested by the extensive amount of alteration observed.

Detailed petrographic and experimental data are necessary for a clearer understanding of migmatite genesis in the study area. These studies are beyond the scope of this thesis. Nonetheless, the

observations made serve as a first approximation and as a springboard for further investigation. Based on the preceding discussion and on the amount of data available, this author speculates that the Leverich Creek migmatites in the conformable and non-directional leucosomes resulted from in situ partial melting and external metasomatic processes, respectively.

Amphibolite Facies Metabasites

Most metabasites within the study area are of the amphibolite facies of Eskola (1939), defined as that facies in which basic rocks are represented by hornblende-plagioclase assemblages with plagioclase compositions more calcic than An_{20} .

Field Occurrence

Field occurrences of the amphibolite facies metabasites occur in the following variety of forms:

1. As gradational millimeter to centimeter-scale conformable layers within quartzofeldspathic gneisses;
2. As centimeter and meter-scale lens-shaped pods;
3. As meter-scale spheroidally weathered cataclastic pods.

Mineralogy

Mineral assemblages are summarized in Table 2. Mineral contents of each thin section are listed in Appendix C. The dominant assemblage is $hb1 + plag +/- qtz +/- bt +/- gt$. Accessory minerals include iron-titanium oxides, zircon, sphene, and apatite. Retrograde phases include chlorite, sericite, prehnite, epidote, and sagenitic

Table 2. Amphibolite facies metabasite assemblages.

Note: Plagioclase compositions indicated where determinable.

Dominant Assemblages

hb1 + plag + qtz + gt + diop

hb1 + plag(40) + qtz

hb1 + plag + qtz + bt + sal

hb1 + plag + bt + qtz

hb1 + plag(51) + bt

hb1 + plag(20) + bt + gt

hb1 + plag + gt + sal

hb1 + plag(73) + gt + bt + qtz

hb1 + plag + gt + qtz

hb1 + plag(42) + sal

Unique Varieties

actinolite + bt

cumm + trem + plag + qtz + gt

rutile after biotite. Main assemblage and retrograde phases for the amphibolite facies metabasites are illustrated in Figure 7. Minerals common to both mafic rocks and the quartzofeldspathic gneisses have been previously described in the quartzofeldspathic gneiss section.

Plagioclase compositions range from An₂₀ (oligoclase) to An₇₃ (bytownite), consistent with upper-amphibolite facies rocks. As in the quartzofeldspathic gneisses, the predominant amphibole present is common hornblende (-, ext. $\chi = 13^\circ - 32^\circ$, z=olive green to blue green,

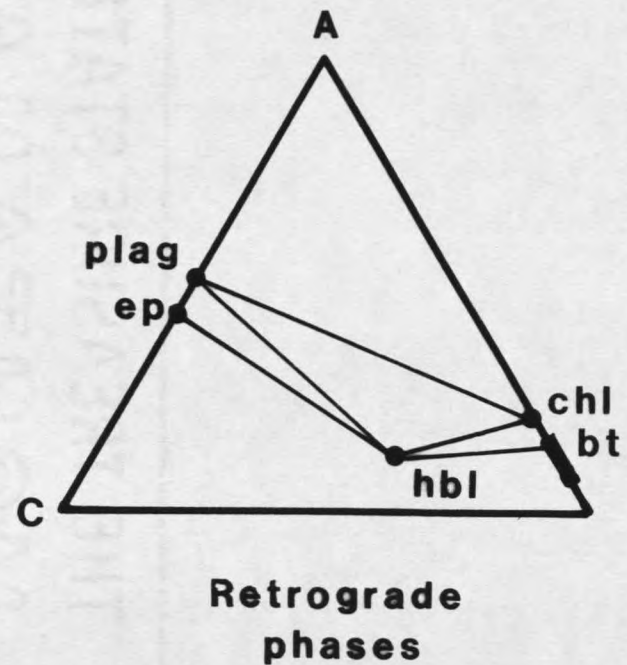
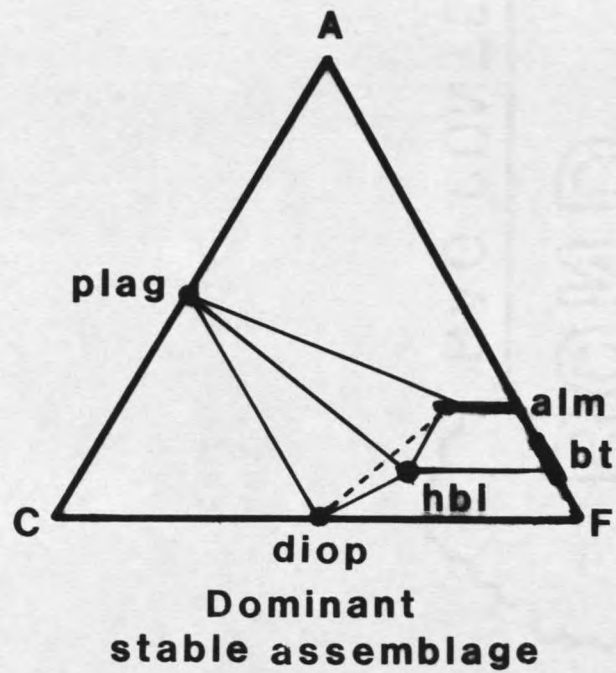


Figure 7. ACF diagrams illustrating dominant stable and retrograde phase assemblages in study area amphibolite facies metabasites.

$2V=80^{\circ}-90^{\circ}$). Foliated and lineated hornblendes must have formed syntectonically. In one thin section, a micro-scale isoclinal similar fold composed of polygonal arcs of axial planar hornblende grains defining a second s-surface is present. The polygonal arc grains provide additional evidence for a syntectonic or post-tectonic crystallization history for the hornblendes. Many hornblendes observed contain inclusions of quartz, plagioclase, and biotite present in the rock, indicating that the hornblendes grew with or at a later stage than those minerals. Patches or rims of hastingsitic hornblende (-, ext. $\chi=12^{\circ}$, $2V=60^{\circ}$, z =greenish blue) occur on common hornblende grains. Hastingsitic hornblende also typically occurs along cleavages and cracks within these grains. Hastingsite was not observed to occur along any definable new s-surfaces. Hornblende exhibits alteration to chlorite or biotite in some thin sections. Clinopyroxene compositions are diopsidic to salitic.

Textures

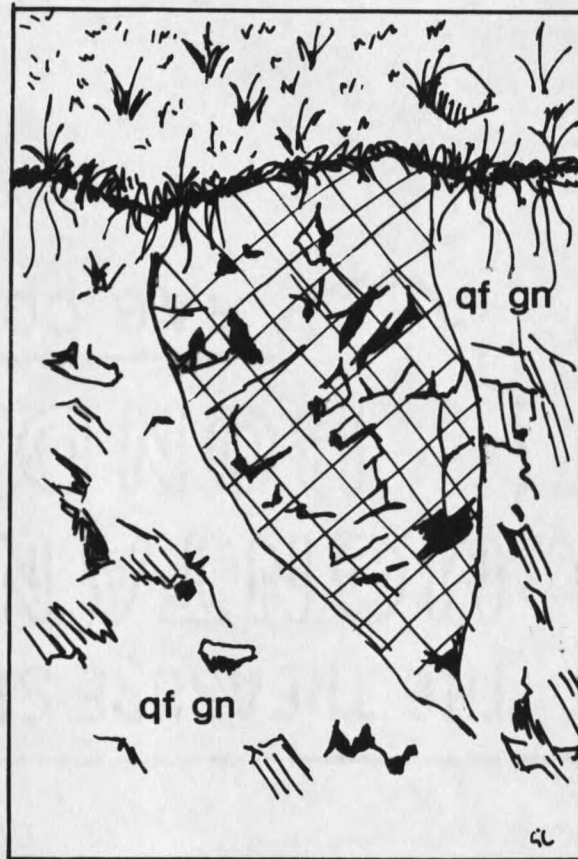
Grain sizes range from fine (.5mm and less) to medium-coarse (3-5mm). Layering occurs from a millimeter to predominately centimeter-scale and alternates with quartzofeldspathic gneisses. The two predominant textures in the amphibolite facies metabasites are: 1) nematoblastic hornblende with interstitial xenoblastic plagioclase and quartz, and 2) granoblastic. Foliation is defined by compositional layering including nematoblastic hornblende, an alignment of biotite grains, and flattened quartz in some thin sections. Mineral lineations were usually too fine to allow measurement in the field. All

degrees of recrystallization, strain recovery, and grain shape are present. Some thin sections display recrystallized and strained grains within the same thin sections, indicating varying degrees of recrystallization. Most exhibit initial textural adjustment but are still texturally inequibrated based on the lack of triple junctions between grains and the presence of curved to serrated grain boundaries of various minerals.

Unique Occurrences

Two unique occurrences of amphibolite facies metabasites occur within a Hyalite Creek outcrop (H-1). With the exception of these, this outcrop is composed predominantly of conformable planar quartzofeldspathic units that are gradationally interbedded with metabasites on a millimeter to centimeter-scale.

The first unique occurrence of metabasite at the Hyalite Creek outcrop (H-1) is a meter-scale pod that occurs in sharp contact with quartzofeldspathic gneiss units (Figure 8). The pod appears to exhibit internal flow or foliation when seen in outcrop. However, this body is insufficiently exposed to enable discernable characterization of its structure. This rock unit is characterized by the main assemblage hbl + plag + salite. One well-developed compositional foliation is expressed in this rock, though the microtexture is classically granoblastic. There are some irregularly-shaped plagioclase porphyroblasts within this rock, though most of the plagioclase is recrystallized. Hornblende and salite grains tend to form subtle islands surrounded by plagioclase. A minor amount of salite clumps

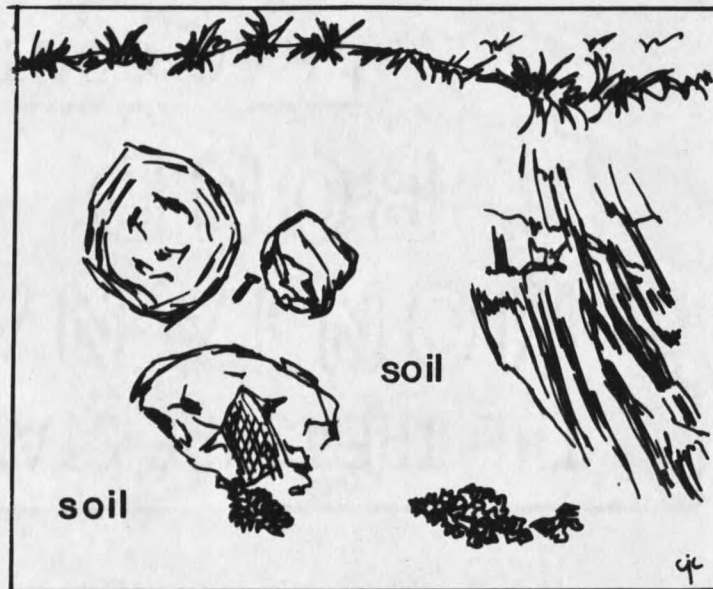


1 meter

Figure 8. Pod (cross-hachured pattern) in sharp contact with quartzofeldspathic gneisses (qf gn).

are surrounded by hornblende. Hornblende patches common within salite grains are suggestive of the reaction $hb1 \leftrightarrow cpx + qtz + plag$.

Tremolite-cummingtonite cataclastic pods occur within the Hyalite Creek outcrop (H-1) as meter-scale spheroidally weathered pods that lie within a highly weathered zone (Figure 9). The microtexture of this rock is characterized by tremolite and cummingtonite grains that



—
1 meter

Figure 9. Cataclastic pods in highly weathered shear zone.

occur in both block form and as bundles of sheared grains surrounding those blocks. Both amphiboles exhibit undulose extinction and have been broken. Extensive alteration of these amphiboles is present.

Subhedral garnets occur as layers and as clusters. Garnets are typically coated with iron-titanium oxide phases in cracks and at grain boundaries. This rock has been intensely deformed. The cracked, strongly undulose grains present in this rock record ductile effects that were subsequently subjected to brittle deformation.

Another unique occurrence of amphibolite facies metabasite is a meter-scale lens-shaped actinolite pod that occurs within a Leverich Creek outcrop (L-1; Figure 10). Quartzofeldspathic gneisses



—|—————|
1 meter

Figure 10. Lens-shaped actinolite pod.

wrap around this pod. The pod is highly weathered, obliterating any measurable structural data. It is therefore not clear what this pod

represents. The pod is essentially a monomineralic actinolite with a major amount of iron-titanium oxide phases and trace amounts of biotite and retrogressive chlorite. A relict decussate microtexture (defined by Spry, 1969 as interlocking, randomly oriented prismatic crystals) characterizes this rock, although it has been recrystallized to the point of appearing nearly granoblastic. No evidence of strain is found within this rock.

Transitional Granulite Facies Metabasites

Mafic rocks of the transitional granulite facies are locally present and are characterized by the dominant assemblage hbl + plag + diop +/- sal + gt and textures suggestive of that grade. One exposure is a meter-scale lens-shaped pod. The other occurs as a meter-scale outcrop.

Mineralogy

Mineral assemblages are summarized in Table 3. Mineral contents of each thin section are listed in Appendix D. Accessory phases include iron-titanium oxides, sphene, and zircon. Retrograde phases include sericite, chlorite, and epidote. Clinopyroxene compositions are diopsidic to salitic. Retrograde patches of common hornblende occur on clinopyroxene grains. All other minerals found within the transitional granulites have been previously described in the quartzofeldspathic gneiss section.

Table 3. Transitional granulite facies metabasite assemblages.

hbl + plag + qtz + gt + diop

hbl + plag + qtz + bt + sal

hbl + plag + gt + sal

hbl + plag + qtz + diop

hbl + plag + gt + sal

Textures

Transitional granulite facies grain sizes range from fine (.5mm and less) to medium (2-3 mm). Textures are variable. Those textures displaying penetrative deformational features on a microscopic scale are characterized by nematoblastic hornblende with interstitial grains of well-recrystallized plagioclase and quartz. One such rock occurs as a meter-scale lens-shaped pod within the Leverich Creek outcrop (L-1; Figure 11). The only evidence of strain in this rock is that some biotite grains exhibit unequal birefringence and pleochroism in places. Very slight to no undulose extinction occurs in quartz grains. It is not clear from field observations what this pod represents as there is insufficient evidence for determining whether or not the pod is folded. This pod is conformable and is in sharp contact with the surrounding quartzofeldspathic gneisses. The gneisses that surround this pod exhibit planar foliation, though several local centimeter-scale intrafolial isoclinal folds are present. This pod occurs only ~20 meters away from the meter-scale actinolite pod described in the amphibolite facies metabasite section (Figure 10). Both of these pods lie in the same orientation

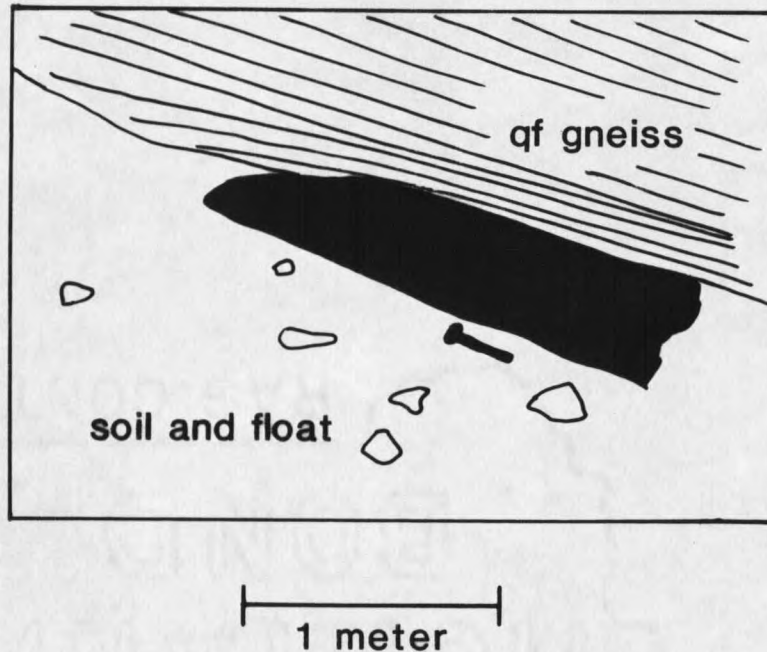


Figure 11. Lens-shaped transitional granulite metabasite.

within the outcrop and are essentially granoblastic while their surrounding gneisses have retained microtextural evidence of intense deformation. It is possible that the pods were deformed at the same time as all other lithologies exposed at this outcrop. If so, why are the pods so well recrystallized? Both pods are mafic. It is likely that the equilibration rates of the metabasite pods may have differed from the quartzofeldspathic gneisses due to their contrasting bulk compositions. The granoblastic texture retained within the mafic transitional granulite unit may represent local conditions where PH20

was $< P_{Total}$ during the later amphibolite facies metamorphic event. This may have enabled the transitional granulite to persist, sealed from the effects of an amphibolite overprint. Another possible explanation for this contrast is that the pods may have been tectonically emplaced. There is no direct evidence of shearing at the contacts between the pods and the gneisses that enclose them. It is possible, however, that any evidence of shearing has since been obliterated through recrystallization.

Granoblastic textures are representative of those rocks that experienced complete recrystallization. A unique granoblastic texture is found in a corona texture (Spry, 1969) metabasite that occurs in the Sourdough Creek drainage area. It is microscopically characterized by a static overgrowth of well recrystallized granoblastic hornblende rimming salite nuclei. These nuclei are commonly poikiloblastic with plagioclase inclusions. Salite grains are characterized by an abundance of hornblende occurring in the form of patches or along cleavages and fractures. Garnet rims are present between plagioclase and salite nuclei. Some small nuclei of granoblastic hornblende contain garnet and iron-titanium oxides in their centers. A rough lineation of some corona rims and iron-titanium oxide grains was observed, hinting at a once present foliation. The texture of this rock may represent transitional granulite facies conditions based on the observation that salite grains show evidence of replacement by and reaction to hornblende. Figure 12 illustrates the ACF diagram for this assemblage.

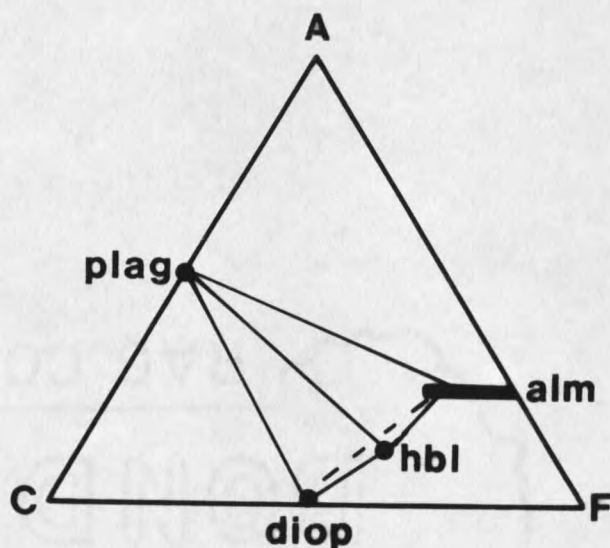


Figure 12. ACF diagram for corona texture metabasite.

Manna and Sen (1974) have made the observation that isobaric cooling of a gabbroic melt has produced coronal textures in mafic granulite gneisses from Saltora, India. James and Hedge (1980) have reported the intrusion of mafic melts just before and during a high grade metamorphic event in the Ruby Range. It is postulated that mafic granulite gneisses in the Kelly area of the Ruby Range may have originated as a gabbroic melt intruding deep in a geosynclinal pile just before or during metamorphism (Karasevich, et al, 1981). This model may be realistic for the corona texture rock observed in the study area. The lack of an observable cross-cutting relationship of

the corona texture metabasite within the study area makes an igneous origin uncertain.

Protolith

Thin-layered metabasite units occur as continuous units within quartzofeldspathic gneisses in the study area. Orville (1969) has outlined three mechanisms by which thin-layered metabasites can be produced:

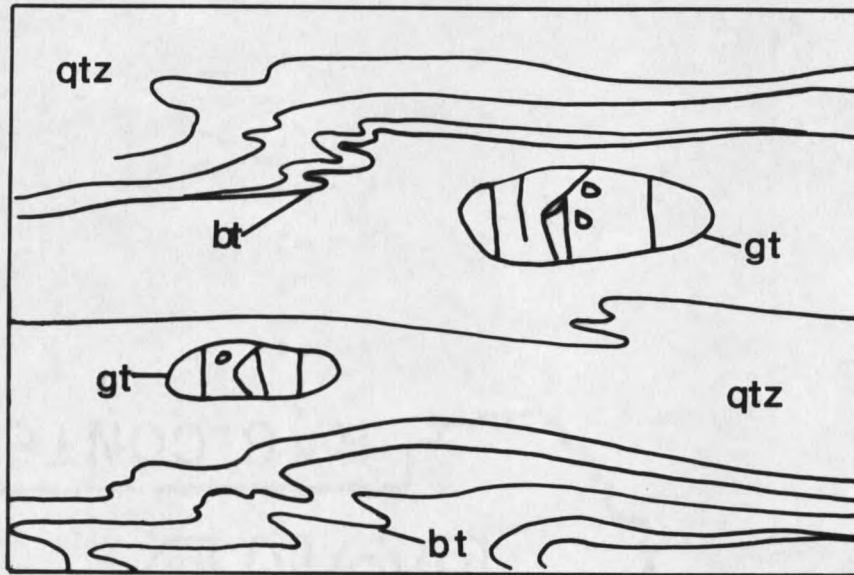
1. Meta-igneous: recrystallization of basic igneous rocks such as intrusive sills, dikes, extrusive flows, or tuffs;
2. Metasedimentary: recrystallization of marl or carbonate-bearing shale;
3. Metasomatic: recrystallization of some parent material combined with addition and/or subtraction of significant amounts of nonvolatile constituents.

Due to the lack of cross-cutting relationships and without geochemical analyses, one can only speculate about the origin of study area metabasites. Evidence from surrounding ranges is suggestive of a predominantly igneous origin for many amphibolites in southwest Montana Archean exposures. Whole rock chemical and Niggli values determined for eight amphibolites in the Copper Mountain and Kelly area of the Ruby Range show that massive, banded, and salt and pepper varieties exhibit identical bulk chemical compositions which are similar to amphibolites in the Madison (Foster, 1962), Spanish Peaks (Spencer and Kozak, 1975), and Beartooth Range (Van deKamp, 1969). Their whole rock compositions strongly resemble tholeiitic basalts.

In addition, their Niggli Ca/Mg and Al-Alk/Ca ratios (Leake, 1964) are compatible with igneous trends and are oblique to trends expected for calcareous shales. Cross-cutting relationships and igneous textures are displayed within metabasites in the southern Tobacco Root Range. Ken Salt (personal communication) has identified cross-cutting relict gabbro and diabase textures within metabasites of the Spanish Peaks area of the Madison Range. Evidence for the amphibolite units occurring within sedimentary units lies in the observations that quartzite interbeds have been observed in some outcrops and conglomeratic units have been reported within amphibolites in the Ruby Range (Smith, 1980).

MYLONITES

Mylonites are recognized as products of strain softening representative of an accommodation of an imposed strain rate within ductile shear zones (White et al, 1980). The localization of high strain rates commonly occurs within approximately planar zones known as shear belts (Ramsay and Graham, 1970). Varying degrees of mylonitization are reflected in study area rock fabrics. A meter-scale ultramylonite zone within the Hyalite Creek outcrop (H-1) best exemplifies the presence of a localized shear zone. This ultramylonite zone is composed of very fine-grained ($\ll .5\text{mm}$) quartz-rich rocks with garnet, plagioclase, tourmaline, and cummingtonite as accessory phases. All of these minerals exhibit evidence of strain. Foliation is defined by a preferred orientation of biotite grains, ovoid garnets (Figure 13), quartz ribbons, and flow textures of ductilely deformed quartz around porphyroblasts. Quartz occurs as ribbons and recrystallized grains. Garnets typically contain inclusions of all the other minerals found in the rock. Garnets, plagioclase, tourmaline, and cummingtonite grains occur as porphyroblasts and represent brittle minerals in a ductile quartzose matrix. These minerals do not show evidence of plastic deformation, though some grains are cracked as described by Mitra (1978). Biotite occurs as very finely-recrystallized grains ($\ll .5\text{mm}$) and is microfolded in places (Figure 13). Extensive recrystallization of quartz and biotite occurs in the mylonites.



0.5 mm

Figure 13. Ultramylonite. Sketched from a microphotograph taken in plane-polarized light. Garnet porphyroblasts occur as brittle minerals in a predominantly quartzose ductile matrix. Note microfolded recrystallized biotite.

Microstructural characteristics of plastically deformed minerals in mylonites yield clues as to the physical parameters of deformation (Boullier, 1980). Hyalite Creek mylonites exhibit several properties of crystal plasticity. Evidence of dislocation glide as a deformation mechanism was observed in the following forms of intracrystalline strain: undulose extinction, slip bands, deformation bands, and crystallographic preferred orientations. Accompanying recovery structures observed include subgrains and recrystallized grains along grain

boundaries. Dislocation creep commonly yields flattened original grains (Tullis et al, 1982). Ovoid garnet porphyroclasts within the mylonites attest to flattening and serve as strain indicators (Figure 13; Ross, 1973). Elongate areas of small strain-free polygonal to inequant grains of quartz with sutured grain boundaries also attest to a high rate of strain and to syntectonic recrystallization (Ross, 1973). Tullis, et al (1973) have indicated that small strain-free polygonal grains around larger original grains represent a high temperature of recrystallization and are probably related to plastic deformation. These features have been observed within the Hyalite Creek mylonites. Reductions in grain size have also been observed. Recrystallization-accomodated dislocation creep under increasing strain conditions has been attributed by several authors to be responsible for the grain size reduction and strain softening conditions that lead to the formation of many mylonites and ductile shear zones (e.g. Mitra, 1978; Boullier, 1980; White et al, 1980; and Tullis and Yund, 1985). Many of the characteristics of the mylonites (e.g. high strain, very fine grain size, mixing of mineral phases which prevent grain growth) are suggestive of a bulk of super-plastic behavior of the rocks as proposed by Boullier and Gueguen (1975).

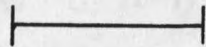
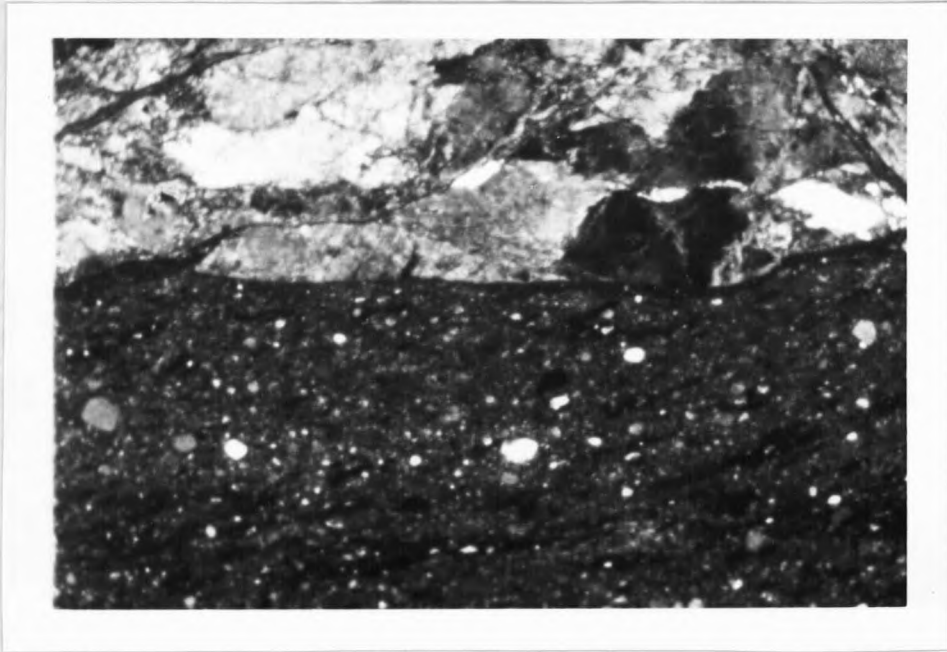
White (1979) has characterized shear zones as "examples of inhomogenous deformation arising because the country rock is incapable of accomodating an imposed strain rate by bulk inhomogenous deformation. Large strains concentrate in these zones because of softening within them." Microstructures of study area mylonites are indicative of such a zone of strain concentration. Study area

mylonite assemblages do not yield clues as to what grade of metamorphism they formed under. However, it is believed that they did not form under peak metamorphic conditions as the rocks have not been extensively recrystallized.

A unique texture observed within a mylonitic unit occurs as a pseudotachylyte and provides additional evidence for shearing processes in the study area. The pseudotachylyte occurs as a dark, microcrystalline matrix band, sandwiched between a quartzofeldspathic gneiss unit. Contacts with this unit are sharp except where the pseudotachylyte locally invades the surrounding gneiss (Figure 14). Numerous rounded quartz, hornblende, and epidote grains lie within a chlorite-rich matrix. The pseudotachylyte band exhibits evidence of having undergone ductile deformation based on the following observations:

1. Inclusions in the matrix display undulose extinction;
2. Xenocrysts of quartz and feldspar are lenticular in shape;
3. Microfolds are present within the matrix;
4. A strong preferred orientation of opaques and chlorite grains, parallel to foliation, occurs in the surrounding quartzofeldspathic gneiss.

Several authors (e.g. Allen, 1979; Francis, 1972; Sibson, 1975 and 1977; and Watts and Williams, 1979) have suggested that pseudotachylyte bands develop by local melting of rock in response to frictional heat generated by seismic slip on a brittle shear fracture. A decrease in temperature during retrogression is probably the main reason for gradual strain hardening leading to increasing differential



0.5 mm

Figure 14. Pseudotachylyte texture. Note sharp contact between pseudotachylyte and surrounding quartzofeldspathic gneiss.

stresses and finally to the generation of pseudotachylytes (Passchier, 1982). The mineral parageneses in study area pseudotachylytes are consistent with the retrograde assemblages reflective of the transformation from amphibolite to granulite facies conditions. Deformed pseudotachylyte bands are generated at crustal levels in between the zone where ductile deformation is dominant and the zone where brittle fracturing produces undeformed pseudotachylytes (Passchier, 1982).

In summary, the presence of mylonitic and pseudotachylitic textures in the study area attest to the intensity and style of deformation that affected the area. Evidence of ductile deformation is reflective of conditions of high metamorphic grade. The localization of these textures is suggestive of the presence of former shear zones.

METAMORPHISM

Basement rocks in southwest Montana underwent high grade regional metamorphism. The following observations of these rocks are indicative of prograde metamorphic conditions which straddled the upper amphibolite/lower granulite grade boundary:

1. Evidence of transition between the two facies is exhibited by corona textures in some metabasites;
2. Granoblastic textures are present;
3. Dark olive-green hornblende and deep red pleochroism in biotite occur;
4. Perthitic kspars are present.

Figure 15 illustrates a petrogenetic grid constraining temperature and pressure conditions for study area rocks. The conditions of these parameters were evaluated using published experimental and theoretical data on pertinent reactions combined with geothermometric studies of garnet-biotite and garnet-clinopyroxene pairs.

Evaluation of metamorphic conditions is difficult because of the partial reequilibration of relict assemblages as well as a lack of limiting reactions. The metamorphic conditions of M1 are constrained by the presence of sillimanite and evidence of partial melting in the form of migmatites in quartzofeldspathic gneisses. In addition, garnet-biotite and garnet-clinopyroxene geothermometry yield temperatures of 680°-720° (David Mogk, personal communication). These observations imply pressures of between 5-7 kilobars (Figure 15). The

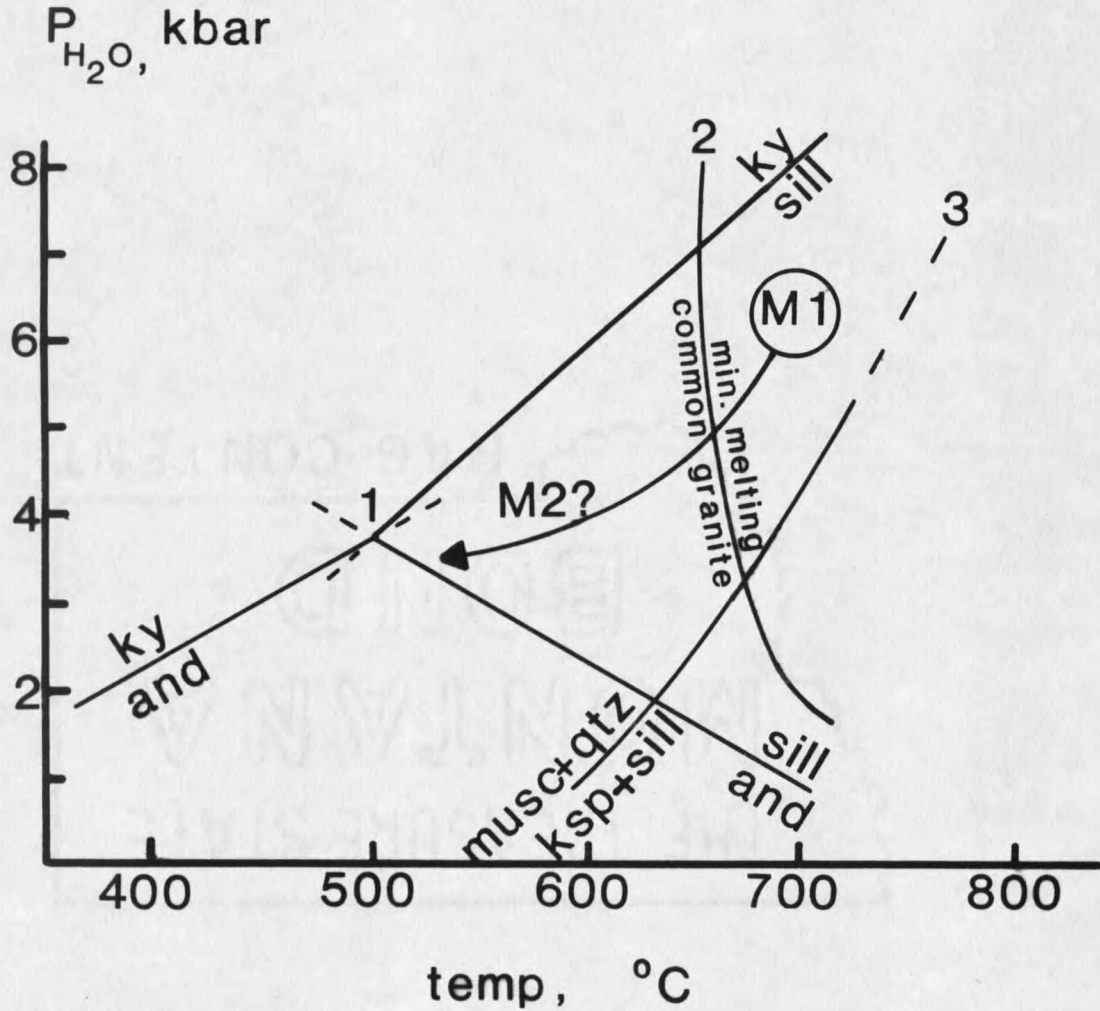


Figure 15. Temperature-pressure diagram for metamorphism of the study area. M1 reflects transitional granulite facies conditions. Arrow illustrates that overprinted epidote-amphibolite facies assemblages (M2) represent retrogression from transitional granulite facies conditions (M1). Excess quartz is assumed in all reactions. Solid lines indicate experimentally verified reactions. Dashed lines indicate extrapolated lines. Reactions shown are: 1) $ky \leftrightarrow and \leftrightarrow sill$ (Holdaway, 1971); 2) minimum melting curve for common granite (Tuttle and Bowen, 1958); and 3) $musc + qtz \leftrightarrow ksp + H_2O$ (Evans, 1965).

metamorphic conditions of M2 are based on the presence of epidote and the lack of partially melted quartzofeldspathic gneisses. Most rocks exhibit evidence of late (post-M2) retrograde effects based on:

1. The presence of extensive chloritization and plagioclase seritization;
2. The replacement of pyroxene by amphiboles;
3. The replacement of common hornblende by hastingsitic hornblende and plagioclase by epidote.

The cause of retrogression is uncertain. Retrograde facies reflect either a separate, latest (M-3?) event under greenschist facies conditions or retrograde processes associated with the waning stages of M2.

DEFORMATION

Basement rocks in southwest Montana have been intensely deformed. With few exceptions, the regional structural grain of Archean rocks in southwest Montana is characterized by fold axes that generally trend to the northeast (Spencer and Kozak, 1975; Vitaliano, et al, 1979; Fountain and Desmarais, 1980). Throughout the study area a structural grain is expressed by foliation that predominantly strikes N45E and dips steeply to the northwest or southeast. Mineral lineations and fold hinge lines predominantly trend northeast or southwest and plunge moderately to steeply in both directions. Folds verge to the southeast and the northwest. Exposures in the study area are limited due to heavy forestation and a thick soil mantle. Figure 16 illustrates structural features found throughout the study area. Representative stereonetts are shown in Figures 17-19.

All folds in the study area occur on a centimeter to meter-scale and exhibit a similar style of folding. Two fold types occur and are most easily recognized within well-foliated quartzofeldspathic gneisses. The earliest recognized period of deformation produced centimeter to meter-scale passive-flow isoclinal folds (F1), some of which are intrafolial folds (Figure 20). The axial plane of these folds is parallel to rock foliation. Some F1 folds are recumbent. Quasi-flexural folds were also produced during F1 and are represented by ptygmatically folded leucosomes and disharmonic folding within

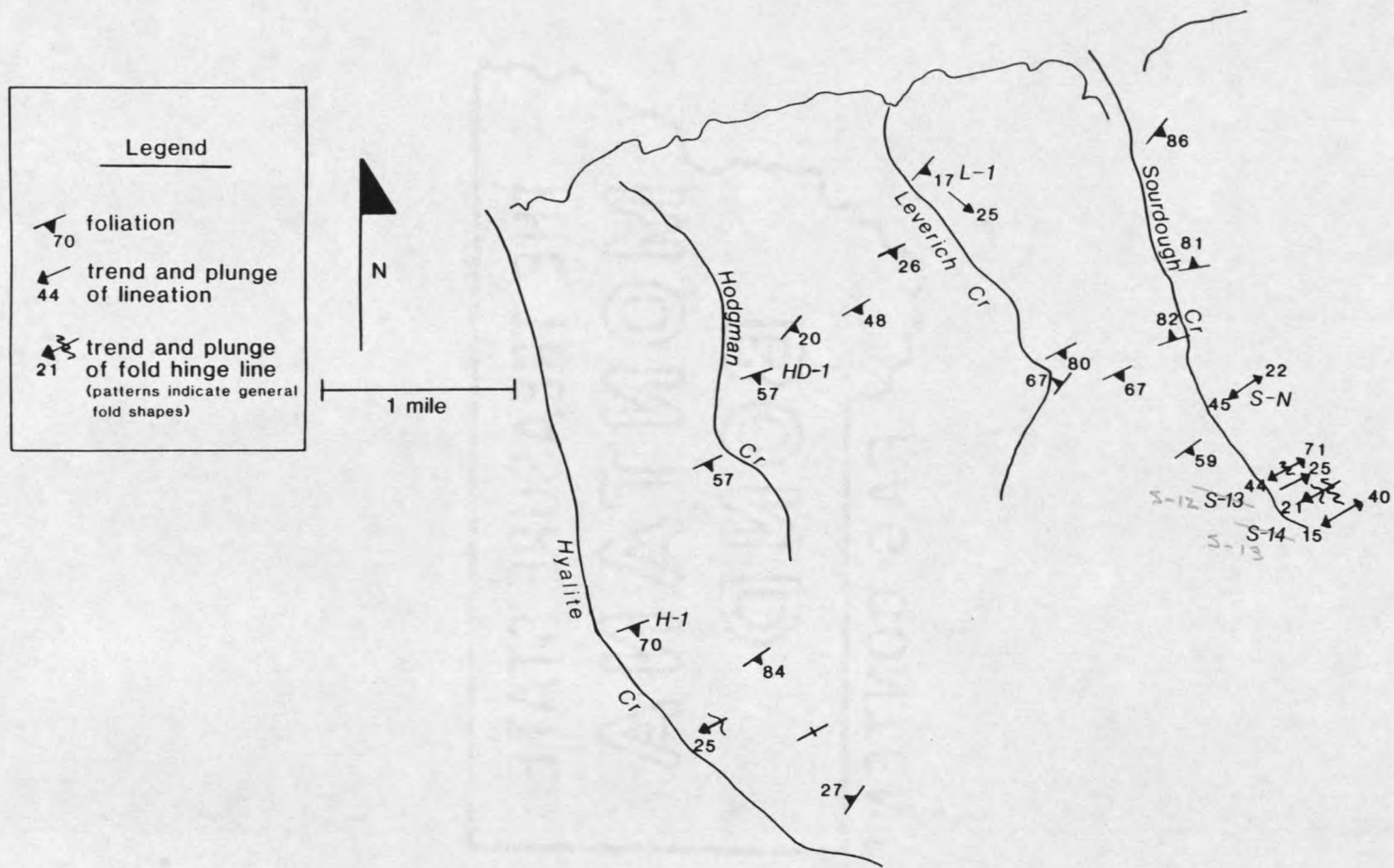


Figure 16. Generalized structure map for study area. (Lettered locations explained in text and in stereonet captions. See also Appendix A.)



- a. Hyalite Canyon (H-1)
 N 52 E, 70 SE.
 71 poles.
 Contours, 1%, 3%, 20%
 30%, per 1% area.



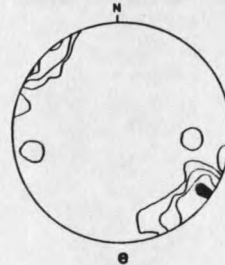
- b. Hodgman Canyon (HD-1)
 N 56 E, 50 SE.
 50 poles.
 Contours, 2%, 10%, 20%,
 30%, per 1% area.



- c. Leverich Creek (L-1)
 N 30 E, 17 SE.
 140 poles.
 Contours, 1%, 10%, 25%,
 4%, per 1% area.

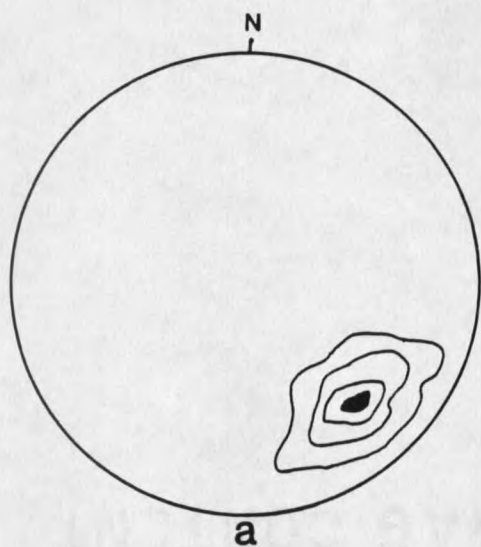


- d. Sourdough Creek (S-13)
 N 51 E, 84 NW,
 N 69 E, 73 SE.
 26 poles.
 Contours, 1%, 5%, 10%,
 15%, per 1% area.

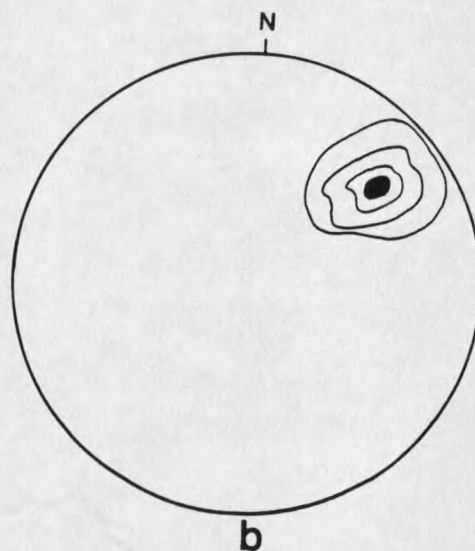


- e. Sourdough Creek (S-12)
 N 36 E, 82 NW,
 N 36 E, 90.
 37 poles.
 Contours, 1%, 5%, 15%,
 25%, per 1% area.

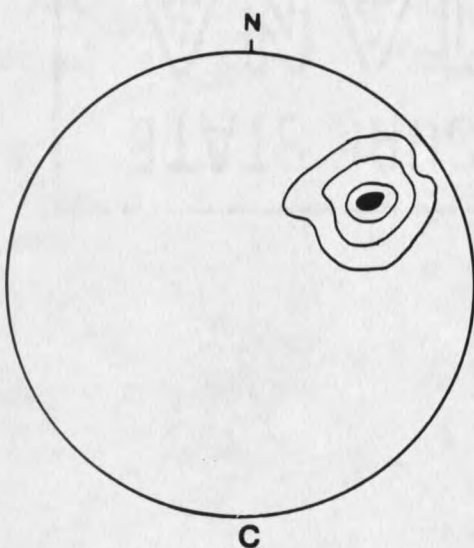
Figure 17. Stereonets illustrating the general strike of foliation from major outcrops within the study area.



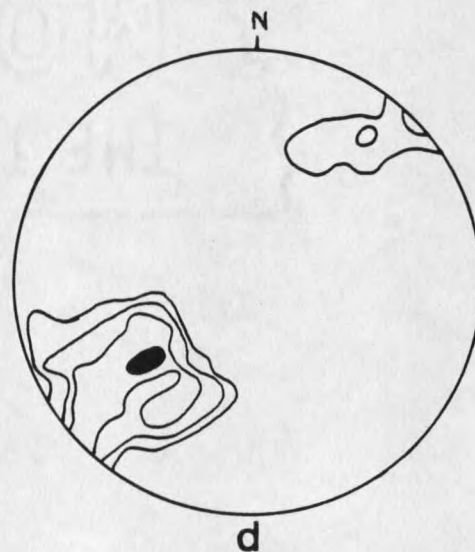
a. Leverich Creek (L-1)
 25, S 67 E.
 32 points.
 Contours, 1%, 3%, 10%,
 20%, per 1% area.



b. Sourdough Creek (S-13)
 40, N 63 E.
 25 points.
 Contours, 1%, 5%, 10%,
 15%, per 1% area.

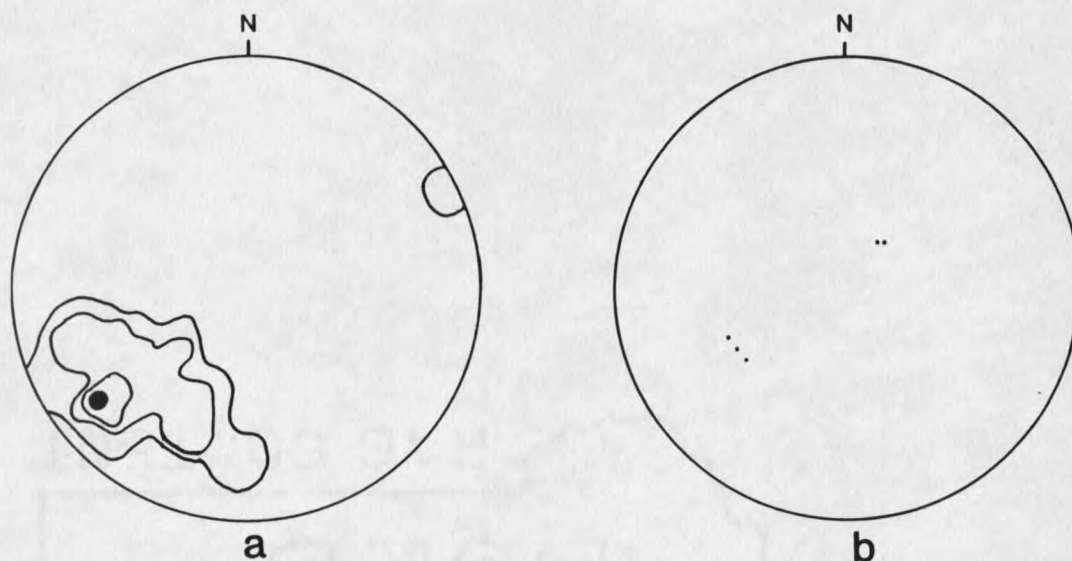


c. Sourdough Creek (S-12)
 25, N 56 E.
 18 points.
 Contours, 1%, 5%, 15%,
 20%, per 1% area.



d. Sourdough Creek (S-N)
 22, N 39 E, 44, S 41 W.
 46 points.
 Contours, 2%, 4%, 15%,
 per 1% area.

Figure 18. Biotite streak and amphibole lineation stereonet.



a. Sourdough Creek (S-13)
 21, S 52 W. 44 points.
 Contours, 2%, 5%, 10%
 20% per 1% area.

b. Sourdough Creek (S-12).
 71, N 29 E, 44, S 60 W.
 5 points. Too few points
 to contour.

Figure 19. Isoclinal and open fold hinge line stereonet.

quartzofeldspathic gneisses (S-13; Figure 21). A second period of deformation produced flexural-flow open folds (F2; S-14; Figure 22), coaxial with F1 folds. F2 folds are generally not overturned and are generally larger (meter-scale) than F1 folds. The principal direction of strain responsible for the deformation of these folds must have remained the same as F2 folds deformed coaxially with F1 folds. The geochronological sequence of fold generations in the study area is based on the degree of closure on folds (Davis, 1984), and the observation that F2 folds folded F1 foliation and compositional layering.

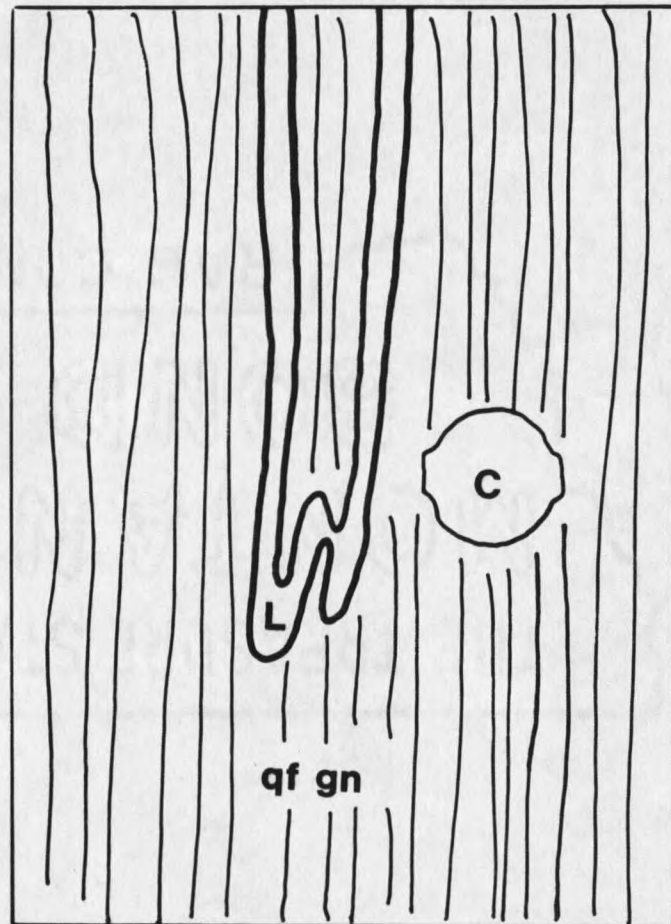
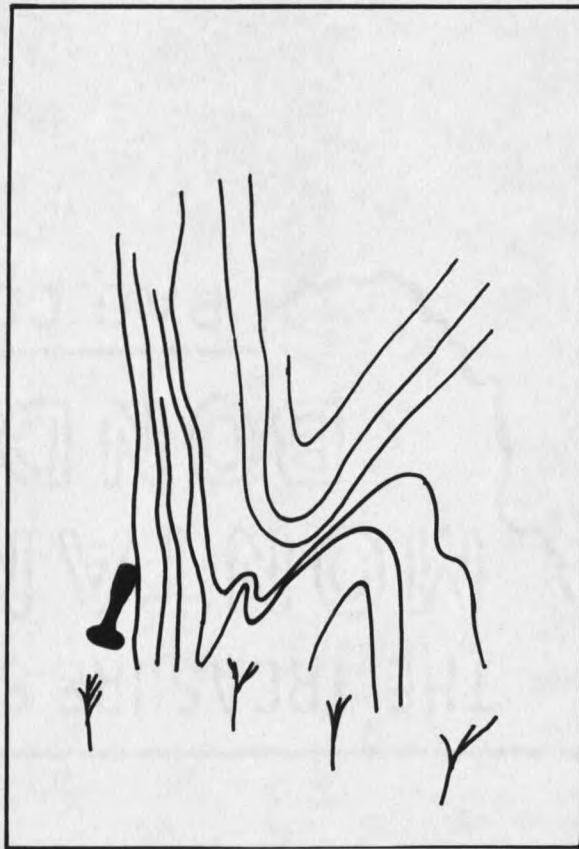
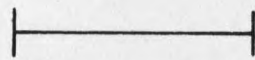


Figure 20. Isoclinal (F1) intrafolial folding of leucocratic unit (L) within quartzofeldspathic gneiss (qf gn). Lens cap (C) diameter = 5 cm.



1 meter

Figure 21. Disharmonically folded (F1) quartzofeldspathic and amphibolite gneisses.

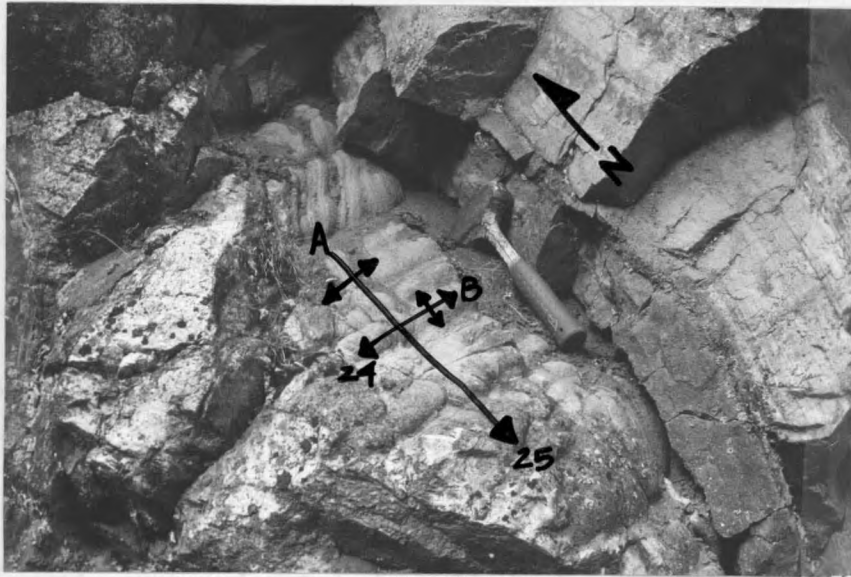


1 meter

Figure 22. Open to broad flexural-flow folds (F2). Dashed lines indicate approximate positions of fold hinge lines.

Both generations of folds presumably formed under high grade metamorphic conditions.

A unique fold style lies in a set of open to broadly folded, centimeter-scale, quartzofeldspathic superposed folds of dome and basin form (S-14; ^{S-13} Figure 23). These folds appear to represent a



30 cm

Figure 23. Superposed folds of dome and basin form. Fold hinge line trends indicated on photo.

localized phenomenon as immediately adjacent folds are not so affected. The dome and basin superposed folds exhibits two different fold hinge line orientations: 25, due south (fold set A, Figure 23), and 24, S73W (fold set B, Figure 23). The latter lies in the same general orientation as the dominant fold hinge line trend for the entire outcrop. A geometric analysis of rock fabric to determine the

relative timing amongst the superposed fold sets is not possible as the structure does not contain any linear minerals. Two realistic possibilities with respect to the relative timing of fold formation are as follows. The superposed folds could have formed contemporaneously as a result of axially symmetric shortening. If the two fold sets formed at different times, it is believed that fold set B would represent the youngest set of folds as they are more coherent and prominent than fold set A. The preferred interpretation is the former. The presence of two fold hinge line orientations within the dome and basin structure is not consistent with the single dominant fold hinge line trend found within the study area (~N45E, Figure 16). It is therefore not realistic to call upon two separate non-coaxial fold events for the generation of superposed folds.

One structural anomaly exists within the Leverich Creek outcrop (L-1). Lineation trends plunge southeast (Figure 18a). This is not consistent with the predominant northeast trend for foliation and fold hinge lines throughout the study area. Although the actual cause is undeterminable, some plausible reasons for this anomaly are:

1. The lineation represents a trend perpendicular to the hinge lines of southeast verging folds in the study area;
2. The lineation represents a localized phenomenon due to rotation of a block along shear zones;
3. Localized strain conditions differed from those that imposed the predominant northeast trend.

CORRELATION OF DEFORMATION AND METAMORPHISM

Based on the presence of granoblastic textures and transitional granulite assemblages, it is believed that the entire study area initially experienced transitional granulite facies metamorphism (M1). Migmatization and the regional foliation (S1) were produced under these conditions. Isoclinal folds that are axial planar to this foliation are also contemporaneous with M1 conditions. Additional evidence for a transitional granulite facies event comes from geothermometric studies. David Mogk (personal communication) has found that garnet-biotite temperatures in quartzofeldspathic gneisses and garnet-clinopyroxene temperatures in the metabasites of transitional granulite grade yield temperatures of 680°-720°. Pressures probably ranged between 5-7 kilobars (Figure 15).

Based on the predominance of epidote-amphibolite facies assemblages, the presence of corona textures in metabasites, hastingsite patches on hornblende grains, and the observation that no new structural elements have been identified within epidote-amphibolite facies rocks, it is believed that epidote-amphibolite facies conditions (M2) were overprinted upon transitional granulite facies rocks (M1), representing a cool-down of the higher grade event (M1). Ductile deformation was contemporaneous with epidote-amphibolite facies conditions (M2) as mylonites in the study area do not exhibit a full range of recrystallization and recovery structures as would be expected if they

had been produced under the earlier peak metamorphic conditions (i.e. transitional granulite facies).

As discussed in the metamorphism section of this thesis, greenschist facies assemblages overprinted upon epidote-amphibolite facies assemblages represent either a greenschist metamorphic event (M-3?) or retrograde effects associated with the waning stages of epidote-amphibolite facies metamorphism (M2).

A small number of rocks within the study area exhibit evidence of brittle failure on a local scale. As these rocks contain epidote-amphibolite facies assemblages and exhibit evidence of extensive retrogression, conditions conducive to brittle behavior must have occurred after M2.

It appears that F1 folds were produced during transitional granulite facies conditions and that broad open coaxial folds reflect a second fold event (F2) as they fold the regional foliation (S1). It is uncertain as to whether F2 folds were produced as part of one continuing metamorphic cycle during the waning stages of transitional granulite facies conditions or later as a separate metamorphic cycle, perhaps under epidote-amphibolite conditions. Although numerous researchers (e.g. Spencer and Kozak, 1975; Vitaliano, et al, 1979; Fountain and Desmarais, 1980; Mueller, et al, 1982) have established that isoclinal folds were produced before large open folds in southwest Montana, these two Archean folding events have not been assigned unequivocal ages with respect to available age dates.

Study area rocks provide clues that contribute to an interpretation of the regional Archean metamorphic and deformational history.

The best reconstruction of metamorphic and deformational events that can be discerned from an integration of petrographic and structural observations within the study area and corroborative evidence from surrounding ranges is presented in Table 4.

Table 4. Interpreted geochronology of metamorphic and deformational events affecting basement lithologies in the northern Gallatin Range.

EVENT

Transitional granulite facies metamorphism (M1), migmatization, and isoclinal folding (F1).

Upper amphibolite facies overprint (M2), open folding (F2), and ductile mylonitization.

Greenschist metamorphism (M3?) or retrogression from amphibolite facies conditions.

Brittle failure.

EVIDENCE

Presence of corona texture exhibiting transition from granulite to upper amphibolite conditions. Tightness of folds is indicative of an earliest fold event.

Upper amphibolite mineral assemblages. Openness of folds indicates later stage of folding than (F1).

Greenschist facies mineral assemblages replacing amphibolite facies minerals.

Cataclastic textures in amphibolite facies rocks.

TECTONIC MODEL

Observations made of Archean exposures in the northern Gallatin Range can be used to address the subject of regional Archean tectonics. Archean terranes have often been subdivided into greenstone-granite or granulite-gneiss terranes (Windley and Bridgwater, 1971; Windley, 1981). Rocks represented in southwest Montana Archean exposures are clearly of the latter category, based on the predominance of high-grade assemblages. The North Snowy Block mobile belt in the Beartooth Range locally defines the boundary between two fundamentally distinct Archean terrains in the northern Wyoming Province: predominantly calc-alkaline granitoids lie to the east and predominantly metasedimentary rocks lie to the west. The presence of a major discontinuity in tectonic style and the presence of large-scale transcurrent faulting in the North Snowy Block mobile belt require that the tectonic evolution of Archean rocks of the study area and adjacent ranges to the west be considered separately (Mogk, et al, in review).

The absence of detailed geochronologic and geochemical data for the study area and adjacent Archean exposures to the west make an interpretation of the tectonic environment very difficult. However, any tectonic model developed for Archean rocks of the study area and adjacent exposures to the west must accommodate the following observations:

1. Quartzofeldspathic gneisses in the study area and in adjacent ranges represent metamorphosed quartz-rich and immature clastic metasedimentary rocks and as such require a silicic source. The presence of carbonates and quartzites in ranges west of the study area is suggestive of stable platform associations in that area. It has been suggested that metasedimentary rocks in the Blacktail Range west of the study area may represent the western edge of a basin proposed by Vitaliano, et al (1979) (Clark and Mogk, 1985). Marble-bearing sequences such as those of the Tobacco Root Range (Vitaliano, et al, 1979) represent the basin's center and the marble-deficient sequences of the northern Gallatin Range represents the basin's eastern margin.
2. A deep crustal level is indicated by the presence of transitional granulite facies assemblages (Perkins and Newton, 1981; Henry, et al, 1982) and associated migmatites. Tectonic thickening is compatible with the pressure and temperature conditions of these rocks.
3. Localized mylonitic fabrics reflect the presence of ductile shear zones.
4. Large-scale isoclinal folds and nappes (defined as sheetlike, allochthonous rock units which have been moved on a predominantly horizontal surface by way of thrust faulting, recumbent folding, or both, Bates and Jackson, 1980) have been observed throughout Archean exposures in southwest Montana (e.g. Vitaliano, et al, 1979; Garihan, 1979).

5. Syn- and post-tectonic granitoids have been recognized in the Spanish Peaks area (Salt and Mogk, 1985) and in the southern Madison Range (Erslev, 1983).
6. Archean exposures in southwest Montana were subjected to a regional metamorphic event at ~2.75 B.Y. (James and Hedge, 1980).

A strong compressional tectonic regime for Archean exposures in southwest Montana is indicated by the presence of granulite facies rocks, isoclinal folds, and nappe structures. The following models are now considered to account for the above-stated observations and constraints:

1. Wholesale Andean-type subduction;
2. Cordilleran-type accretionary tectonics;
3. A-type subduction, with or without limited ocean opening.

Andean-Type Subduction

Wilson (1981) and Fountain and Desmarais (1980) have proposed that the tectonic evolution of Archean rocks in southwest Montana can be attributed to an Andean-type subduction regime. Several observations made of study area rocks and those in adjacent ranges, however, are not compatible with a large-scale oceanic subduction model.

1. The predominance of silicic metasedimentary rocks represented by study area lithologies and the stable platform assemblages represented in ranges to the west sharply contrast with rocks of oceanic affinity. Although small fragments of greenstone belts suggestive of oceanic crust lie to the south of the

study area in the southern Wyoming province (e.g. the Owl Creek Range as well as the South Pass area of the Wind River Range, Condie, 1975), such rocks have not been recognized in southwest Montana Archean exposures. Geochemical data from quartz-thoeliitic amphibolites from the Tobacco Root Range imply a continental mantle origin (Hanley, 1976). In addition, modal abundances of amphibolite units found within the predominantly quartzofeldspathic terrane are not significant enough in volume to be regarded as oceanic crust.

2. There is an absence of lithologies that could be interpreted as metaturbidites or as volcanoclastic rocks typical of a eugeoclinal affinity.
3. Quartzofeldspathic gneisses in the study area are in part K-spar rich. It is suggested that the source area for these rocks could have been the 2.8-2.75 B.Y. granitoids associated with an andesitic arc complex emplaced in the eastern Beartooth Range at about 2.8 B.Y.. If study area rocks were indeed derived from these granitoids, it is believed that the 2.75 B.Y. metamorphic event was not ocean-subduction related as no arc complex of appropriate age exists that would be supportive of such a model (the 2.8 arc complex in the eastern Beartooth Range was emplaced before the rocks in the study area were metamorphosed at 2.75 B.Y.), and is thus too old to be associated with the 2.75 B.Y. metamorphic event).

4. Large-scale magmatic thickening of appropriate age, a signature of Andean-type subduction processes, has not been observed.
5. Andean-type subduction cannot account for the amount of crustal thickening necessary to give rise to transitional granulite facies assemblages within rocks of supracrustal origin such as those so prevalent throughout Archean exposures in southwest Montana.
6. Ophiolite sequences have not been observed.

The Question of Accretion

Recent research in the Madison Range is highly suggestive of a complex tectonic evolution of Archean exposures in southwest Montana. Erslev (1983) has reported the occurrence of two dissimilar lithologic terranes in the southern Madison Range separated by the northeast-trending Madison mylonite zone. This zone trends parallel to the isotopic age transition zone of Giletti (1971) and represents a major Precambrian fault zone (Erslev, 1983). Based on field and petrographic observations, Erslev (1983) believes that the two dissimilar lithologic terranes supports the hypothesis of two dissimilar age terranes via tectonic juxtaposition. Ken Salt (personal communication) has also observed abrupt changes in lithology and metamorphic grade separated by a mylonitic shear zone in the Spanish Peaks area. Several other researchers have recently provided data that is suggestive of an accreted terrane model for Archean rocks in southwest Montana. Mueller et al (1984) have found that chemical features of

metamorphosed supracrustal assemblages in the Beartooth display chemical features suggestive of separate provenances. These chemical differences in conjunction with lithologic variations and differences in metamorphic history suggest that the rock suites evolved in separate areas and were subsequently juxtaposed through accreted terrane processes. Due to the fundamental differences in the nature of southwest Montana Archean basement rocks with dominantly igneous rocks in the Beartooth Range and dominantly metasedimentary rocks in the ranges to the west, it has been suggested that the ancient sialic crust in the Beartooth Range served as a nucleus for the accretion of younger terranes to the west (Mogk, et al, in review; Mogk et al, 1985). Mogk, et al (in review) have postulated that the mechanism responsible for this juxtaposition is analogous on a small-scale with the tectonic features described for the Cordillera of western North America (e.g. Burchfiel and Davis, 1972; Coney, et al, 1980).

All of the above observations are highly suggestive of accreted terranes. Several aspects of this problem are unclear at this time. For example, there is the question of scale. It remains to be discerned whether Archean exposures in southwest Montana represent displaced terrains via telescoping of one continuous basin or whether anomalous exposures are indicative of the emplacement of exotic terranes by way of wholesale accretion. It is possible that lithologies in the study area and in adjacent ranges to the west did not develop as a basin adjacent to a Beartooth highland but were derived elsewhere and were subsequently juxtaposed with the Beartooth Range. The question of timing must also be considered. Exposures in southwest

Montana may record the activity of many separate tectonic events as opposed to one orogeny. For this reason it is quite probable that one unifying tectonic model cannot address all of the problems associated with understanding the Archean tectonic evolution of the area.

It is currently not possible to determine whether Archean exposures in southwest Montana represent allochthonous accreted terranes or collapsed basin deposits. Detailed stratigraphic relationships, geochemical analyses, additional as well as more precise age-dating, and paleomagnetic studies are needed in order to expand upon the theory of accretionary tectonics for Southwest Montana Archean exposures. It is suggested that accretion of exotic terranes may have played only a minor role in the tectonic evolution of study area rocks and ranges to the west as strike-slip faulting is a large component of accretionary tectonics and this cannot account for the generation of transitional-granulite grade assemblages.

A-Type Subduction

Figure 24 illustrates stages of an inferred A-type (continental) subduction model for Archean rocks in southwest Montana. This model was proposed by Martin and Porada (1977), Martin (1983), and later presented by Kroner (1981) to explain the tectonic evolution of the Pan-African Damara orogenic belt. A first stage involves the deposition of sedimentary rocks into a intracontinental or ensialic basin (Figure 24 a.). Platform sediments indicated by the assemblages present in the study area and in ranges to the west (e.g. Spencer and Kozak, 1975; Vitaliano, et al, 1979) are indicative of the presence

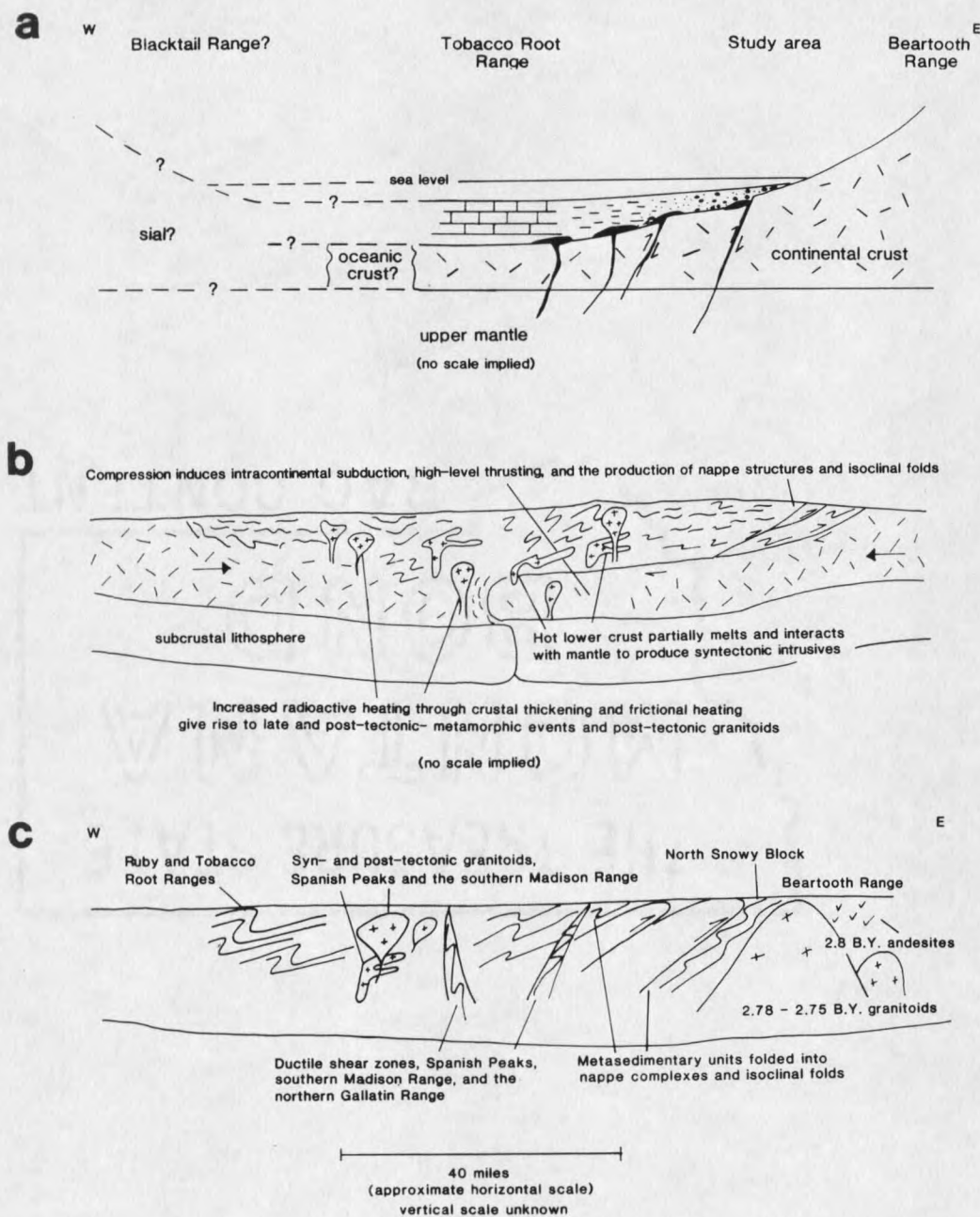


Figure 24. Suggested stages in the Archean tectonic evolution of southwest Montana (excluding the Beartooth Range) involving A-type (continental) subduction. a) Pre-tectonic setting. b) Compressional tectonics resulting from A-type subduction (modified from a model of the Pan-African Damara Belt by Kroner, 1981). c) Structural and lithologic features within southwest Montana Archean exposures.

of such a basin. Attenuation of the crust accommodates the intrusion of basalts which form extensive but thin layers within the metasedimentary rocks. This model is similar to that described by Stewart (1972) and Einsele (1985) to account for the presence of basaltic units found within sedimentary lithologies. Limited oceanic opening is possible within an A-type subduction model (Martin and Porada, 1977; Martin, 1983). A subsequent compressional tectonic regime via A-type subduction induces shortening of the overlying sedimentary cover, producing nappe complexes and interstacking of sedimentary units (Figure 24 b.). Nappes in the Tobacco Root Range (Vitaliano, et al, 1979) and the Ruby Range (Garihan, 1979) testify to the telescoping of the sedimentary cover via large-scale compressive stresses (Figure 24 c.). A-type subduction also provides a mechanism for subjecting supracrustal rocks to migmatization and transitional granulite facies conditions as a result of tectonic thickening via crustal underthrusting. An over-riding of sialic plates establishes the crustal thicknesses necessary for the generation of transitional granulite grade conditions. The deep crustal levels that Archean rocks in southwest Montana represent clearly could not have resulted from thin-skinned tectonics. Mylonitic shear zones result from intraplate displacements by way of intense thrusting. Such shear zones have been identified in the Spanish Peaks (Salt and Mogk, 1985) and the southern Madison Range (Erslev, 1983; Figure 24 c.). Syn- and post-tectonic granitoids result from lower crustal melting associated with tectonic thickening via A-type subduction. Such metamorphosed intrusives within the Spanish Peaks area (Salt and Mogk, 1985) and a meta-igneous

terrane in the southern Madison Range (Erslev, 1983) have been recognized (Figure 24 c.).

An insufficient amount of data for this area precludes a thorough understanding of the tectonic setting for Archean rocks in southwest Montana. This author does not discount the possibility of other collisional models such as oceanic subduction or accretionary tectonics but suggests that available data and observations currently best support an A-type subduction model of an ensialic basin. With additional geochronologic and geochemical data, as well as additional field work, the nature of the tectonic setting for Archean rocks in southwest Montana will become more clear.

SUMMARY AND CONCLUSIONS

Archean metamorphic rocks in the northern Gallatin Range in southwest Montana are predominately composed of regionally metamorphosed quartzofeldspathic gneisses with minor amounts of metabasites, representative of supracrustal assemblages composed of metasedimentary and metavolcanic rocks. These rocks range from epidote-amphibolite to lower granulite facies in grade and have been subjected to intense deformation during regional high grade metamorphism. Evidence of greenschist facies retrogression in some of the rocks studied indicates either a separate, later metamorphic event, or low temperature conditions associated with a late stage of prior high-grade metamorphism.

Mineralogical and textural features indicate that the study area initially experienced transitional granulite facies metamorphic conditions under pressures of 5-7 kb and temperatures of 680°-720°. A regional foliation parallel to lithologic layering was produced and migmatization and isoclinal passive-flow folds were probably contemporaneous (F1) with this event. A second deformational period produced broad open folds, coaxial with F1 folds. Throughout the study area a dominant structural grain is expressed by a general N45E trend amongst fold strikes as well as fold and lineation trends.

It is believed that Archean lithologies in the study area and in adjacent ranges to the west represent thick sedimentary sequences

deposited within an ensialic basin. Metabasite units within the metasedimentary rocks may represent basaltic intrusions. Regional high-grade metamorphism subsequently affected the area. The generation of transitional granulite facies assemblages and associated migmatites, large-scale isoclinal folds and nappe structures, and ductile shear zones attests to a compressional regime that involved tectonic crustal thickening. Based on available information and observations, the preferred model for the tectonic evolution of Archean rocks within the study area and adjacent ranges to the west is that of A-type (continental) subduction. Additional research involving geochronologic and geochemical study as well as detailed fieldwork will contribute to a clearer understanding of the tectonic evolution for Archean rocks in southwest Montana.

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APPENDICES

APPENDIX A

LOCATIONS OF MAJOR OUTCROPS THAT WERE STUDIED IN DETAIL

APPENDIX A

<u>Outcrop</u>	<u>Legal Description</u>	<u>Narrative Description</u>
H-1	SW 1/4, NE 1/4, 23, T3S, R5E	2.3 miles south along Hyalite Creek Road.
L-1	NE 1/4, SE 1/4, 12, T3S, R5E	Along abandoned logging Forest Service road parallel to Leverich Creek, 1/3 mile south of range front.
S-12 S-13	NE 1/4, NW 1/4, 20, T3S, R6E	1.6 miles south along Forest Service logging road following Sourdough Creek.
S-23 S-14	NE 1/4, NW 1/4, 20, T3S, R6E	1.8 miles south along Forest Service logging road following Sourdough Creek.

APPENDIX B

MINERAL CONTENTS OF QUARTZOFELDSPATHIC GNEISSES

M = major amounts (> 5%), Tr = trace amounts (< 5%), - =not present.

Thin sections

Mineral	H1A	H1C2	H-3-2	H-5-4	H-9	H-10	H-10-1	H-12-1	H-12-2	H-13-2
Quartz	M	M	M	M	M	M	M	M	M	-
Plagioclase	M	-	M	M	M	M	M	M	M	M
Kspar	-	-	-	M	-	-	M	M	-	-
Garnet	Tr	M	M	-	-	M	Tr	-	-	-
Biotite	Tr	M	M	M	Tr	M	Tr	Tr	M	-
Amphibole ¹	-	Tr	-	-	M	Tr	-	-	Tr	M ²
Opaque phases	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Tourmaline	-	Tr	-	-	-	-	-	-	-	-
Muscovite	-	-	-	-	M	-	Tr	Tr	-	-
Sericite	M	-	M	M	-	-	M	Tr	Tr	Tr
Epidote group	-	-	-	-	Tr	Tr	Tr	-	Tr	Tr
Zircon	Tr	-	Tr	Tr	Tr	Tr	Tr	-	Tr	Tr
Chlorite	-	-	Tr	-	Tr	Tr	Tr	-	Tr	Tr
Apatite	Tr	-	-	-	-	-	-	-	-	-
Cordierite	-	-	-	-	-	-	-	Tr	-	-
Sillimanite	-	-	-	-	-	Tr	-	-	-	Tr

1 Amphiboles are of hornblende composition unless otherwise indicated.

2 Cummingtonite.

3 Gedrite.

Table 5. Mineral contents of quartzofeldspathic gneisses.

M = major amounts (> 5%), Tr = trace amounts (< 5%), - = not present.

Thin sections

Mineral	L-5	L-14	MIG.1	S-1-2	S-1-3	S-2	S-3-1	S-3-3	S-22	S-24	S-52Gn
Quartz	M	M	M	M	M	M	M	M	M	M	M
Plagioclase	M	M	M	M	M	M	M	M	M	M	M
Kspar	Tr	-	M	M	M	M	M	-	-	M	M
Garnet	-	-	-	Tr	-	-	-	Tr	Tr	-	Tr
Biotite	M	M	-	M	M	M	M	M	M	Tr	M
Amphibole	-	M	-	-	-	-	-	M	-	Tr	-
Opaque phases	Tr	Tr	Tr	Tr	Tr	-	Tr	Tr	Tr	Tr	Tr
Tourmaline	-	-	-	-	-	-	-	-	Tr	-	-
Muscovite	Tr	-	-	Tr	Tr	Tr	Tr	-	M	-	-
Sericite	M	M	M	Tr	Tr	M	M	-	M	M	Tr
Epidote group	Tr	Tr	Tr	-	-	Tr	-	-	-	Tr	-
Zircon	-	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Chlorite	Tr	Tr	M	-	-	Tr	Tr	-	Tr	-	-
Apatite	-	-	-	-	-	-	-	Tr	-	Tr	-
Cordierite	-	Tr	-	-	-	-	Tr	Tr	-	-	-
Sillimanite	-	-	-	-	-	-	-	-	-	-	-

APPENDIX C

MINERAL CONTENTS OF AMPHIBOLITE FACIES

M = major amounts (> 5%), Tr = trace amounts (< 5%), - = not present.

Thin sections

Mineral	H-1B3	H-1E	H-4	H-5-1	H-6	H-7	L-7	L-10	L-19	MIG2	MGU	S-1-1	S-3-2	S-3-4	S-6	S-52
Amphibole ¹	M	M	M	M	M ²	M	M ³	M	M	M	M	M	M	M	M	M
Plagioclase	M	M	M	M	-	M	-	-	M	Tr	M	M	M	M	M	M
Garnet	M	-	M	-	M	-	-	-	-	-	M	M	M	M	-	M
Quartz	M	-	M	-	Tr	M	-	-	Tr	M	Tr	M	Tr	T	M	-
Biotite	Tr	-	Tr	Tr	-	-	Tr	Tr	M	-	-	Tr	M	M	M	Tr
Clino- pyroxene	-	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Opaque phases	Tr	Tr	Tr	Tr	M	Tr	M	M	Tr	-	Tr	Tr	M	Tr	Tr	Tr
Sphene	M	-	Tr	Tr	-	Tr	-	-	-	-	M	Tr	-	Tr	-	-
Epidote group	-	-	-	-	-	Tr	-	-	-	Tr	Tr	Tr	-	-	Tr	-
Zircon	Tr	Tr	-	Tr	-	-	-	-	-	Tr	-	Tr	-	Tr	Tr	Tr
Chlorite	Tr	-	-	-	-	-	Tr	Tr	Tr	M	-	-	Tr	Tr	-	-
Sericite	M	M	Tr	-	-	M	Tr	-	-	-	M	Tr	-	M	M	-
Apatite	-	-	Tr	Tr	-	-	-	-	-	-	Tr	-	-	-	-	-

1 Amphiboles are of hornblende composition unless otherwise indicated.

2 Cummingtonite and tremolite.

3 Actinolite.

Table 6. Mineral contents of amphibolite facies.

APPENDIX D

MINERAL CONTENTS OF TRANSITIONAL GRANULITES

