THESIS

STRUCTURAL GEOLOGY AND TECTONIC SETTING OF THE CHERRY CREEK METAMORPHIC SUITE, SOUTHERN MADISON RANGE

Submitted by

Wendolyn Rivers Sumner

Department of Earth Resources

In partial fulfillment of the requirements

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY WENDOLYN RIVERS SUMNER ENTITLED STRUCTURAL GEOLOGY AND TECTONIC SETTING OF THE CHERRY CREEK METAMORHIC SUITE, SOUTHERN MADISON RANGE BE ACCEPTED AS FULFILLING IN PART THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

Committee on Graduate Work

Larry K. Burne

Erle Thompson

Eric G. Erslev

Adviser

H. S. Boyne

Department Head

ABSTRACT OF THESIS

STRUCTURAL GEOLOGY AND TECTONIC SETTING OF THE CHERRY CREEK METAMORPHIC SUITE, SOUTHERN MADISON RANGE

The Cherry Creek Metamorphic Suite, exposed in the core of the southern Madison Range in the northwestern Wyoming province, is a well-preserved, carbonate-quartzite-pelite shelf association of Archean age containing a coherent stratigraphic sequence. Relict sedimentary structures (161 measurements) reveal that stratigraphic up is to the southeast. Trace element geochemistry of the meta-turbidites indicates that the sediments were deposited in a back arc basin analogous to the Sea of Japan. Comparison of major element chemistry of the pelites with other suites in the northwest Wyoming Province suggest a similar provenance throughout the region.

Repetition and truncation of the Cherry Creek stratigraphy occurs along a series of narrow, southeast-dipping mylonite zones of Late Archean age. Petrofabric analyses of C-S surfaces, asymmetrical mineral retorts, and rolled garnets indicate oblique thrusting to the northwest. Strain analysis of psammitic portions of meta-turbidites indicates largely flattening strains and bulk shortening of the Cherry Creek Metamorphic Suite, with associated plane strain localized in thrust zones. Prograde (middle-amphibolite facies) mineral growth lineations parallel fold axes in zones of heterogeneous shear, suggesting synchronous prograde metamorphism and deformation.

Down-plunge projection of fabric, strain and map relationships demonstrate tectonic thickening of the Cherry Creek Metamorphic Suite by thrust imbrication and duplex stacking. This thin-skin deformation is closely analogous to many post-Archean convergent belts, suggesting similar tectonic processes during the Archean.

Wendolyn Rivers Sumner
Department of Earth Resources
Colorado State University
Fort Collins, Colorado 80523
Summer 1988

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INTRODUCTION

Statement of Problem

Plate tectonic processes are well documented for the Early Proterozoic (Hoffman, 1980; Karlstrom et al., 1984; Condie, 1982); however, evidence for modern plate tectonic processes during the Archean is limited. The nature and driving forces of Archean tectonic regimes remain highly debated due to the fragmentary rock record preserved in Precambrian shields.

Many workers propose a significant change in the crust-mantle system between the Archean and the Proterozoic based on differences in rock composition, tectonic style, and the relative abundance of specific rock types from the two eons (Taylor and McLennan, 1985; Windley, 1984; Condie, 1983). Archean provinces are characterized by an abundance of high-grade gneiss and greenstone belts and tend to lack continental margin and shelf associations. These differences in petrogenetic environments have led to exotic plate tectonic models for the Archean that bear little resemblance to modern settings (Green, 1972; Condie; 1983). The increased occurrence of stable shelf suites through geologic time is an important yet unexplained temporal pattern with major implications for early crustal evolution (Taylor and McLennan, 1985; Gibbs et al., 1986).

Limited studies of Archean shelf associations may bias our understanding of Archean tectonic regimes. A comparison of provenance characteristics of Archean associations worldwide (Tables 1 and 2) shows that carbonate bearing shelf associations are particularly rare in Archean shield provinces. The apparent lack of Archean continental margin and shelf associations may be either a function of fewer continental margin rocks in the past or the result of preferential reworking and recycling of continental margins through time (Veizer and Jansen, 1985). The characterization of Archean continental margin deformation histories may provide additional information on the variety of tectonic processes during the Archean.

In the northwestern Wyoming Province, the Cherry Creek Metamorphic Suite is an anomalously well-preserved, by Archean standards, carbonate-quartzite-pelite shelf association. Massive dolomite marbles form up to 27% of the stratigraphic section (Table 1) and contain a Sr isotopic composition more consistent with Phanerozoic carbonates than Archean carbonates (Gibbs et al., 1986). Similarly, abundant pelitic rocks of the Cherry Creek Metamorphic Suite sequence contain post-Archean geochemical signatures including negative europium anomalies and steep LREE patterns. This anomalous Archean supracrustal

Table 1. Preliminary characteristics of selected gneiss belts worldwide. Sequences and ages are after Taylor and McLennan (1985). Lithologic percentages and sedimentary structures are from primary references.

SEQUENCE	AGE (Ga)	GRADE (P&T)	%CARBONATE	%QUARTZITE	%METAPELITE	%VOLCANICS	SED.STRUCTURE	REFERENCE
Western Gneiss Terrain Western Australia	3.6-3.4	amp.-gran. (5-6.5Kb) (750-840C)	Present	Present	Very Abundant	Trace	preserved x-beds	Blight,D.F.,1978 Gee et al,1981 Myers & Williams,1985
Limpopo Southern Africa	3.5-3.3	amp. & gran. (10Kb,800C)	~15%	~17%	~50%	~15%	none reported	Coward et al,1976 Eriksson & Kidd,1985 Horrocks,1983
Labrador	3.8-3.6	predominantly amphibolite & granulite	Present	Present	>20% Abundant	>50% Abundant	none reported	Collerson et al,1976 Windley,1984
Atlantic Granulite Belt Brazil	2.7	amp. & gran. (4-7Kb) (780-850C)	Present	Present	Present	Present	none reported	Wernick,1981
Napier Complex Aust. Antarctic Territory	3.8-3.3	amp. & gran. (8-10Kb) (900C)	<1% Trace	<3% Trace	~10% Present	>80% Abundant	none reported	Sandiford &Wilson,1986
South India	3.4	amp. & gran. (9-10Kb) (720-840C)	Present	Present	Abundant	Abundant	none reported	Beckinsale et al,1980 Harris et al, 1982 Weaver et al,1978
Kapuskasing Canada	2.8-2.6	amp. - gran. (5.4-8.4) (<600->800C)	None	None	Present	Abundant	none reported	Taylor et al, 1986
NW Wyoming Province	3.4-2.7	gs. - amp. (3-7Kb) (500-800C)	3%	27%	57%	12%	x-beds graded beds	Gibbs et al, 1986 Erslev, 1983

Table 2. Provenance characteristics of selected Archean metasedimentary assemblages worldwide. Sequences and ages are from Taylor and McLennan (1985). Lithologic percentages and sedimentary structures are from primary references.

SEQUENCE	AGE (Ga)	GRADE (P&T)	%CARBONATE	%QUARTZITE	%METAPELITE	%VOLCANICS	SED. STRUCTURE	REFERENCE
Isua-Akilia assoc. West Greenland	3.8	amphibolite (550C, 5Kb)	23%	16%	8%	23%	destroyed	Nutman et al. 1984; McLennan et al. 1984
Fig Tree Group South Africa	3.4	sedimentary	0%	6% (chert)	77% (shale)	17%	flute casts scour casts cross-beds graded beds	Condie et al. 1970; Eriksson 1980; McLennan et al. 1983
Moodies Group South Africa	3.4	sedimentary	0%	45% (sandstone) (subarkose)	47% (shale)	8%	sym. ripples graded beds trough x-beds	Eriksson 1980; McLennan et al. 1983
George Creek Group Western Austrailia	3.4	sedimentary	0%	abundant (sandstone)	abundant (shale)	present	graded beds ripples trough x-beds	Eriksson 1982; McLennan et al. 1983
Malene Supracrustals West Greenland	3.05	mid-upper amphibolite (575C, 5Kb)	0%	17%	66%	17%	destroyed	Dymek et al. 1983
Kambalda Yilgarn Block Western Austrailia	2.8-2.7	greenschist	0%	16% (chert)	0%	84%	not present	Bavinton et al. 1980
Kalgoorlie Yilgarn Block Western Austrailia	2.8-2.7	greenschist	0%	5%	30%	65%	not present	Nance et al. 1977
Yellowknife Supergroup Canada	2.7-2.6	greenschist to amphibolite	0%	0%	35%	65%	pillows graded beds volc. lapilli	Jenner et al. 1981
South Pass Greenstone Belt U.S.A	2.7-2.6	greenschist	0%	8%	40%	52%	graded beds	Condie 1967; Bayley et al.

assemblage suggests a greater diversity of Archean petrogenetic environments than those encompassed by the traditional greenstone belt - gneiss belt classifications.

Purpose

This study's primary objective is to characterize the Archean deformation and the probable tectonic setting of the Cherry Creek Metamorphic Suite in the Henrys Lake Mountains segment of the southern Madison Range (Figure 1). Specifically, this study interprets the large scale structural geometry for the Cherry Creek Metamorphic Suite through reconstruction of the stratigraphic sequence, tops indicators, shear sense determinations, strain analysis, and a down plunge projection through the study area. A secondary objective of this study is to interpret the protoliths and probable depositional setting of the Cherry Creek Metamorphic Suite through observation of relict primary structures and geochemical analysis of quartz-biotite schist and amphibolite. On a larger scale this study contributes to the understanding of tectonic environments in the northwestern Wyoming Province.

Several episodes of deformation and metamorphism often complicate the precise determination of the structural evolution of crystalline terranes. In the northwestern Wyoming Province, a clear understanding of the tectonic processes that preserved the Cherry Creek Metamorphic Suite requires the definition and subtraction of later deformation events. This study area was selected because it shows the least effects of Early Proterozoic crustal reworking and resetting of K-Ar clocks in the northwestern Wyoming Province (Giletti, 1971; Erslev and Sutter, in prep.). Similarly, Phanerozoic deformation of the crystalline rocks is limited to block faulting with minimal penetrative deformation during Laramide thrusting and Recent basin and range extension (Schmidt and Garihan, 1983; Erslev, 1983).

Specific questions this study addresses are:

1) What is the structural style and sequence of Archean deformation in the Henrys Lake Mountains?

2) Do the present exposures of the Cherry Creek Metamorphic Suite represent primary stratigraphy or a tectonic stratification?

3) What was the depositional environment and tectonic setting of the Cherry Creek Metamorphic Suite and how does this relate to the tectonic development of the northwestern portion of the Archean Wyoming Province?

Location

The Madison Range, located in southwestern Montana and eastern Idaho trends 80 km north-northwestward from the Henrys Lake Mountains, Idaho, to the southwest of Bozeman, Montana (Figure 1). The study area is located in the Henrys Lake Mountains segment of the southern Madison Range, 13 km west of West Yellowstone, Montana, along the

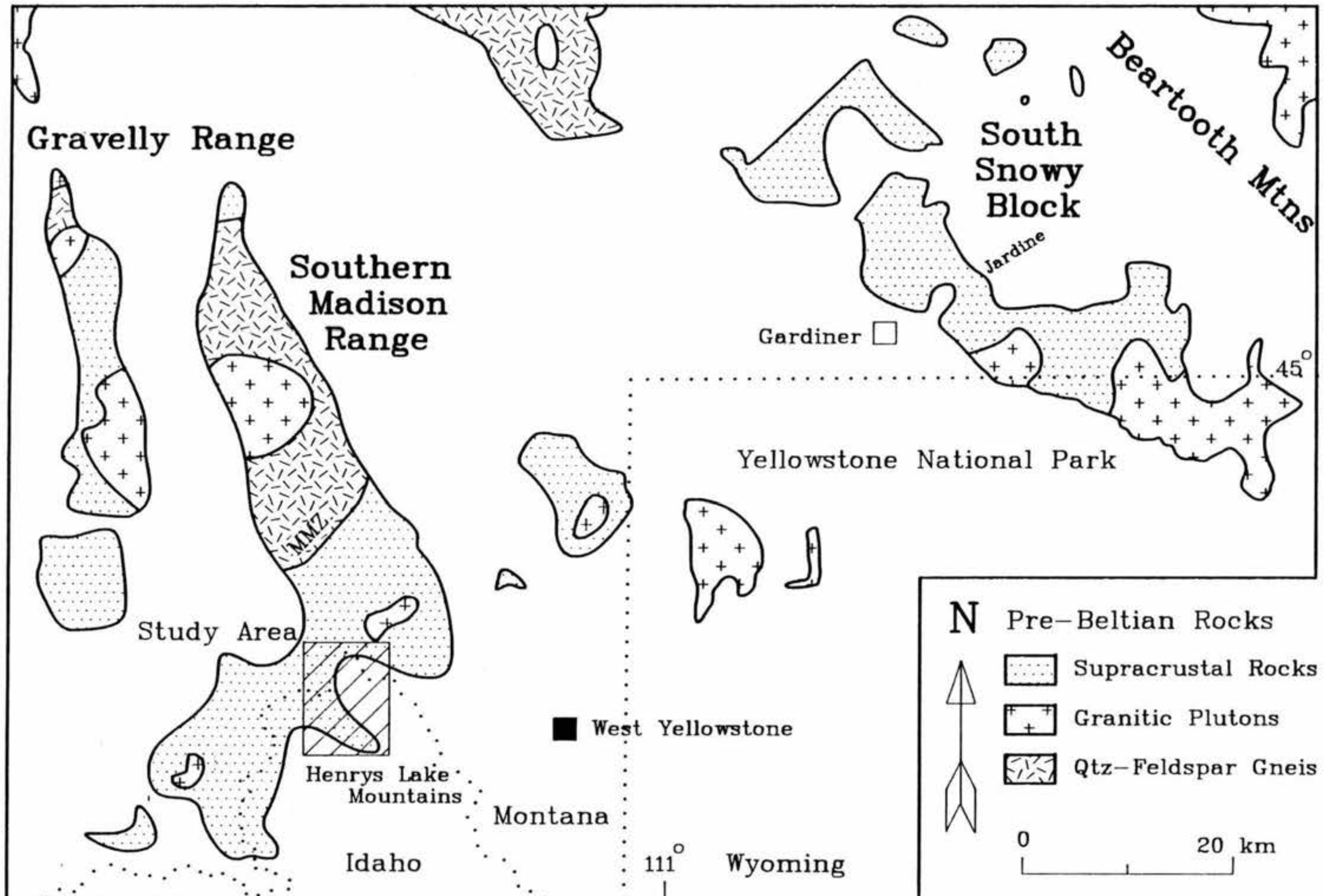


Figure 1. Locality map and distribution of Pre-Beltian rocks.

continental divide. The study area is covered in portions of the Henrys Lake and Hebgen Dam 15 minute quadrangles.

Access

U.S. Highway 287 along the Madison River valley provides general access to the Henrys Lake Mountains. Two unimproved roads in the Mile Creek and Little Mile Creek drainages penetrate a short distance into the area, but access to most of the area is by game trails. Private land flanks the western portion of the field area and several gates block vehicular access to the Targhee and Gallatin National Forest land.

Three months during the summer and fall were spent mapping the Precambrian rocks in 1985 and 1986. Glaciated rock exposures and steep alpine ridges that trend perpendicular to regional foliation provide an excellent three--dimensional view of the Precambrian geology. The entire field area is above 1800 m. The highest point is an unnamed 3290 m peak south of Sheep Mountain and several other peaks exceed 3100 m. There is a maximum of 980 m structural relief between the Madison Range ridge crest and the adjacent Madison River valley. Extensive rock outcrops along southwestern facing slopes are sparsely vegetated and provide excellent exposures.

CHAPTER 2

PREVIOUS WORK

Regional Geologic Setting

The Pre-Beltian rocks in southwest Montana and eastern Idaho form the northwestern extent of the Archean Wyoming Province (Figure 1). The rocks are exposed in the cores of Laramide (Cretaceous to early Tertiary) uplifts in the Madison, Gallatin, Tobacco Root, Gravelly, and Ruby Ranges along with the Beartooth Mountains. The metamorphic rocks in the northern Wyoming Province are part of a poorly constrained collage of gneiss complexes and metasedimentary rocks. The metamorphic and structural history of much of the Wyoming province remains obscure due to discontinuous exposure between ranges coupled with complex deformation histories.

Ongoing investigations of the petrogenesis of the Archean rocks are beginning to focus on regional tectonic syntheses for the Wyoming Province (Erslev, in press; Karlstrom and Houston, 1984; Karasevich et al., 1981; Schuster et al., 1987; Mogk et al., 1988). Isotopic dating of these rocks reveals that the basement exposures are middle Archean (Giletti, 1971; James and Hedge, 1980; Shuster and others, 1987; Erslev and Sutter, in prep.). A Rb-Sr whole-rock analysis of a suite of quartzofeldspathic gneisses from Madison County yielded a 2.75 Ga isochron (James and Hedge, 1980) and this age is interpreted as the last major prograde thermal event in the northwestern Wyoming Province.

There is a transition from Archean to Early Proterozoic K-Ar ages toward the northwest margin of the Wyoming Province (Giletti, 1971). Northwest of the line, K-Ar ages are less than 1.8 Ga (Figure 2). Southeast of the line, K-Ar ages are dominantly greater than 2.5 Ga. A regional Proterozoic thermal event, at about 1.8 Ga, is probably responsible for the resetting of K-Ar clocks. ^{40}Ar-^{39}Ar dates from a retrograde shear zone, the Madison mylonite zone in the southern Madison Range, also yield a Proterozoic date for thermal reworking and deformation of the Archean basement (Erslev and Sutter, in prep.).

Southern Madison Range

The southern Madison Range, a major Laramide fault block (Witkind, 1964), is bound by the Cabin Creek thrust fault along its eastern boundary and is truncated by the younger Madison Range normal fault (Tertiary to Recent) along its western boundary. The Madison Range fault is one of the largest Cenozoic faults in southwest Montana and can be traced for 70 miles from Big Springs, Idaho, to Ennis, Montana (Pardee, 1950). Recent faulting during the Hebgen Lake earthquake of 1959 demonstrates that active extensional tectonics still affect the area.

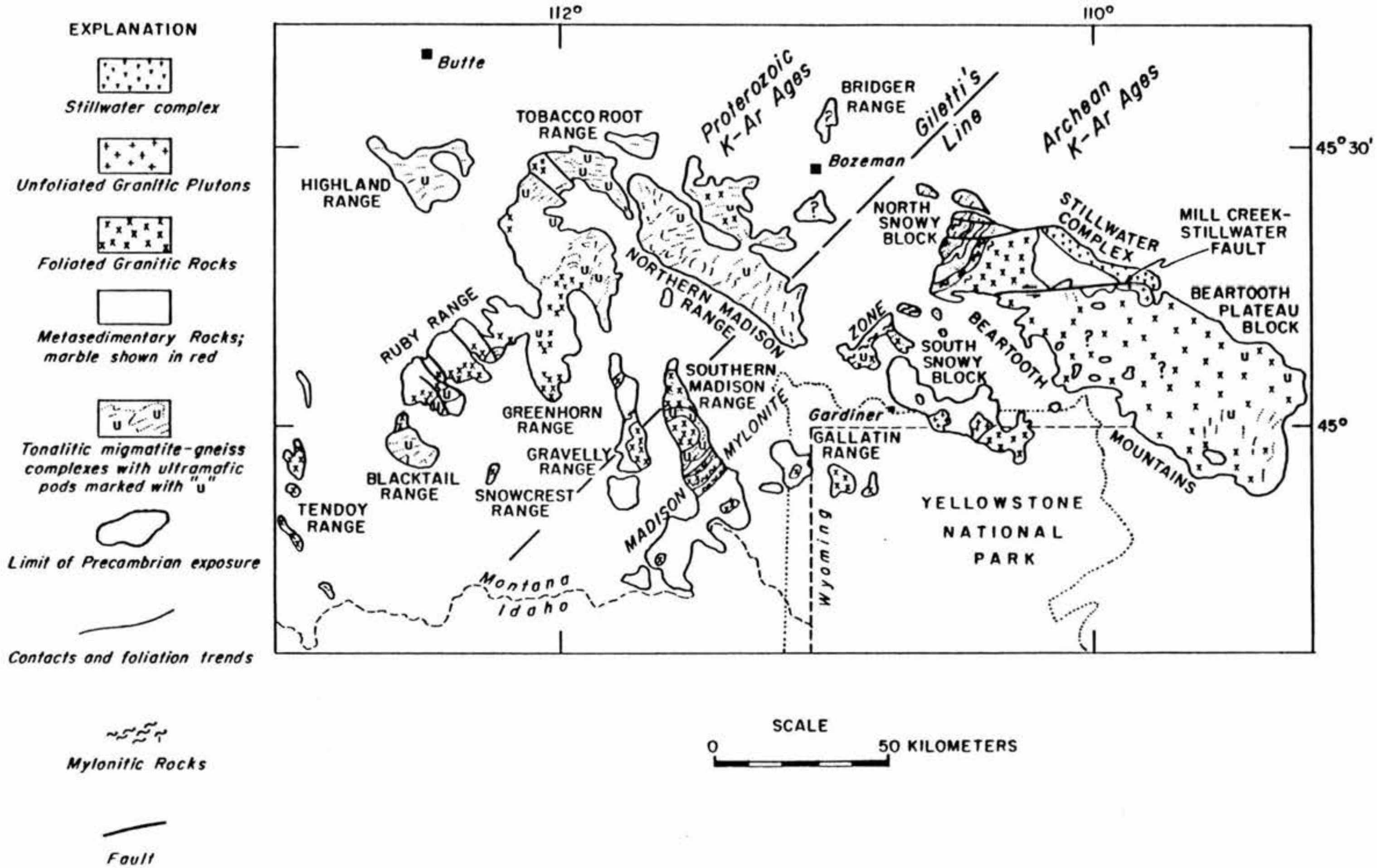


Figure 2. Northwest Wyoming Province and Giletti's (1971) K-Ar transition in age distributions after Erslev in preparation.

There are very few studies of the Precambrian geology in the southern Madison Range. In the central portion of the southern Madison Range, Erslev (1981; 1983) mapped two different pre-Beltian lithologic and metamorphic domains (Figure 3). The northern domain consists of tonalitic to granitic feldspathic gneisses and minor metasedimentary lithologies. The gneisses surround a central granitic augen gneiss dome. The southern domain is a supracrustal domain consisting of dolomitic-marble, quartzite, pelitic and semi-pelitic schist and amphibolite.

Erslev (1981) documented three metamorphic equilibrations in the northern gneiss complex, with an early granulite-facies metamorphism indicated by enclaves of bronzite + spinel bearing ultramafic pods and two pyroxene migmatites. A subsequent amphibolite facies metamorphism is indicated by mineralogies of rocks from both domains suggesting a regional thermal reworking. Middle-to-upper amphibolite facies assemblages (> 6 kb) characterize the southern domain based on garnet-biotite geothermometry (600 C) and the mineral assemblage quartz + staurolite + garnet + kyanite + biotite (Erslev, 1981). The two domains are separated by the Madison mylonite zone, which is characterized by retrograde epidote amphibolite facies assemblages.

In the southern domain, south of the gneiss complex and the Madison mylonite zone, Erslev (1983) correlated the metasedimentary sequence with the Cherry Creek Metamorphic

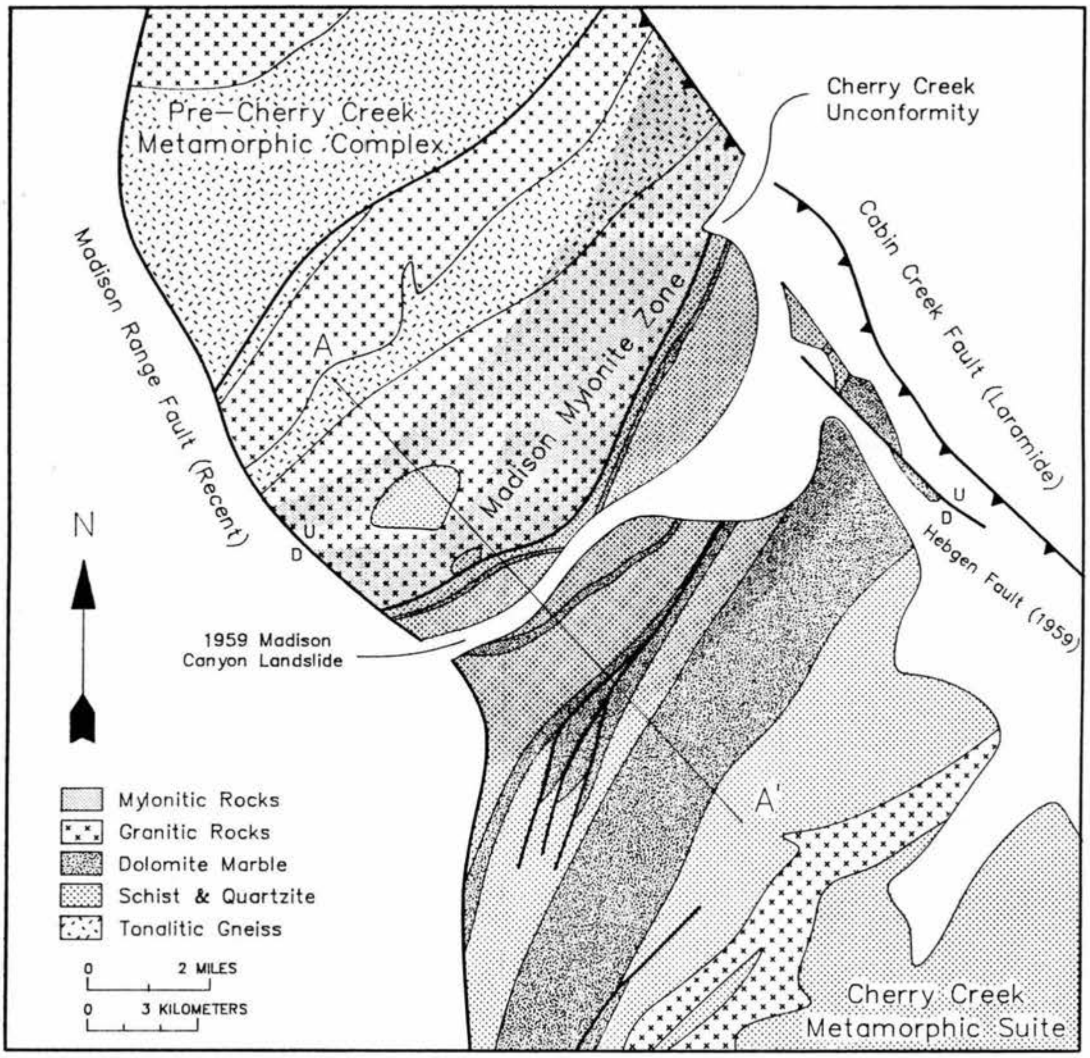


Figure 3. Simplified geologic map of the central portion of the southern Madison Range showing the distribution of the Pre-Cherry Creek and the Cherry Creek Metamorphic Suite. (After Erslev, in press).

Suite based on similarities found in the type section in the Gravelly Range (Peale, 1896). The metasedimentary sequence is along strike with the metasedimentary units int the Henrys Lake Mountains (Witkind, 1972). $^{40}Ar-^{39}Ar$ analysis of hornblende from an amphibolite in the suite yields a 2.7 Ga date for prograde metamorphism in the southern domain (Erslev and Sutter, in prep.). U-Pb analysis of zircons from a granodiorite sill that intrudes the Cherry Creek Metamorphic Suite yields a minimum age of 2.58 Ga for the Cherry Creek Metamorphic Suite (Shuster et al., 1987).

Henrys Lake Mountains

The study area is located within the Henrys Lake Mountains of the southern Madison Range (Figure 1). The Cherry Creek Metamorphic Suite forms the core of the mountains and is unconformably overlain by a sequence of dominantly carbonate Paleozoic rocks and a sequence of clastic sedimentary Mesozoic rocks (Witkind, 1972). Quaternary volcanics related to the Yellowstone caldera and Quaternary glacial deposits are also found in minor amounts in portions of the study area.

Freeman, Sweet and Tillman (1950) described the general geology of the Henrys Lake Mountains with special emphasis placed on descriptive Phanerozoic stratigraphy. The Precambrian lithologies described by these workers consist of garnet-staurolite-kyanite schist, green quartz-sericite schist, brown weathering marble, hornblende schist and granite gneiss. Based on the presence of marble and green quartzite they suggested a possible correlation with the "Cherry Creek Formation" in the type locality in the Gravelly Range (Peale, 1896).

Witkind (1972) mapped the Henrys Lake Mountain Quadrangle and subdivided the Precambrian rocks into Pre-Belt metamorphic rocks consisting of "paragneisses" of mica-schist, quartzite, dolomite, and crystalline "ortho-gneisses" consisting of meta-granodiorite and amphibolite. Pre-Beltian intrusive (nonfoliated) rocks were subdivided into diabase and gabbro.

Erslev (1981) mapped the Cherry Creek Metamorphic Suite in a domain south of the Madison mylonite zone in the Hebgen Dam quadrangle on strike with the Henrys Lake Mountains. Erslev (1983) documented recumbent folding associated with prograde metamorphism and minor structural repetitions of the Cherry Creek rocks along ductile faults. The association of prograde mineral assemblages (middle-amphibolite facies) with these fault zones and their later rotation along the Madison mylonite zone suggested an older age of deformation. The Archean deformation event has been confirmed by ^{40}Ar-^{39}Ar studies of amphibolite from the suite (Erslev and Sutter, in prep.).

Previous studies in the study area have concentrated on the following: 1) regional quadrangle scale mapping and general subdivision of Precambrian lithologies (Witkind, 1972) 2) documentation of petrology, structures and temperature/pressure relationships of metamorphic assemblages based on geothermometry and geobarometry (Erslev, 1981; 1983). However, the detailed stratigraphy, petrofabric analysis of the ductile faults, and the large scale structural geometry remained largely undefined prior to this study.

The focus of this study is on the regional stratigraphy, petrofabric and strain analysis, and cross-sectional data in order to characterize large scale structural geometry of the Cherry Creek Metamorphic Suite in the southern Madison Range. Geochemical analysis of the pelitic-schist unit and amphibolite unit provide additional information for probable protoliths of the Cherry Creek Metamorphic Suite units and interpretations of tectonic environment.

CHAPTER 3

CHERRY CREEK STRATIGRAPHY AND LITHOLOGIES

Nomenclature and Previous Work

Many workers have adhered to the Cherry Creek and pre-Cherry Creek nomenclature (Peale, 1896; Tansley et al., 1933; Reid, 1957, Heinrich, 1960; Okuma, 1971; Garihan, 1973; Erslev, 1980); however, these formal stratigraphic names in regional correlation are still widely debated (Desmarais, 1978; James and Hedge, 1980; Wilson, 1981; Mogk, 1984; Clark, 1987). The debate concerning lithologic correlations between ranges revolves around the relative ages of the metamorphic suites and variations in lithology. Relative age determinations based on the principal of stratigraphic superposition are limited because criteria such as stratigraphic tops and erosional unconformities are often lacking. However, ongoing geochronologic investigations (Shuster et al, 1987; Erslev and Sutter, in prep) are verifying Pre-Cherry Creek and Cherry Creek age relationships and will be discussed in the following section.

Peale (1896) defined the type section for the Cherry Creek Metamorphic Suite in the Cherry Creek area of the Gravelly Range. He suggested the "Cherry Creek" marbles, mica schists, and quartzites were younger (Proterozoic) than the "Pre-Cherry Creek" gneisses (Archean) based on stratigraphic superposition without tops evidence.

The name "Cherry Creek" was extended regionally based on the predominance of metasedimentary lithologies, particularly on the presence of dolomitic marble. This criteria led to stratigraphic correlation in the Tobacco Root Range (Winchell, 1914) the Ruby Range (Perry, 1948) and the Henrys Lake Mountains (Freeman and others; 1950).

A controversy concerning the relative age of the "Cherry Creek" rocks and the "Pony" gneisses began when Runner and Thomas (1928) suggested that evidence for the relative age of the gneiss and metasediments was lacking. They suggested that selective metamorphism of the Cherry Creek rocks may account for differences in metamorphic grade and that the rocks are the same age.

Erslev (1983) proposed a resolution to the "Cherry Creek" controversy based on metamorphic, structural and stratigraphic relationships in the southern Madison Range. Erslev (1983) documented a basal conglomerate containing clasts of Pre-Cherry Creek lithologies at the contact between the two domains. This suggested that the Cherry Creek metasediments unconformably overlie the Pre-Cherry Creek gneisses. He also documented a relict granulite metamorphism and an early deformation event in the gneiss domain that are lacking the metasedimentary domain. Erslev (1983) also used the greater variability of fold axes and axial planes in the northern domain to support an older age for the Pre-Cherry Creek Metamorphic Complex. This age has been confirmed by Rb-Sr and U-Pb zircon studies of the Middle Archean gneisses of the complex (Shuster and others, 1987). Erslev (1981) suggested that the Cherry Creek metasediments should be called the Cherry Creek Metamorphic Suite based on the North American Commission on Stratigraphic Nomenclature of igneous and high-grade metamorphic rocks (Henderson and others, 1980). Based on similarities in the stratigraphic succession in the type locality and relative age determinations this study continues the use of the Cherry Creek Metamorphic Suite nomenclature.

Cherry Creek Stratigraphy

Reconstruction of the local Cherry Creek stratigraphic sequence imposes important constraints on the large scale structural geometry of the study area. Detailed field traverses along ridge crests trending perpendicular to regional foliation reveal a coherent stratigraphic succession. The stratigraphic column of the Cherry Creek Metamorphic Suite in Figure 4 was constructed by measuring unit thicknesses (dip corrected) in an area mapped by Erslev (1983) which is on strike with the study area. In this area, major unit contacts are laterally continuous, undisrupted by folding, and lack obvious unit repetition. Structural complication of this section is limited to individual unit thickening due to thrust flats (Erslev, pers. com.). The lithologic sequence in this area

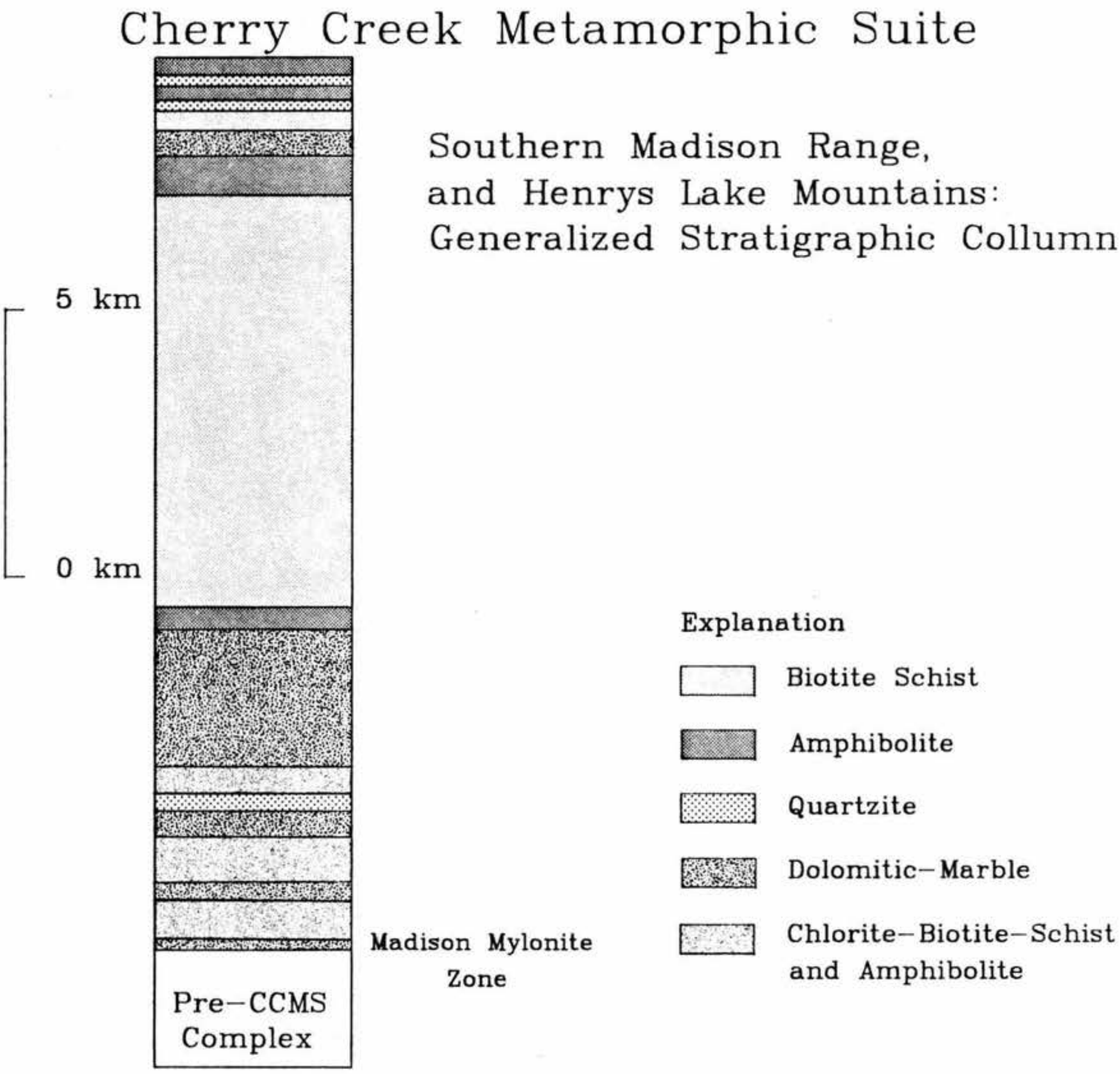


Figure 4. Generalized stratigraphic column of the Cherry Creek Metamorphic Suite for the Henrys Lake Mountains.

provides the best approximation of primary stratigraphy. Relict graded bedding, minor cross-beds, and scour casts in the biotite schist (meta-turbidite) provided 153 stratigraphic-up directions (Figure 5). Local graded beds in pebbly quartzites (3) and graded-volcanic lapilli (5) provided additional tops information.

Out of 161 measurements of sedimentary structures, 65% indicate stratigraphic up is to the southeast. The area around Sheep and Coffin Lakes gives evenly contradictory tops, with 50 to the southeast and 44 to the northwest. This area of contradictory tops corresponds to a zone of intense shear-folding and thickening within the biotite schist unit. If these readings are omitted, 82% of the measurements give tops to the southeast, which is consistent with the stratigraphic interpretation of Erslev (1983).

Lithologic Descriptions

Quartz-Biotite-Plagioclase Schist

Pelitic and semi-pelitic schist form the primary lithologies in the southeastern portion of the study area (Figure 5) and are well exposed along glaciated portions of the continental divide. Over 600' of nearly vertical exposure in the upper portion of the Little Mile and Mile Creek drainages reveals that hornblende-schist is interbedded with semi-pelitic schist along the northwestern contact with the amphibolite unit. The sequence grades into progressively more pelitic schist to the southeast.

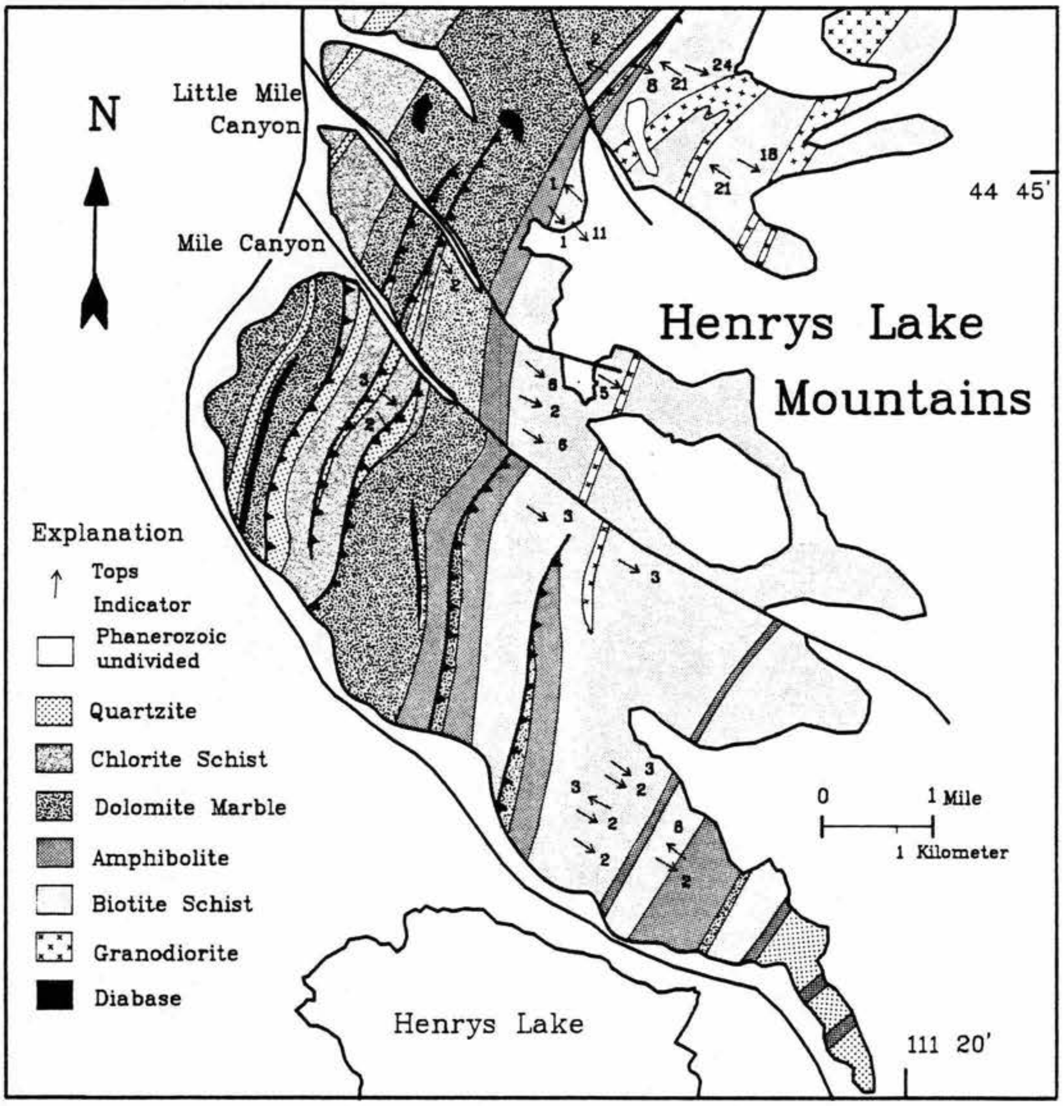


Figure 5. Geologic map of the Henrys Lake Mountains modified from Witkind (1972) and Erslev (1983).

Garnet + biotite assemblages flank the northwestern contact with the amphibolite unit while toward the southeast first staurolite and then kyanite are found as new mineral facies in the biotite-schist (Plate 1). This may reflect an increase in compositional maturity up section (eg, from mafic to semi-pelitic to pelitic).

Relict bedding in the biotite-plagioclase-quartz schist is well defined by abrupt changes in grain size and texture. Graded-bedding is the dominant primary sedimentary structure with massive bedding in basal quartzo-feldspathic layers (5cm-15cm) fining upward into crenulated micaceous and porphroblastic zones (e.g., reverse metamorphic grading; Figure 6). Texturally, the schists exhibit multiple sets of coarser sandstone layers with sharp basal contacts that fine upward into silt and mudstone laminae. The beds resemble partial Bouma sequences with AE divisions most apparent (Bouma, 1962; Walker, 1979). Other observations of relict sedimentary structures include two small scale cross-beds (1-3 cm) and three basal scour features (10cm by 5 cm) with rip-up clasts observed in one locality. Individual beds range from .5cm to 30cm with well defined regional foliation parallel to bedding and compositional layering.

In thin-section, the schist is dominated by monocrystalline and polycrystalline quartz showing moderately undulose extinction. Grain boundaries of the quartz

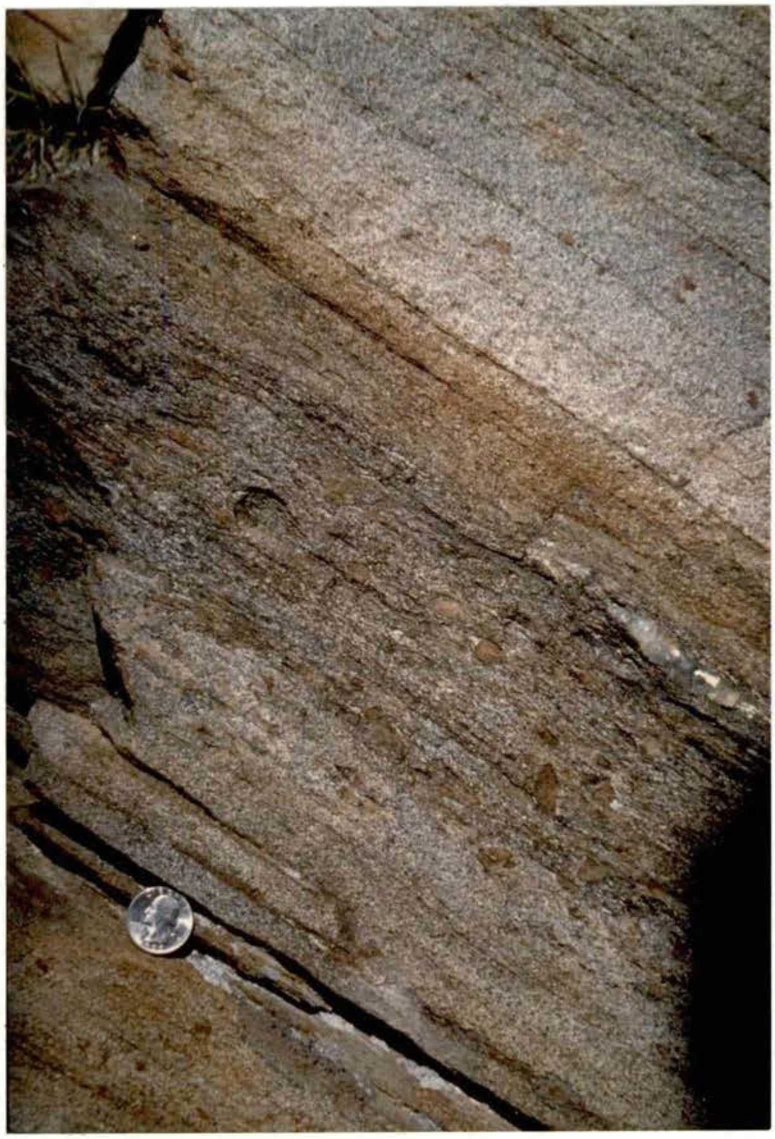


Figure 6. Relict graded bedding in biotite-schist.

are best observed in plain light where they are accentuated by impurities and rimmed with biotite. Grain size is variable (.03mm-2mm) with larger grains flattened and well aligned and smaller grains subrounded to subangular. Plagioclase (An_{5-25}: Michelle Levy technique) makes up one-third of the overall schist composition and exhibits albite, carlsbad and complex twin types. The plagioclase is mostly unaltered, with fine sericite rims except in thin sections that have been highly chloritized. Polycrystalline fragments containing quartz and plagioclase are rare and may represent recrystallized primary lithic fragments.

The typical mineral assemblage in the schist consists of quartz, plagioclase, biotite, with lesser amounts of almandine garnet + muscovite + staurolite + kyanite + sillimanite + chlorite. Biotite content is variable, from 12%-25% in psammatic portions up to 50% or more in the pelitic zones. Biotite in some samples is intergrown or completely replaced by chlorite, and contains numerous zircon inclusions with pleochroic halos. Poikilitic to euhedral staurolite is common, with inclusions of quartz, sericite, biotite and garnet. Kyanite, when present, is partially altered to sericite. In proximal zones adjacent to meta-granodioritic sills, the kyanite is rimmed with sillimanite.

Dolomite Marble

Dolomite marble forms one of the thickest and most laterally continuous units in the field area and is locally over 2.5 kilometers thick. Two major bands of dolomite marble traverse the area with two thinner lenses to the southeast (Figure 5). Contacts with the amphibolite and hornblende schist are sharp and generally conformable; however, mylonitic textures and shearing was noted between the overlying schist in the vicinity of Sheep Lake. Contacts with the lower chlorite schist unit are generally sheared and are marked by mylonitic textures and an increase in chlorite and quartz in the hornblende schist.

The marble varies from massive to finely laminated in outcrop and weathers to a light-brown, "elephant-skin" crenulated texture. Fresh surfaces have a pearly luster and vary from grey to white, with golden flecks of phlogopite apparent on some broken surfaces. Laminated and banded sequences consist of alternating layers of carbonate and resistant quartz. Foliation, due to alignment of flattened dolomite grains, phlogopite and chlorite parallels quartz banding and most likely reflects primary layering or bedding. The quartz interlayers vary in thickness from millimeters to several meters and are typically crenulated and often boudinaged forming lenses and nodules. One locality in the vicinity of Reynolds Pass contained "cabbage head" structures that resemble oncolitic-stromatolites (Figure 7).

Figure 7. Probable oncalitic stromatolites in dolomite -marble.

In thin-section, the marble is dominated by anhedral to euhedral bands of flattened, highly twinned dolomite interspersed with equant quartz grains. Close to the chlorite-schist contact the marble displays ribbon texture with alternating layers (mm scale) of flattened dolomite grains, interstitial sericite and chlorite, and anhedral quartz. Minor and accessory minerals include tremolite, phlogopite, minor epidote and hematite.

Mesoscopic to microscopic tight, to isoclinal folds were observed near contacts with the hornblende-schist and throughout narrow zones (10-20m) within the major marble unit. In thin-section, tight similar folds are defined by thin laminae of alternating dolomite, quartz, sericite and phlogopite.

In the area of the abandoned "Montbestos Mine" in Little Mile drainage, a large diabase dike cross-cuts regional foliation in the marble. The contact zone is associated with an alteration zone consisting of pods, lenses and seams of lime-green serpentine intergrown with chrysotile asbestos. Acicular sprays of tremolite and talc are found overprinting foliation in thin section in this area. Talc was also observed in the hinge zone of a megascopic fold along the northwest face of Little Mile Canyon.

Quartzite

Two types of quartzite are found in the field area. The first is a massive, white to green resistant cliff former with occasional color banding and minor micaceous interlayers defining a weakly developed foliation. The massive quartzite lacks relict primary textures and resembles the massive quartz layers in the marble unit. The second type of quartzite is schistose and banded, with the foliation defined by green muscovite and lesser amounts of biotite and chlorite and locally contains relict graded bedding.

The resistant, massive quartzite is intercalated with the major dolomite units and forms sharp, conformable contacts. In thin section the quartzite is composed of polycrystalline undulose quartz grains with mortar texture. Muscovite forms interstitially and surrounds stringers and lenses of quartz.

The muscovite-quartz schist is highly banded with intercalated zones of lensoidal quartzite surrounded by muscovite, biotite, and minor chlorite. Garnetiferous zones in this quartzite altering to hematite yield rusty-orange horizons. Minor mineral phases include plagioclase and kyanite. Accessory minerals in thin section include rutile, clinozoisite, zircon, and minor iron-oxides.

In the northwest portion of the study several layers of quartzite repeat and pinch out along strike parallel to a given structural horizon. This quartzite is intercalated with amphibolite and chlorite schist and forms map-scale attenuated lenses. Mylonitized zones of quartzite locally contain kyanite. In thin-section, sheared kyanite and mylonitized quartz stringers reveal a great deal of attenuation in these zones (Figure 8). A well exposed protomylonitic contact with the northwestern marble unit in the Little Mile Creek drainage contains stretched quartzite lenses and pods, resembling a coarse conglomerate, in a carbonate micaceous matrix.

Relict graded-bedding in a "pebbly"-quartzite on the southwestern ridge of Mile Drainage in the vicinity of peak 9324 reveals that stratigraphic up is to the southeast. In thin-section, this "pebbly" zone contains millimeter to centimeter lenses of polycrystalline quartz rimmed with biotite. The quartz blebs are surrounded by a matrix consisting of fine-grained, anhedral quartz, muscovite, biotite and chlorite, with accessory magnetite.

Chlorite Schist Unit

This unit is the lithologically most diverse unit in the study area, exhibiting compositional variation on a millimeter to meter scale. The dominant lithologies are hornblende-quartz-chlorite schist and amphibolite and is locally interbanded with iron-rich chlorite-biotite schist and chloritic phyllite. Outcrops of this unit are finely crystalline, black to dull olive green and vary from massive to compositionally banded on a millimeter to

Figure 8. Sheared kyanite from protomylonite zone, plane polarized light, 4.4 mm across the horizontal dimension.

centimeter scale. While these rocks are mineralogically diverse, they exhibit consistent field characteristics and were grouped into one field mapping unit referred to as chlorite-schist unit. This unit correlates with the amphibolite unit of Witkind (1972).

This diverse lithologic package in thin section consists of interlayered hornblende-quartz-chlorite schist, amphibolite, chloritic phyllite with quartz augen, garnet-amphibole schist, and chlorite-biotite-garnet schist. Diabase sills with foliated fine-grained chill margins are common within this sequence and along unit contacts. A large diabase in the lower portion of the drainage north of little mile is internally foliated within the chlorite schist sequence.

The hornblende-quartz-chlorite schist is finely crystalline (grain size varies from microns to .05mm) and consists of 25-40% quartz, 5-20% plagioclase (An_{5-25}), 20-35% hornblende, 5-15% chlorite, 5-15% biotite, 2-5% epidote, 2-8% calcite with accessory magnetite. Calcite occurs as minute .05-1mm bands parallel to compositional layering and in small scale tight folds (2cm-12cm).

Toward the contact with the dolomite marble to the southeast the rocks are a dark green to black and phyllitic. In thin section these rocks show a highly diminished grain size (from microns to .05mm) revealing an overall mylonitic texture with selvages of ultramylonite.

Compositionally, these rocks resemble the hornblende schist with an increase in chlorite (15-20%) and quartz (45%).

Amphibolite

Amphibolite and hornblende gneiss and schist form sharp conformable contacts with the thick marble unit. The contact with the lower marble unit to the northwest forms a distinctively consistent marker, traceable along strike throughout the study area. The amphibolite grades into hornblende-quartz schist and biotite-schist to the southeast. The upper amphibolite-biotite schist contact also forms an excellent continuous marker horizon along strike.

Massive layers of amphibolite are intercalated with compositionally banded amphibolites. Within the layered amphibolites feldspar and quartz augen are locally graded, suggesting graded lappilli zones or possibly primary sorting of igneous phenocrysts (Figure 9). Relict zoning is locally present with recrystallized plagioclase phenocrysts with epidote cores and quartz+plagioclase rims. Large hornblende augen are generally euhedral, exhibiting diamond shaped basal sections. Plagioclase compositions determined by the Michelle Levy method range from An_5-An_{30}. Some amphibolites display actinolite splays forming core replacement textures on the larger amphibole augen.

Figure 9. Graded lapilli zones in amphibolite.

Minor and accessory minerals include epidote, calcite, chlorite, and magnetite.

Meta-granodiorite

A continuous, foliated granodiorite sill (30m wide) within the biotite-schist unit extends from the Coffin Lakes area through Targhee Peak and tapers out in the vicinity of the Wild Rose Ranch. Along the margin of the main sill, several smaller (3cm-20cm) satellitic sills show sharp contacts and chill margins with the surrounding biotite schist. Xenoliths of the biotite schist are found flattened and parallel to foliation in the granodiorite near the contacts (Figure 10). U-Pb zircon analysis of the meta-granodiorite yields a 2.585 + 6.6 Ga age (Shuster et al., 1987).

The granodiorite is porphyritic containing relict plagioclase phenocrysts set in a fine grained groundmass consisting of quartz, plagioclase, microperthite, hornblende, biotite and chlorite with accessory sphene, zircon, epidote and magnetite. Relict igneous textures in the granodiorite are common, with oscillatory zoning apparent in some plagioclase. Hornblende is mostly poikilitic containing blebs of quartz with some euhedral hornblende present in minor amounts. The sills are foliated and mylonitic textures are absent.

Euhedral garnets were observed in the vicinity of Targhee Peak where the sill becomes thinner. Muscovite occurs with the garnets here and hornblende drops out,

Figure 10. Xenolith of biotite schist in meta-
granodiorite.

giving the rock a white appearance. Toward the southwest, the sills thin to the centimeter scale are intercalated with the biotite schist unit.

Diabase Sills and Dikes

Diabase sills and dikes strike northwest to northeast parallel to regional foliation with few cross-cutting relationships observed. In the vicinity of the Monbestos Mine, a large diabase dike cuts across the major marble unit and exhibits a 10 cm wide chill margin. An approximately 100m wide zone of alteration in the adjacent marble contains abundant asbestos that was mined during the 1920's (Freeman and others, 1950).

Sub-ophitic texture is apparent in the diabase in hand-sample, with laths of plagioclase partially enclosed in a matrix of augite. One sill found in the canyon north of Little Mile canyon is foliated and chloritized. Diabase sills are commonly found parallel to mylonitic contacts, particularly in the chlorite schist unit.

CHAPTER 4

STRUCTURAL FABRIC AND MAP SCALE GEOMETRY

Introduction

The pre-Beltian rocks in the Southern Madison Range are part of a complex, polydeformed metamorphic terrain that has undergone a long history of deformation characterized by variations in structural style, metamorphic grade, and overprinting relationships. In the northwestern Wyoming Province, a clear understanding of the tectonic processes that preserved the Cherry Creek Metamorphic Suite requires the characterization and subtraction of Phanerzoic and Proterozoic deformations from the overall rock fabric.

Phanerozoic Deformation

Phanerozoic deformation of the crystalline basement is limited to block faulting with minimal penetrative deformation during Laramide thrusting and Recent basin and range extension (Witkind, 1964; Schmidt and Garihan, 1983; Erslev, 1983). The Hebgen Lake earthquake of 1959 reactivated the Hebgen and Madison Range faults dropping the adjacent basins, reflecting the presently active extensional tectonic regime (Witkind, 1964).

Recent fault scarps flank the western edge of the Madison Range with scarps locally 10 to 30 feet high.

Two major splays off the Madison Range fault were mapped (Figure 5; Plate 1) in this study. The faults dissect the core of the range along Little Mile and Mile canyons and offset northeasterly striking Precambrian lithologies. A normal fault in the northern part of the study area west of Coffin Mountain offset a section of Paleozoic rocks at the Idaho border (Erslev, 1983). Despite the abundant normal faulting in the range, the majority of the Paleozoic strata capping the Henrys Lake Mountains dips uniformly to the southeast and suggests minor internal deformation.

Proterozoic Deformation

Epidote-amphibolite facies assemblages and ductile shearing concentrated along the Madison Mylonite zone characterize the early Proterozoic (1.9 Ga; Erslev and Sutter, in prep.) deformation. Figure 11, a cross-section across the shear zone (Erslev, in prep.), exhibits a reversal in regional foliation dip (toward the northwest) in a 4 km wide zone adjacent to the Madison Mylonite zone. Thrusting of the Pre-Cherry Creek Metamorphic Complex to the north over the Cherry Creek Metamorphic Complex resulted in a broad, recumbent fold with a subhorizontal fold axis trending N40E.

The Cherry Creek Metamorphic Suite south of the shear zone is relatively unaffected by Proterozoic shearing, as seen by the lack of reset ^{40}Ar-^{39}Ar ages (Erslev and Sutter, in prep.). Additionally, foliations dip opposite

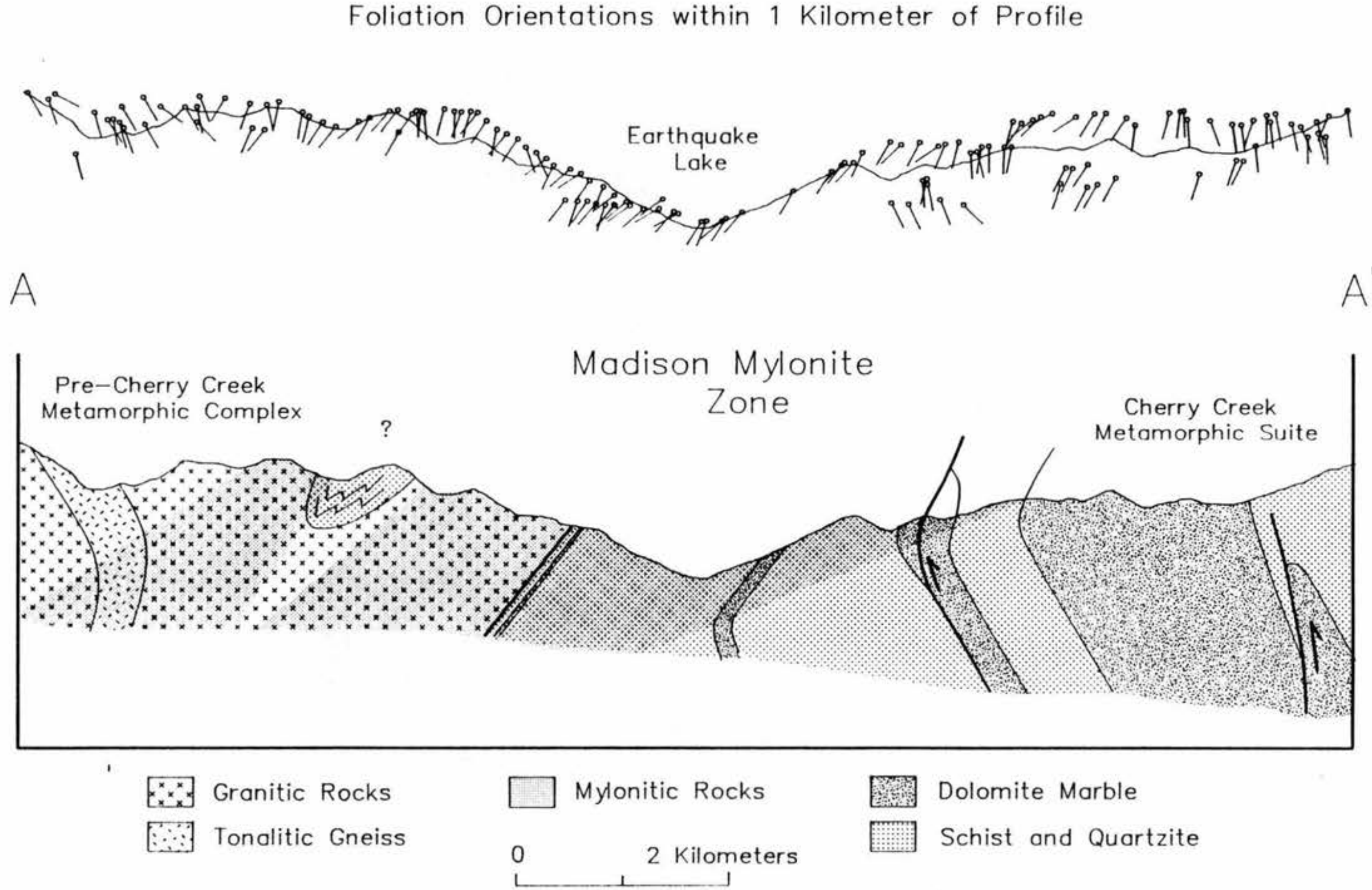


Figure 11. Cross-section through the Madison Mylonite Zone. Note the large drag flexures of the Cherry Creek Metamorphic Suite adjacent to the MMZ. Cross-section line shown in Figure 3. (From Erslev, in press).

that of the Madison mylonite zone and generally lack epidote-amphibolite facies assemblages.

Field Methods

The Cherry Creek lithologies were mapped on United States Geological Survey 7 $^{1}/_{2}$ minute quadrangle proofs on a scale of 1:24,000 during the summer of 1985 and part of the fall of 1986 (Plate 1). Regional characteristics of lithologic sequences and contacts were examined over a 30 square mile area. Unit contacts and truncations were traced parallel to lithologic strike to determine whether these zones represent facies changes, fold hinges, or fault zones. Structural data from these traverses were combined with information on published maps by Witkind (1972) and Erslev (1983).

Orientation and variation of megascopic structures and fabrics were recorded in the field. Orientation data include measurements of regional foliation, fold axes and axial planes, lineations, schistosity surfaces, mylonitic unit contacts, and brittle fault zones. Collection of 120 oriented hand-samples permitted additional information for evaluation of small scale petrofabrics and strain analysis.

Megascopic fabric analysis included shear sense measurements of C-S surfaces and porphroblast asymmetries using the criteria of Simpson and Schmidt (1983). Axial ratios of elongated quartz clasts and cobbles in a proto-mylonitic zones were measured in outcrop where possible. Eighty-two thin sections were made from oriented hand-samples for additional petrofabric and strain analyses.

Observations: Map Scale Geometry

The geologic map (Plate 1; Figure 5) pattern reveals a series of stratigraphic repetitions and truncation of lithologic units along strike. Similar relationships were noted in the Cherry Creek stratigraphic succession in the Gravelly Range (Heinrich and Rabbitt, 1960) and in the central southern Madison Range (Erslev, 1983). Heinrich and Rabbitt (1960) reported marked variation in thickness and petrology along strike in the Gravelly Range and interpreted these differences as facies changes. Erslev (1983) mapped a thrust repetition of the Cherry Creek sequence in the vicinity of Sheep Mountain and noted that the thrust did not cut the overlying Phanerozoic sediments suggesting, a Precambrian deformation event. This study examines the nature of these stratigraphic repetitions and truncations.

In the Henrys Lake Mountains, a good example of unit repetition and truncation along strike is the repeated dolomite-amphibolite-biotite schist sequence along the southwestern flank of the range (Figure 5). In general, the total thickness of the stratigraphic sequence increases to the southwest. For example, from the northeast to the southwest in Figure 5, the thickest dolomite unit is split by a chlorite-schist and quartzite sequence. Duplication of the marble unit and three repetitions of the chlorite-schist and quartzite assemblage occurs southwest along strike in this complex zone.

The apparent individual unit thicknesses actually increases to the northeast, where the major marble unit increases from .8 to 2.0 km in thickness. Similarly, the major biotite schist section increases from 3.2 to 5.5km in thickness, suggesting thickening within individual units in addition to overall thickening of the stratigraphic sequence along lithologic strike.

Fabric Data

Regional Foliation

Metamorphic assemblages (e.g., quartz + biotite + garnet + staurolite + kyanite in pelitic schists) are consistent with moderate grade, amphibolite facies metamorphism ($600^{o}C$, > 6 kb) based on garnet-biotite geothermometry and aluminosilicate stability in rocks to the north (Erslev, 1983). Regional foliation generally strikes northeasterly with moderate to steep dips to the southeast (Figure 12A). Foliation generally parallels compositional layering and graded-bedding except along fold hinges where it is perpendicular. Locally, evidence for bedding transposition parallel to regional foliation exists in discrete shear zones where intrafolial isoclinal folds developed.

In a fabric plot of regional foliation (Figure 12A) the broad maxima of poles to schistosity reflect a gently folded macroscopic, arcuate map pattern with a northeast-

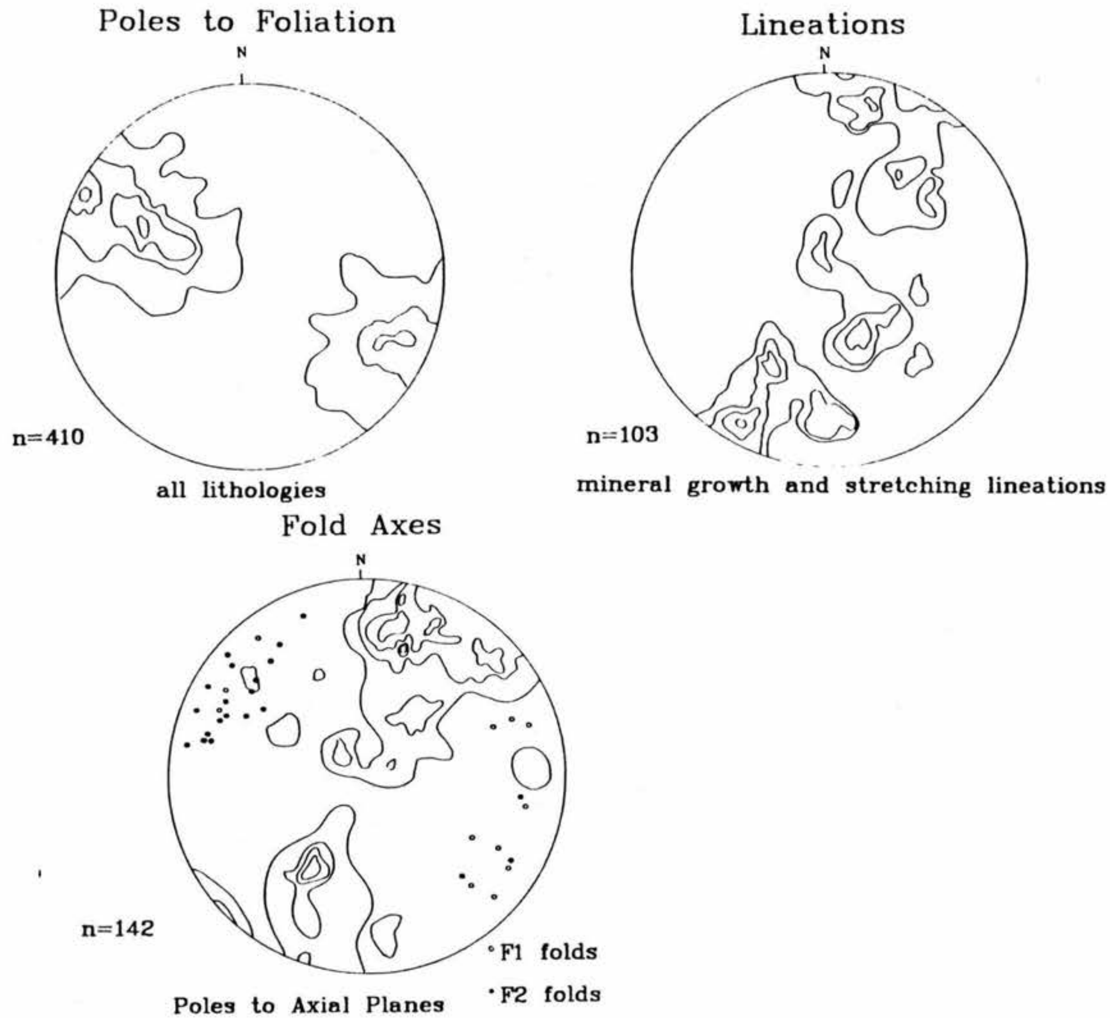


Figure 12. Fabric Data. Contours represent 1,3,5 and 7% per 1% for poles to foliation (a) lineations (b) and fold axes (c).

trending fold axis. The predominantly southeasterly dips suggest little effect on regional foliation during Madison Mylonite deformation. However, in the northwest portion of the study area, rotation of regional foliations toward the northwest occurs as a result of Proterozoic ductile shearing in the Madison Mylonite zone (Figure 11).

Folds and Lineations

There is a wide variety in the scale and the style of folding throughout the field area. A major problem in using style to determine fold generations (Turner and Weiss, 1963) is that during one orogenic event overlapping fold styles may develop diachronously. Competency contrasts between lithologies may also result in variation in fold styles. Additionally, later deformations may produce the same fold style which may be confused with earlier folding. In some orogens, an F_2 fold may actually be older than a F_1 fold elsewhere in the sequence because the precise timing of deformation may vary across an orogenic belt (Hobbs et al., 1976).

Consequently, groupings of fold generations must be used with caution in interpreting a deformation chronology. Overprinting is the only reliable criteria for identifying fold phases and establishing their sequence of development (Hobbs et al., 1976). In the study area, based on overprinting criteria, two fold phases are recognized.

F_1 Folds

The oldest recognized folds in the study area are isoclinal-to-tight, similar folds on the scale of millimeters to tens of meters. The folds occur in all lithologies and are locally intrafolial and rootless and display axial planar schistosity (Figure 13 A). These folds are typified by hinge thickening and limb attenuation suggesting passive flow and flexural flow as folding mechanisms (Figure A & B). Prograde amphibolite facies assemblages define axial planar schistosity suggesting that prograde metamorphism is synkinematic with deformation. In fold hinges, schistosity is superposed on and perpendicular to compositional layering.

Boudinage is locally developed in lithologies with sharp competency contrasts and along attenuated limbs of folds (13C). Lensoidal quartzite boudins are common in the marble unit and reflect layer parallel extension with respect to foliation. Quartzite stringers in the biotite-schist unit are also attenuated and boudinaged along their limbs (Figure 13 D).

F_1 Fold Axes and Lineations

Prograde sub-horizontal fold axes trend dominantly to the northeast (Figure 12C). In thin section, mineral growth lineations defined by biotite, muscovite, hornblende and staurolite are parallel to small scale fold axes (Figure 12B). The fact that mineral growth lineations

Figure 13. F_1 tight similar-to-isoclinal folds in dolomite marble (a) and biotite schist (b). c. Limb attenuation and boudinage in biotite schist. d. Quartzite boudins in dolomite marble.

A

B

C

D

parallel fold axes in these zones suggests prograde mineral growth concurrent with deformation.

Prograde mineral stretching lineations (X) include elongated and attenuated quartz, biotite, and locally kyanite. The stretching lineations are subparallel to the regional foliation dip with an average trend and plunge of S50E, 65^{o} (Figure 12D).

<u>F_2 Folds and S_2 Axial Planar Cleavage</u>

F_2 folds are found in the chlorite schist unit and amphibolite on the northwestern flank of the study area. F_1 folds are refolded by similar to open concentric F_2 folds whose axial planes are subparallel to secondary zones of mineral growth and compositional banding (Figure 14). S_2 axial planar cleavage dips moderately to the northwest with an average dip of 55 degrees. Scattered F2 fold axes trend dominantly southwest, with subhorizontal to moderate plunges and are coaxial with F1 fold axes.

Lineations from the Madison mylonite zone (Erslev, 1983) exhibit a maximum trend of 221^{o}, and a 7^{o} plunge subparallel F2 fold axes in the study area. The coaxial nature of these folds with F_2 folds in the study area and the fact that S_2 axial planar cleavage parallels the axial plane of the Madison Mylonite zone suggest that they are correlative.

The mineralogy associated with S_2 reflects a lower grade assemblage characterized by chlorite, actinolite and epidote and is also suggestive of Madison Mylonite Zone

Figure 14. F_2 fabric in chlorite schist unit. a. Refolded fold in amphibolite. b. sheared fold limb and S_2 cleavage. c. S_2 cleavage zones


A
B
DNAG
C

assemblages. C-S surfaces typify these rocks in thin section, with discrete zones of chloritized and sheared garnets and biotite. Mineral streaking lineations plunge to the northwest in these zones and subparallel the stretching lineations in the Madison mylonite zone (5NW, 52NW; Erslev, 1983).

In summary, the critical observation from regional fabric data is that prograde amphibolite facies assemblages define F_1 folding, axial planar cleavage development (parallel to regional foliation) and parallel both mineral growth and stretching lineations. Consequently, the majority of the deformation occurred during the Archean based on ^{40}Ar-^{39}Ar dating of prograde assemblages (Erslev and Sutter, in prep.). Retrograde assemblages and warping of regional foliation toward the northwest increases in intensity toward the Madison Mylonite Zone. Regional fabric data from this section is incorporated into the cross-sections and regional deformation models in the following chapters.

CHAPTER 5

STRAIN ANALYSIS

Methods

Deformed quartz and plagioclase grains in psammitic portions of the biotite schist were measured for local estimates of finite-strain in prograde assemblages. The samples (Plate 2) are from clastic rich, basal layers exhibiting relict graded-bedding. Detailed strain measurements were made from 12 biotite schists, two quartzites, and one pebbly meta-siltstone.

Strain measurements were analyzed from oriented thin-sections of principal planes (ac and bc) for all samples and the ab plane for 3 of the 15 samples. Oriented thin sections were cut perpendicular and parallel to the lineation direction defining the ac and bc principal planes. The oriented sections were projected through a slide projector and tracings of the grain shapes were made using plane-polarized light.

The end-points of the major and minor axes of over 150 elliptical grains were digitized using an IBM PC and the coordinates were recorded in a data file. The data file was then input into INSTRAIN, an integrated strain analysis program developed by Erslev (1988), that generates Fry center to center plots (Fry, 1979), normalized Fry center to center plots (Erslev, in press), and R_f-0 plots with mean (harmonic and arithmetic) ellipticity values (Ramsay and Huber, 1983). An in depth explanation of the theory behind each of these strain techniques is beyond the scope of this work and the reader is referred to the above references for further explanation. The basic techniques and assumptions inherent in center-to-center analysis will be briefly explained in the following section.

The Fry and Normalized Fry techniques determine the strain ellipse by plotting distances between adjacent centers. The Fry method assumes an initial non-random, anticlustered grain center distribution. The Fry method works best for well packed, well sorted sandstones in which the grain centers are equal distances from each other. The normalized Fry method is preferable for poorly sorted packed aggregates and does not assume an initial anti-clustered distribution. The normalized Fry technique normalizes center to center distances and eliminates the error due to sorting and imperfect anticlustering. Center to center distances are normalized by dividing the center to center distance between two grains by the sum of their average radii. This technique greatly increases the resolution of the strain ellipse and is preferable for meta-greywackes with moderate to poor sorting.

During deformation, an originally uniform distribution of centers will rearrange their position. Distances between grain centers perpendicular to the applied stress will increase, while distances between grain centers parallel to the applied stress will decrease. The original spherical shape will be deformed into an ellipsoid that approximates the strain ellipsoid with three principal strain axes of X, Y, and Z (Ramsey, 1967, Fry, 1979).

Two-dimensional ellipses and mean axial ratios were determined from mutually perpendicular principal sections. Flinn (1962) plots (Figure 15) summarize three-dimensional strain states in two dimensions.

Results

An initial experiment was run with 20 observers to determine the minimum number of strain markers necessary to get a consistent value of R_S (Figure 16). Starting with 20 grains and increasing up to 440, the mean value levels off after about 100 points. For rapid analysis then, 100 to 150 data measurements were made to determine the strain value. This test was run with all four strain techniques with sample 11ac (Figure 17). This test assumed that 20 observers measuring the same data set will give a fairly accurate representation of the population average.

An additional plot determines the relative variability in measuring the strain ellipse between the Fry and normalized Fry methods (Figure 18). The error bars represent one standard deviation from the mean value averaged from 20 observers. This shows that R_S measurements are more consistent with the Normalized Fry

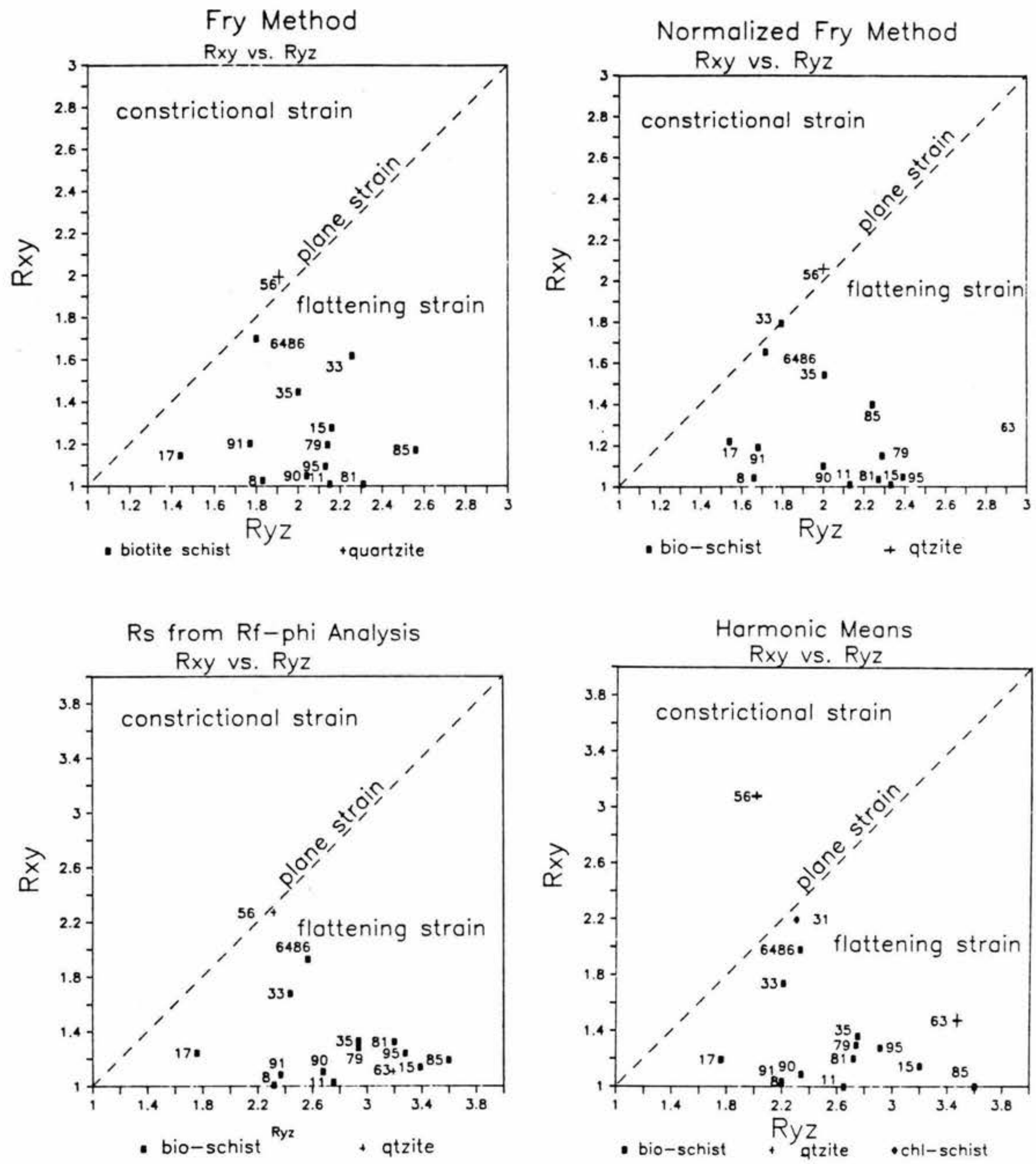


Figure 15. Flinn summary plots of X/Y versus Y/Z ratios of deformed quartz and feldspar grains in metasediments.

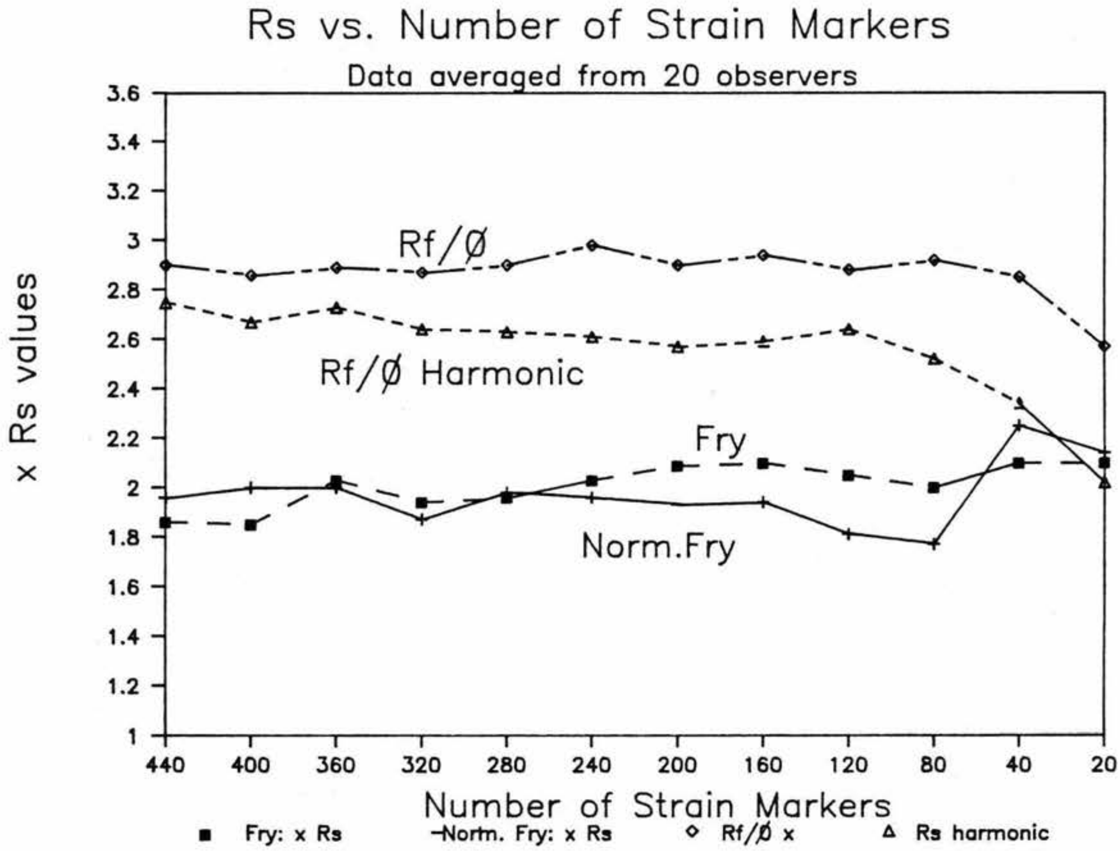
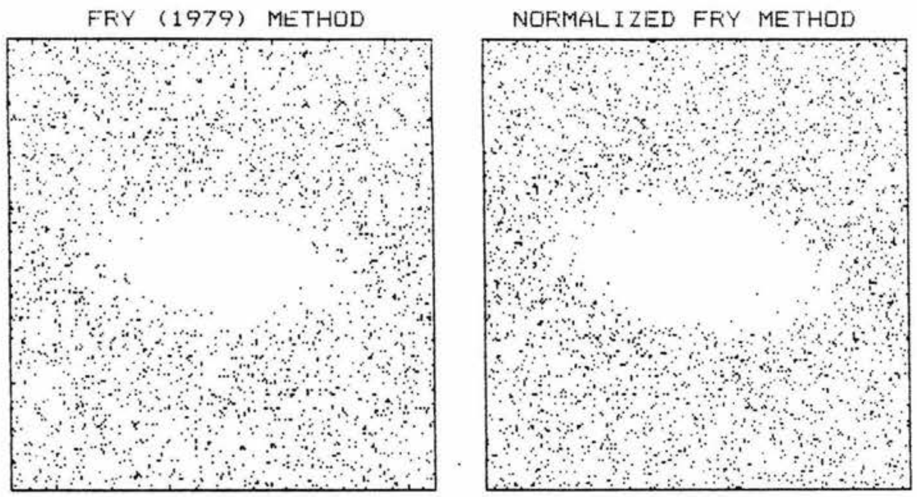


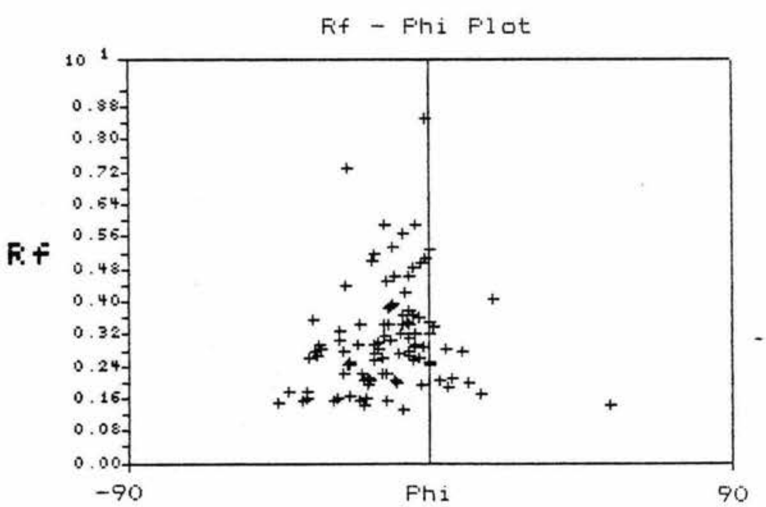
Figure 16. Summary of test run with 20 observers to determine the minimum number of strain measurements required for a fair estimate of R_S.

Figure 17. Computer generated plot of the Fry, Normalized Fry and the Rf-phi methods of strain analysis for sample 11 ac.

INTEGRATED STRAIN ANALYSIS

Project: Southern Madison Range
Sample #: 11ac
400 objects in file a:set5





Harmonic Mean = 2.67
Mean Phi = -11.6 Degrees

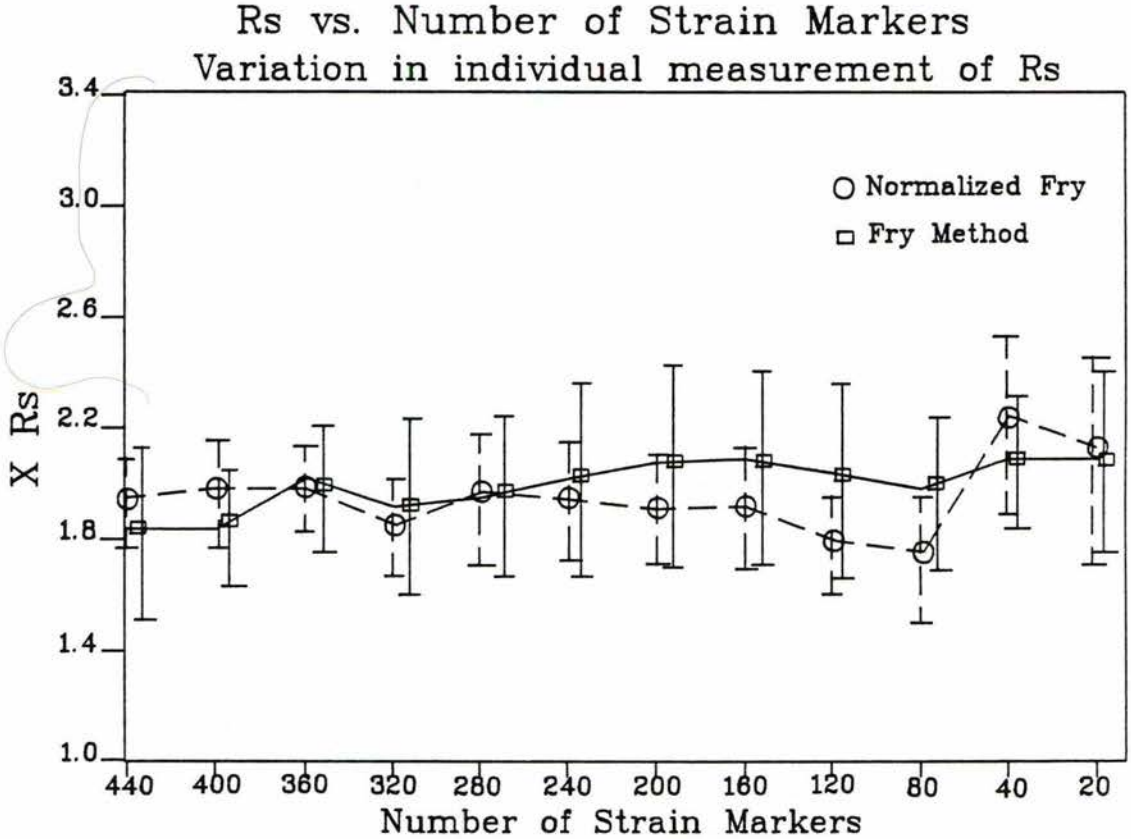


Figure 18. Comparison of R_S measurements utilizing the Fry and Normalized Fry strain methods. Error bars represent one standard deviation for measurements made from 20 observers.

method. This consistency is due to better resolution of the strain ellipse with the normalized Fry method.

Flinn (1962) plots in Figure 15 summarize the results of the strain measurements for 15 samples (30 thin sections). Shape and orientation data for deformed quartz grains in the sandy portions of the meta-greywackes give fairly consistent orientations, shapes and magnitudes across the study area, with local variation corresponding to zones of ductile shear. Fabrics and measured finite strain ellipsoids within the regionally foliated material show largely flattening strains produced by bulk shortening with a principal strain axes of (X/Z:Y/Z:X/Y) of 2.1:2.1:1 in a representative sample (Figure 19 A). The flattening strain probably relates to the development of bedding-parallel foliation due to bulk shortening. This is consistent with abundant examples of boudinage within the plane of foliation that indicate layer parallel extension.

Two of the samples collected from mylonite zones, a quartzite and a pebbly-siltstone, plot close to or directly on the plane strain line, indicating that shortening on a bulk scale may be partly accommodated through strongly non-coaxial deformation (simple shear). Strain analysis using deformed quartz clasts from one of these zones (Figure 19 B) shows principal strain ratios (X/Z:Y/Z:X/Y) of 3.76:-1.95:1.92. The X direction in this sample, defined by a mineral stretch lineation oriented S30E, 70SE, exhibits asymmetric dynamically recrystallized quartz tails showing

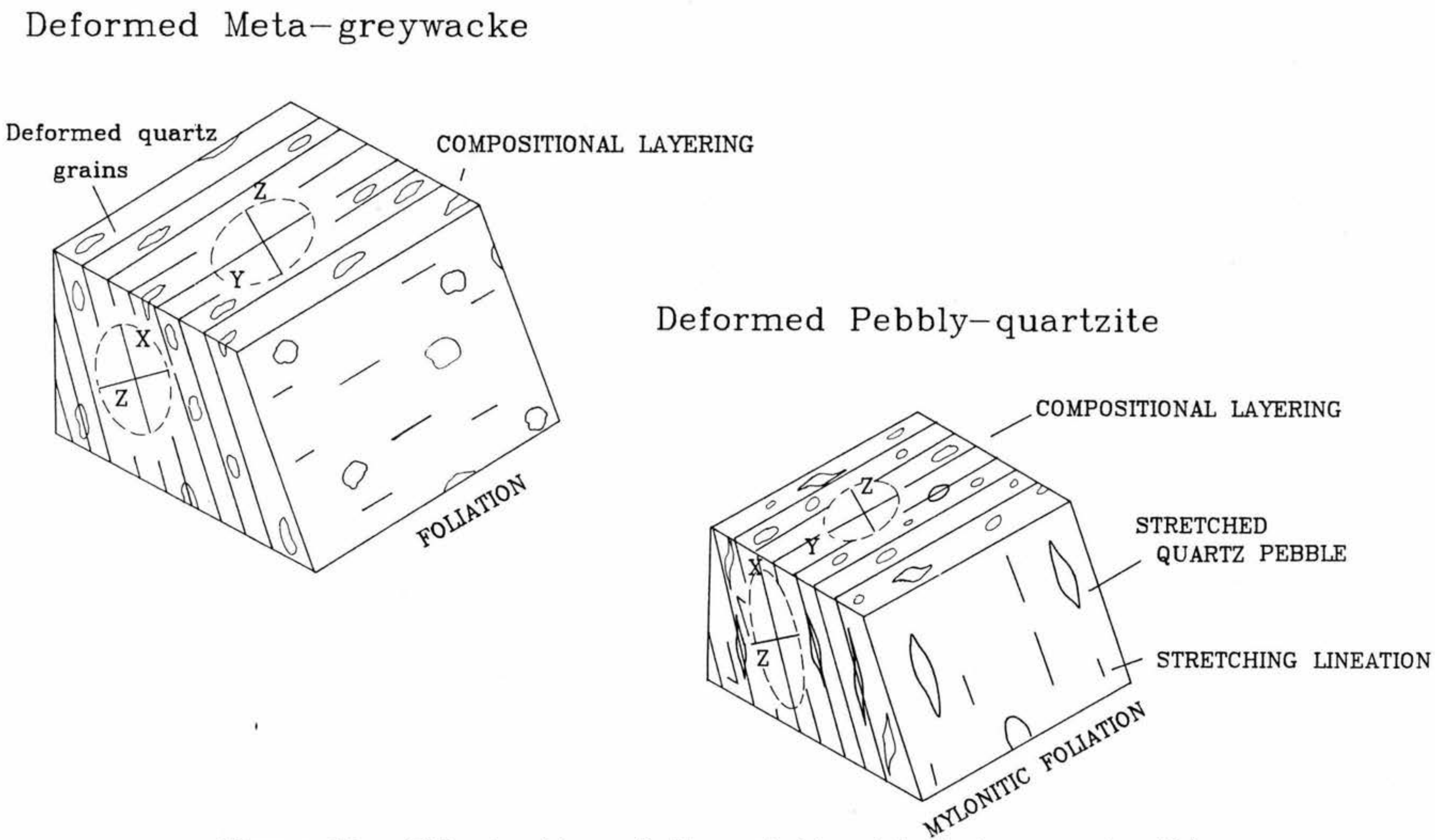


Figure 19. Illustration of the relationship between mylonitic foliation, mineral growth and stretching lineations and the relative strain ellipses plotted in the XZ and YZ planes. a. Pure flattening. b. Plane strain.

northwest vergence in the XZ plane. Additional shortening occurs in localized zones of isoclinal to tight-similar folding, where sub-horizontal fold axes parallel mineral growth lineations parallel the maximum extension direction of the average strain ellipsoid. Axial planar cleavage in these folds parallels regional foliation supporting the idea of tectonic foliation development.

Shear Sense Determinations

Methods

To determine the shear sense in the mylonite zones, the asymmetry of mineral grains was measured directly in three outcrops and in the X-Z plane of 22 oriented thin sections (Figure 20). In thin sections cut parallel to the X-Z plane, shear sense determinations were measured using the criteria of Simpson and Schmid (1983) from asymmetric porphyroclasts of quartz, feldspar, staurolite, kyanite, C-S surfaces, oblique and elongate mineral grains, and rolled garnets.

Results

Shear sense determinations from prograde mineral assemblages are summarized in Figure 20, a stereonet plot of X-Y planes with shear sense directions measured in the X-Z plane indicated with arrows. Mineral stretching lineations paralleling the X strain direction show dominantly reverse (high-angle thrust) motion, with tectonic transport toward the northwest.

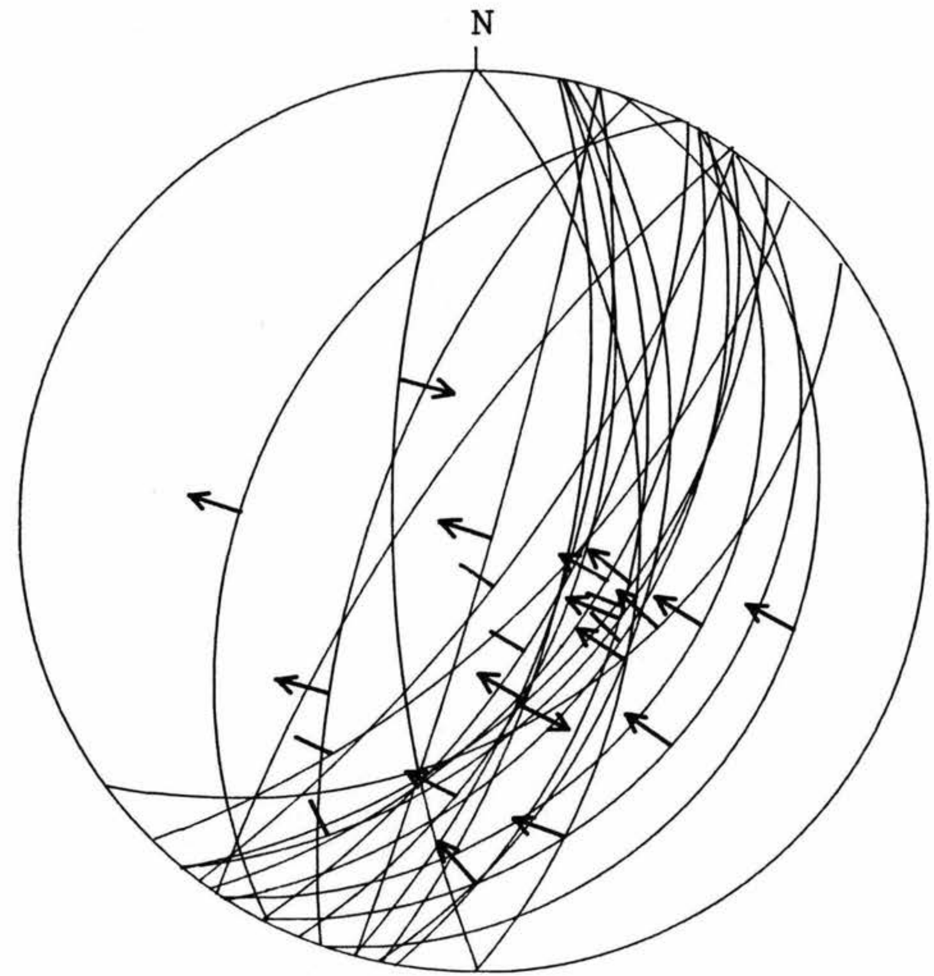


Figure 20. S-surface orientations (X-Y) planes and shear sense plotted in the XZ plane, with arrows indicating the displacement of the hanging wall relative to the footwall.

CHAPTER 6

STRUCTURE SECTIONS AND INTERPRETATIONS

Prograde Mylonite Zones

Detailed examinations of unit contacts reveal that unit duplications and truncations occur along a series of generally concordant, southeast-dipping mylonite zones, varying in thickness from centimeters to meters. Tectonic duplication and bulk thickening of the Cherry Creek sequence increases to the southwest, while individual unit thicknesses increase to the northeast. Repetition of Cherry Creek lithologic sequences along these ductile shear zones is the result of thrust duplexing based on shear sense and tops indicators. In the following section, three field traverses and corresponding cross-sections are described in detail.

Little Mile-Canyon Ridge Section

Tectonic repetition of the stratigraphic section is evident in a northwest-southeast transect along the ridge bisecting Little Mile and Mile Creek (Figure 21). In this traverse, a quartzite - hornblende schist - marble package is repeated along a complex, 600m wide zone of ductile shear that topographically corresponds to a major saddle bisecting the major marble unit. Within the shear zone, dismembered quartzite horizons pinch out locally along

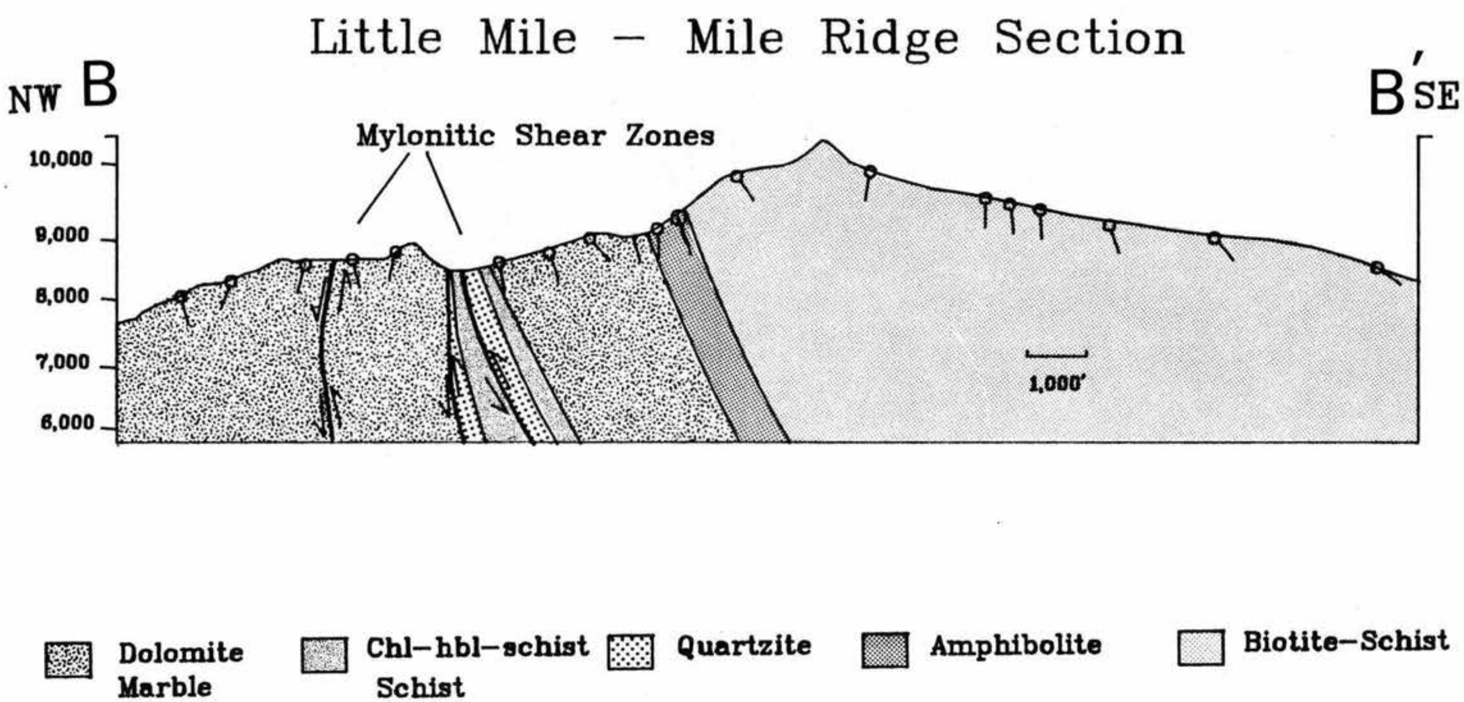


Figure 21. Little-Mile - Mile Ridge structure section.

strike and are intercalated with the chlorite-hornblende schist unit.

Several annealed, protomylonitic breccias with large quartzite clasts (Figure 22) are locally kyanite bearing. Attenuated quartzite clasts define a 2 m wide shear zone that parallels adjacent unit contacts. The northwestern contact of the hornblende - schist contains an unusual protomylonite, containing large, elongated clasts of marble in a quartzite rich matrix and is bounded by chloritized-hornblende-schist mylonite. The maximum stretch direction (S50E;78SE) from quartz clasts in these zones parallels the foliation dip. Mylonitized ribbon quartzites in this zone locally display flaser fabric. Graded-bedding in pebbly--quartzites reveal that stratigraphic up the southeast in this locality.

In thin section, the average quartz grain size in the mylonites is greatly diminished (average grain size = .05-1mm) with larger quartz grains (1mm-2mm) characterized by asymmetric quartz tails. Shear sense, determined from oriented thin-sections containing asymmetric quartz porphroblasts, show a reverse slip component, with overall vergence toward the northwest. Mineral stretching lineations are characterized by asymmetric dynamically recrystallized quartz tails. Mineral growth lineations defined by muscovite trend to the northeast and parallel sub-horizontal fold-axes in the adjacent hornblende-schist and marble units.

Figure 22. a. Protomylonite zone between dolomite marble and quartzite/chlorite schist unit.

This shear zone is interpreted to be a zone of thrust duplication with vergence toward the northwest based on stratigraphic repetition, tops indicators (Figure 5) and shear-sense indicators.

Black Mountain Ridge Section

The Black Mountain ridge section, a traverse along the continental divide (Figure 23), trends northwest (perpendicular to foliation) along Black Mountain Ridge. This northwest trending (perpendicular to foliation) section provides continuous exposure above treeline. In this area, a stratigraphic succession of marble and amphibolite is repeated along a ductile shear zone characterized by mylonitized biotite-schist and amphibolite. Tops indicators in the biotite-schist units indicate stratigraphic up to the southeast (Figure 5). A thin marble sliver, in ductile-fault contact with the underlying amphibolite, is observed off the ridgecrest to the southwest and pinches out along the ridge suggesting that the fault cuts up section.

In the mylonitized biotite schist C-S surfaces (Figure 24 A) record reverse shear with vergence toward the northwest. Based on these shear sense indications, and regional stratigraphy, this ductile shear zone is interpreted as a thrust zone.

Duplication of the major marble unit occurs to the northwest along this traverse. A hornblende-schist unit bisects the major marble unit and is locally highly folded

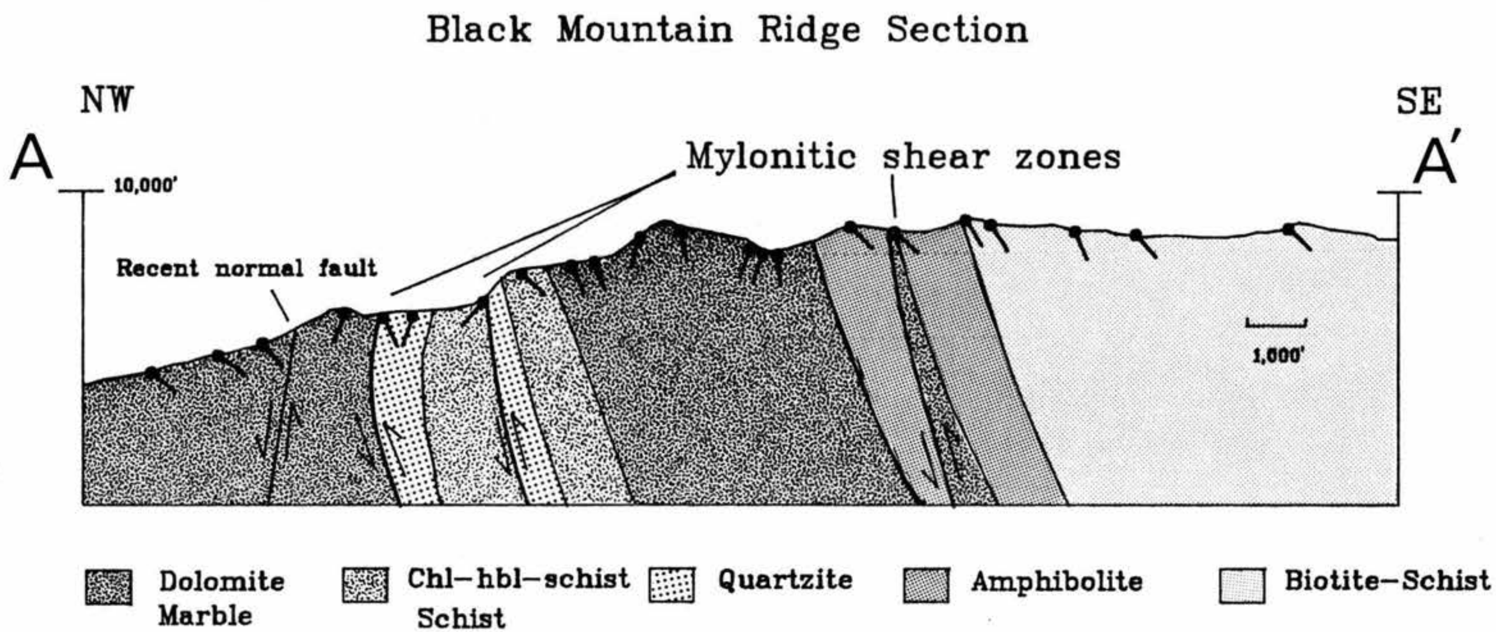
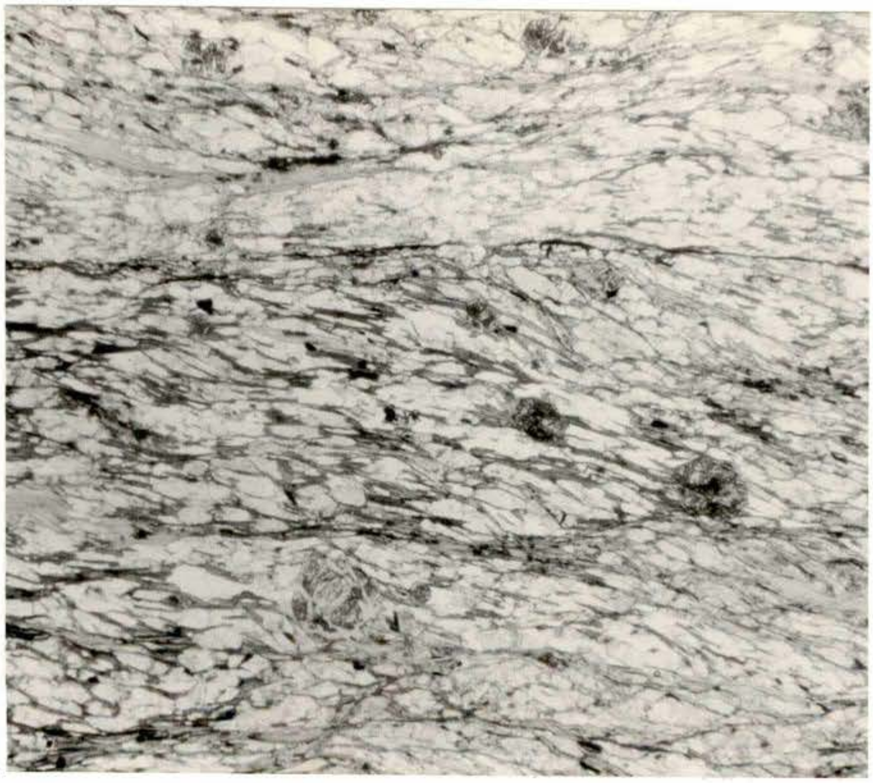
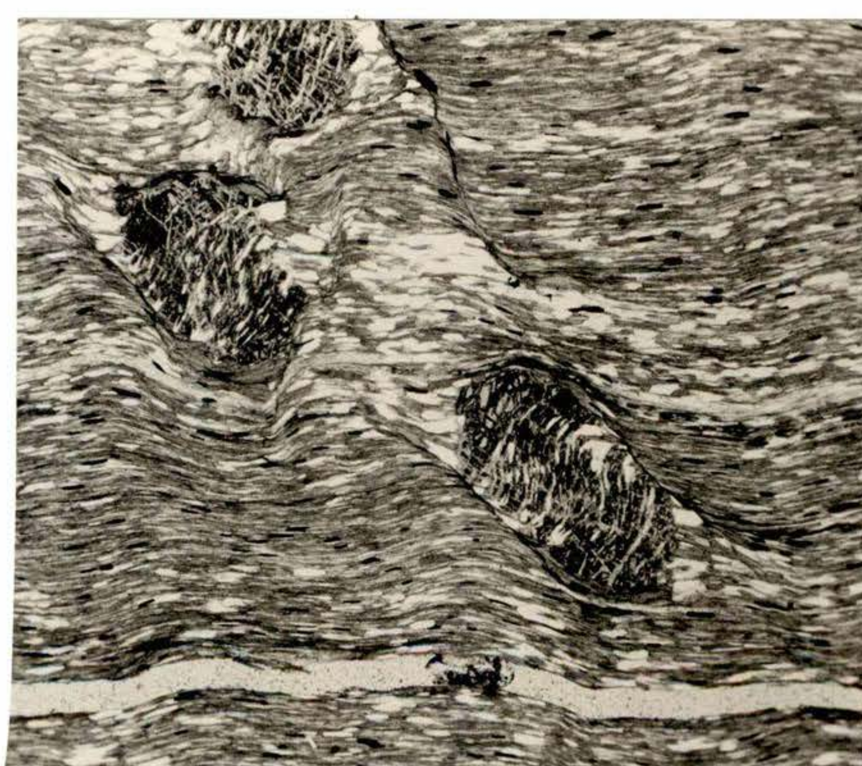


Figure 23. Structure section across Black Mountain ridge.

Figure 24. Mylonitic fabrics of the X-Z plane from oriented samples. a. C-S surfaces in sheared biotite schist. b. Rotated porphroblastic garnet in hornblende-biotite-garnet schist. Reverse shear sense is indicated in both sections. Photomicrographs are 4.4 mm across the horizontal direction.



A



B

and sheared (Plate 1). Rolled-garnets in sheared amphibolite record reverse motion with vergence toward the northwest (Figure 24B). Mineral assemblages characterized by garnet, hornblende and biotite are locally retrograde with biotite replaced by chlorite. Channelized fluids associated with the Madison mylonite zone may account for the lower amphibolite mineral assemblages toward the northwest in the chlorite-hornblende schist unit.

Sheep Mountain Ridge Section

Figure 25 shows the structural repetition of a marble, amphibolite, biotite schist sequence above Sheep Lake. The ductile fault does not cut the overlying Cambrian Flathead sandstone indicating Precambrian faulting. Preliminary ^{40}Ar-^{39}Ar analyses from an amphibolite in a less deformed portion of this zone suggests an Archean metamorphic thermal equilibration age of 2.7 Ga (Erslev and Sutter, in prep.). Megascopic and oriented thin sections show highly strained quartz stringers and microfolds that are offset en echellon along a series of microshears with apparent normal offset. The regional foliation in this zone and the ductile shear zone dip toward the northwest due to rotation adjacent to the Madison Mylonite zone. If the northwest dipping fault zone is rotated back to a southeast dipping configuration (parallel to the other ductile shear zones), these offsets record thrust motion toward the northwest. The exact timing of movement in this zone is complicated by overprinting relationships; none the less,

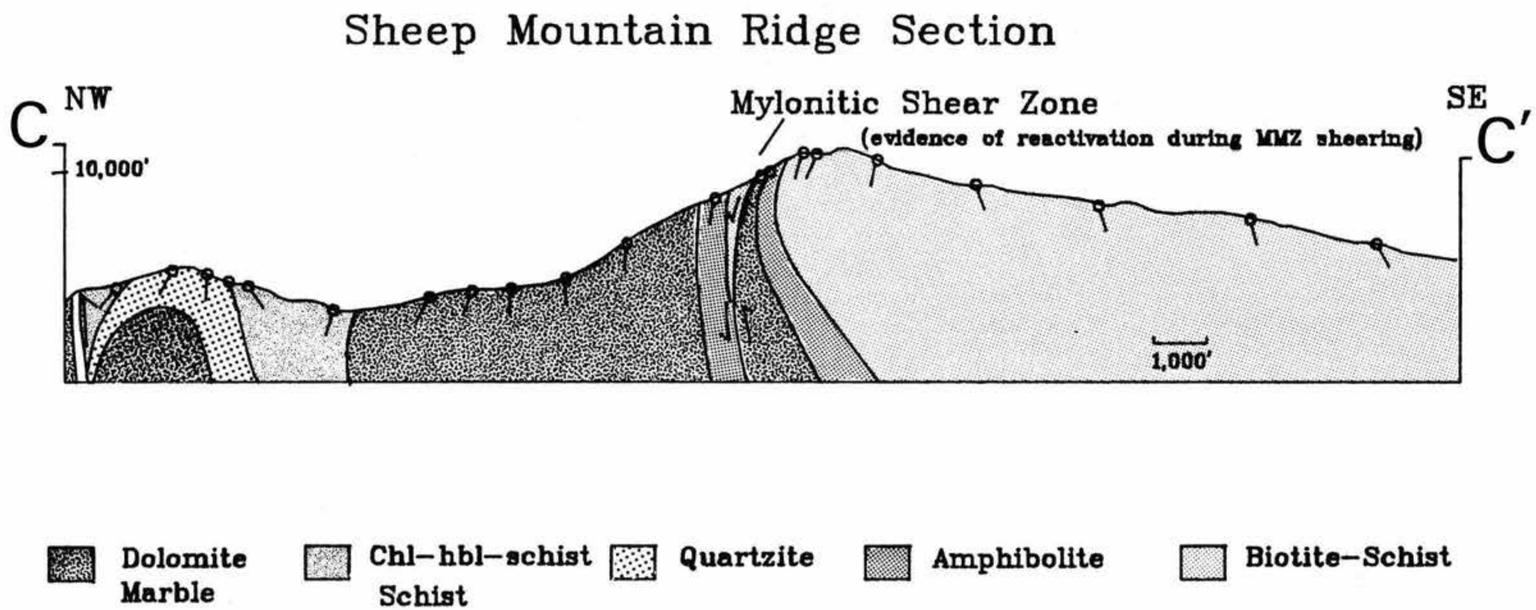


Figure 25. Sheep Mountain Ridge structure section.

the stratigraphic repetition of the Cherry Creek sequence in this zone is consistent with other prograde thrust zones in the study area.

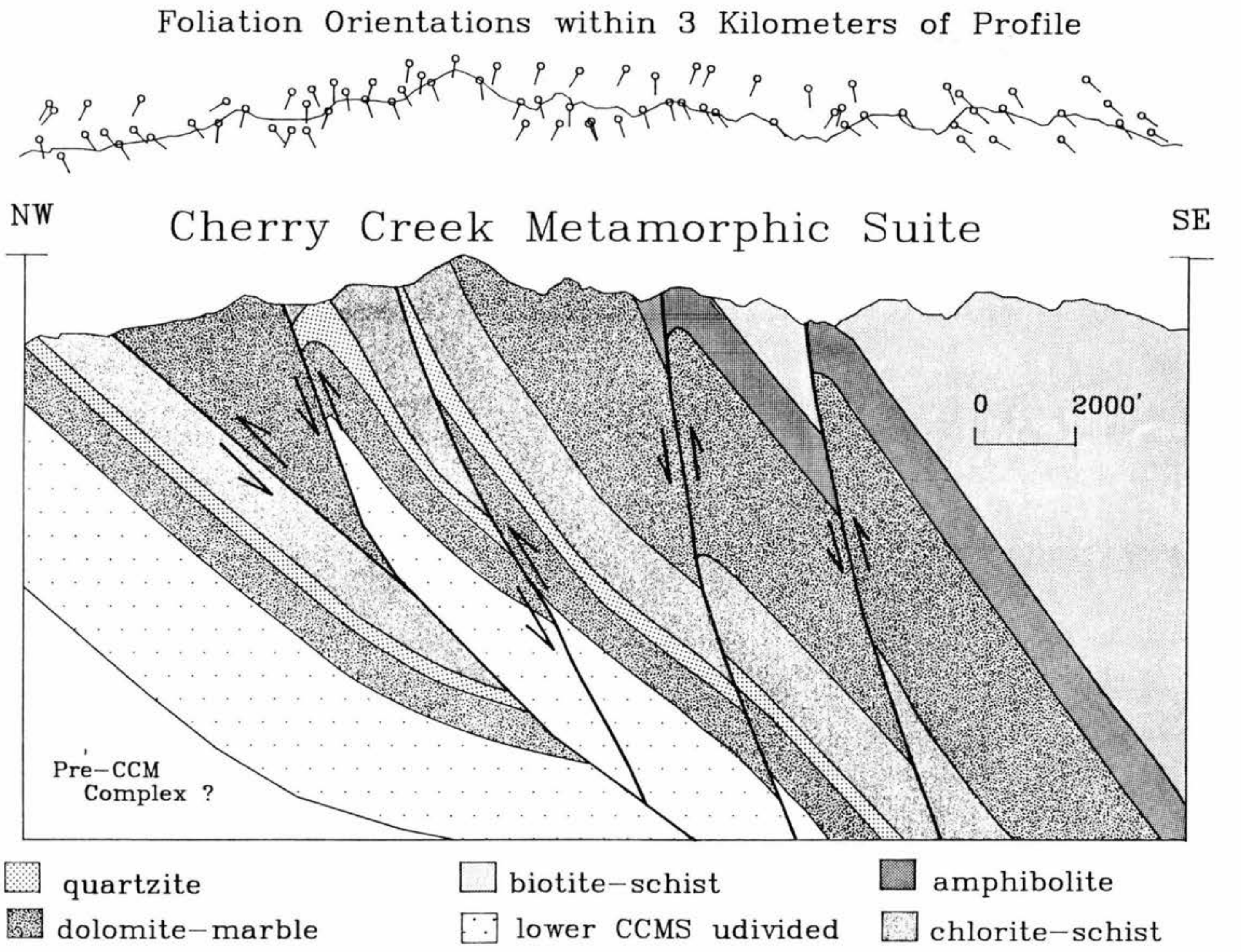
Methods for Structural Modeling

A structural model was developed for the deformation of the Cherry Creek Metamorphic Suite by constructing a down-plunge projection (Mackin, 1950) incorporating regional stratigraphic and structural data. The data were compiled from 8 parallel cross-sections oriented perpendicular to the regional fold axis (N20E) trend. Data for each section include lithology, facing directions, contact relationships (mylonitic versus stratigraphic) and strain data. In the down-plunge view, exposures in the southwest represent structurally lower levels, while units along strike to the northeast represent structurally higher levels. This is suggested by the consistent cutting up section of thrusts from the southwest toward the northeast.

Structural Interpretation

The down-plunge cross-section in Figure 26 shows tectonic thickening due to thrust repetition of the Cherry Creek stratigraphy along ductile mylonite zones. The consistent facing directions in the meta-sedimentary units on opposite sides of these mylonites, and the increase in unit thickness of the sheared assemblages suggests bulk thickening of the Cherry Creek Metamorphic Suite with the development of an imbricate thrust stack (duplex structure) during thin-skinned thrusting. Ductile shear zones with

Figure 26. Cross-section of the regional structure constructed using the down-plunge method (Mackin, 1950) of the Henrys Lake Mountains.


Foliation Orientations within 3 Kilometers of Profile
NW
Cherry Creek Metamorphic Suite
SE
0
2000'
Pre–CCM
Complex ?
quartzite
dolomite–marble
biotite–schist
lower CCMS udivided
amphibolite
chlorite–schist

rolled garnets and sheared kyanite suggest this shearing was syn-to-late kinematic with amphibolite facies metamorphism. In plan view, perpendicular to the cross-section line, the geologic map (Figure 5; Plate 1) resembles a longitudinal cross-section across a thrust belt (Woodward and others., 1985). From this vantage point, it is apparent that many unit truncations along lithologic strike are the result of lateral ramps in thrusts cutting up-section to the northeast. Localized zones of recumbent, tight-to-isoclinal folding in the 4 km thick biotite schist may represent lateral ramp and thrust flat transitions. The complex regional map pattern may be viewed as an original stratigraphic sequence duplicated by thrust faulting along generally southeast-dipping mylonite zones.

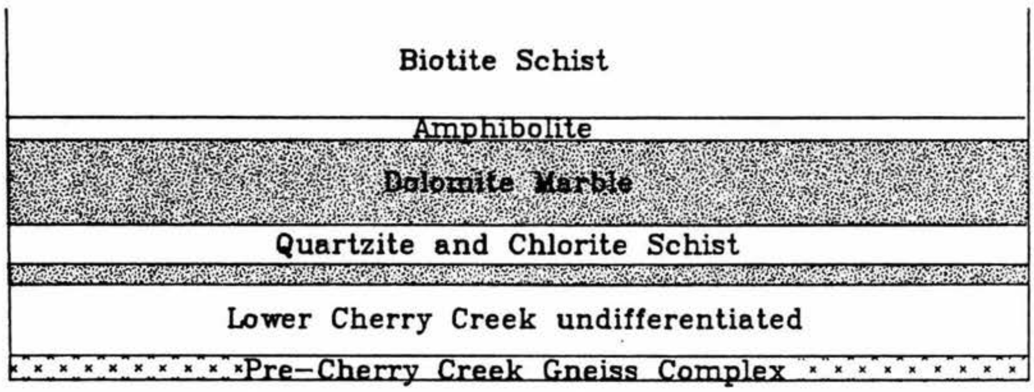
Fabric analysis and strain analysis of the Cherry Creek Metamorphic Suite reveal a combination of S and LS tectonites regionally in the Cherry Creek sequence in the Southern Madison Range. Studies of the Moine thrust complex (Elliot and Johnson, 1980) have documented similar fabrics where a combination of flattening and simple shear is associated with thrust duplexing. Progressive simple shear can accommodate significant crustal shortening and forms synchronously with a flattening component parallel to the foliation direction. Lineation directions in this orogen are oriented in the maximum elongation direction or parallel to fold axes. Similarly, LS tectonite development is associated with profound crustal shortening and nappe development in the Archean and Proterozoic rocks from the Great Lakes region (Holst, 1984).

Sequential Deformational Model

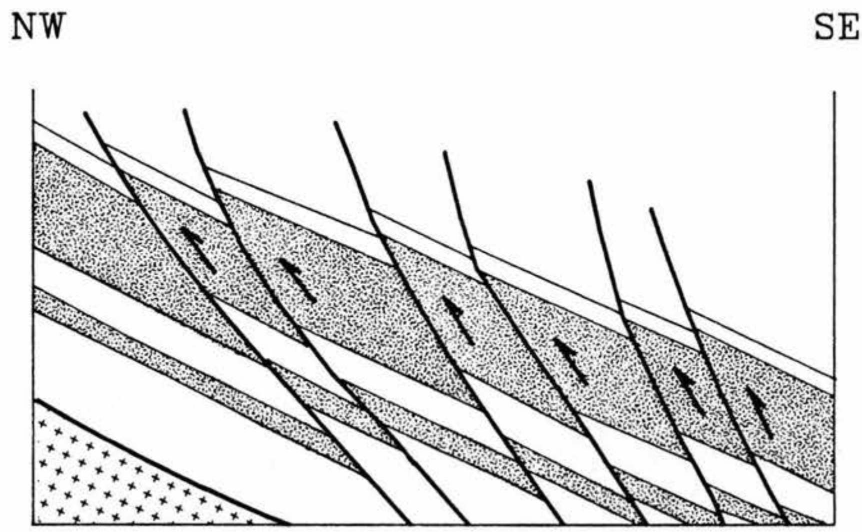
The sequential deformation model shown in Figure 27 is based on the regional geology constrained by the necessity to approach cross-section balance or restorability (Woodward and others, 1985). The sequential deformation model is a non-unique interpretation of the geology based on structural data and regional geochronology. It should be noted that variations in strain have not been rigorously incorporated into the sections here. The model is analogous to interpretations of thin-skinned thrusting and duplexing along many post-Archean continental margins (e.g., Boyer and Elliott, 1982; Elliott and Johnson, 1980; Suppe, 1983). Figure 27A shows the restored primary stratigraphy compiled from the regional stratigraphic column (Figure 4). In Figure 27B, thrusting is interpreted to be synkinematic with prograde, middle-amphibolite facies metamorphism (based on regional fabric data, Chapter 4 and 5) of Late-Archean (2.7 Ga) age. Facing directions in zones of lithologic repetition and shear sense indicators suggest initial thrusting during a compressional orogeny occurred with northwest vergence in the thrust belt. Bifurcation of faults in ramp areas often leads to the development of horses, or fault bounded slices of the stratigraphic sequence, forming a duplex geometry

Figure 27. Sequential deformation model. a. Original stratigraphic sequence of the Cherry Creek Metamorphic Suite. b. Archean (2.7 Ga) thrusting synkinematic with middle-amphibolite facies metamorphism, showing thrust vergence toward the northwest. c. Proterozoic thrusting (1.9 Ga) of opposite shear sense along the Madison Mylonite Zone and associated epidote amphibolite facies metamorphism.

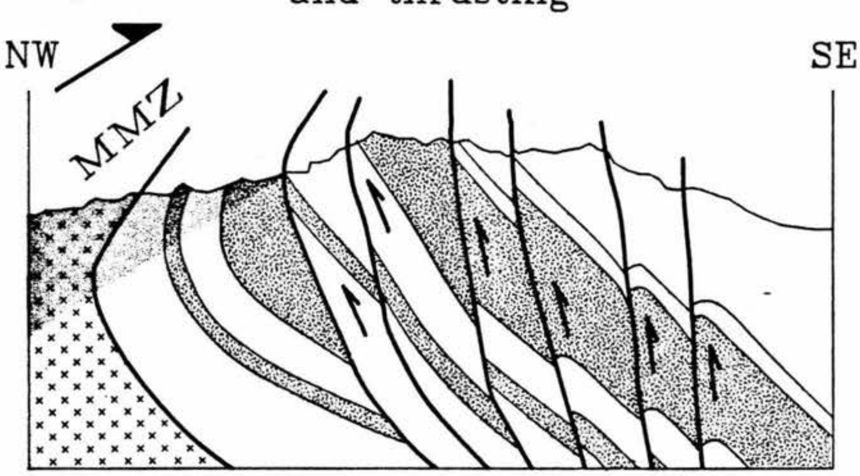
Sequential Deformation Model



A. Original Stratigraphy



B. Archean (2.7 Ga) metamorphism and thrusting



C. Proterozoic (1.9 Ga) thrusting along the Madison mylonite zone

(Suppe, 1982). The fact that continued thrusting in hinterland regions often rotates early thrusts to higher angles provides a plausible explanation for the steep dips in the southern Madison Range.

Figure 27C shows Proterozoic (1.9 Ga) thrusting of the Pre-Cherry Creek Metamorphic Complex (the basement upon which the Cherry Creek units were deposited) over the Cherry Creek Metamorphic Suite in the Madison mylonite zone. This event rotated the regional foliation within the ductile shear zone through the vertical, forming a north-west-dipping zone of Proterozoic basement reworking.

In summary, detailed mapping suggests that strati-graphic repetition occurs along a series of ductile mylonite zones. Shear sense indicators from prograde mineral assemblages and regional stratigraphy suggests that these repetitions are the result of thrust duplexing. Vergence of the Cherry Creek stratigraphic package is toward the northwest. Regional fabric data suggests these ductile shear zones equilibrated syn-to post-kinematically during middle amphibolite facies metamorphism.

CHAPTER 7

GEOCHEMISTRY, PROTOLITHS AND TECTONIC SETTING

Purpose

Geochemical signatures in the sedimentary rock record provide an overall average of upper crustal composition exposed at the time of erosion. Consequently, sediment chemistry provides critical information concerning the nature of the upper crust and its petrogenesis (Taylor and McLennan, 1985; Gibbs and others, 1986; Veizer, 1985). Archean shelf associations have received little attention in formulating models for Archean crustal evolution (Gibbs and others, 1986) because there are fewer Archean examples. In fact, most studies of sediment chemistry focus on greenstone belts of Archean age and shelf associations of Proterozoic and later ages.

This sampling bias led many workers to propose a major change in the crust-mantle system between the Archean and the Proterozoic. However, Gibbs and others (1986) have demonstrated that for some terranes, geologic setting rather than age accounts for most of the geochemical differences previously attributed to the Archean-Proterozoic boundary. This analysis looks at the chemistry of meta-pelites/greywackes and amphibolites from the Cherry

Creek Metamorphic Suite and provides additional data on Archean shelf associations.

Methods

Whole rock meta-sedimentary samples were analyzed for major, trace, and rare earth elements by the U.S. Geological Survey analytical labs in Denver, Colorado. X-ray fluorescence determined major element chemistry of the 14 meta-pelite/greywackes and 6 amphibolites. Inductively-coupled argon plasma (Crook and Licht, 1982) determined trace element and REE abundances. Five duplicate amphibolite samples were analyzed for trace and REE abundances by neutron activation analysis (Jacobs and others, 1977) at New Mexico Institute of Science and Technology, Socorro, New Mexico. Samples localities are listed in Plates 3 and 4.

Meta-Greywacke/Meta-Pelite Geochemistry

Major Elements

Table 3 presents major and trace element data of 14 metasediments. The average SiO_2 content is 64% with the highest SiO_2 contents (around 70%) from the basal coarser fraction of the graded greywacke-pelite beds. The pelitic portion of these sequences have SiO_2 contents less than 60% and elevated Al_2O_3, FeO+MgO, and K_2O/Na_2O ratios. Table 4 shows that SiO_2, TiO_2, Al_2O_3, FeO and MgO for the Henrys Lake samples all fall within the 95% confidence interval for average Archean clastic rocks (Taylor and McLennan, 1985). The average CaO and Na_2O analyses fall below the

Table 3. Whole rock and trace element chemistry of pelitic schist, Henrys Lake Mountains.

Sample WT%	C-16	C-24	C-23	C-28	C-29	WS-84	WS-30	WS-83	HS-39G	HS-48	WS-6486	C-35	WS-86	WS-13
SiO2	70.5	65.8	66.2	66.4	68.6	55	69.8	69	67	64.9	64.4	57.5	70.6	59.6
Al2O3	13.2	14.4	14.4	14.1	13.2	19.4	12	13.3	14.1	15.3	14.4	18.8	12.5	18.4
Fe2O3	5.91	6.9	8.05	6.72	6.5	11.1	10.1	6.19	6.72	8.07	11.1	9.06	5.92	7.64
MgO	2.93	3.38	3.76	3.13	2.74	4.82	2.29	2.52	3.03	3.64	2.7	4.86	2.9	4.03
CaO	1.46	1.55	1.17	1.65	2.21	1.84	0.09	2.57	1.87	1.44	1.75	1.34	1.37	2.16
Na2O	1.97	2.18	1.34	2.38	2.45	1.68	1.5	2.35	2.5	1.7	2.2	1.6	1.92	2.35
K2O	1.97	2.91	2.89	2.55	1.41	3.56	1.85	1.85	2.36	2.83	2.07	3.83	2.46	3.45
TiO2	0.69	0.58	0.64	0.6	0.6	0.92	0.68	0.6	0.65	0.6	0.65	0.76	0.53	0.76
P2O5	0.07	0.09	0.07	0.09	0.1	0.16	0.07	0.1	0.1	0.08	0.09	0.07	0.07	0.19
MnO	0.04	0.09	0.08	0.05	0.07	0.13	0.04	0.08	0.07	0.1	0.08	0.09	0.07	0.09
Total	98.74	97.88	98.6	97.67	97.88	98.61	98.42	98.56	98.4	98.66	99.44	97.91	98.34	98.67
K2O/Na2	1	1.33	2.15	1.07	0.57	2.12	1.23	0.78	0.94	1.66	0.94	2.4	1.28	1.47
FeO+MgO	8.84	10.28	11.81	9.85	9.24	15.92	12.39	8.71	9.75	11.71	13.8	13.92	8.82	11.67
Mn ppm	280	690	590	420	540	900	340	600	540	740	670	680	580	560
Ba	600	530	670	610	360	700	180	510	570	600	440	870	500	780
Ce	58	59	62	64	64	55	78	44	59	64	53	63	70	92
Co	17	24	23	24	21	33	42	16	22	25	26	37	20	24
Cr	180	240	250	180	160	250	130	160	180	240	190	300	240	160
Cu	24	53	46	37	38	43	31	52	42	45	1	34	48	20
Ga	11	16	13	18	16	19	15	17	16	14	17	24	14	18
La	34	42	36	40	39	33	44	33	37	38	32	36	43	55
Li	31	37	47	44	27	50	23	29	31	42	35	73	39	54
Ni	55	95	100	84	67	140	100	45	83	93	93	170	75	92
Pb	20	31	22	28	27	18	6	23	27	29	30	25	35	36
Sc	13	16	17	15	13	29	21	13	15	19	17	23	13	17
Sr	120	110	70	170	140	130	15	140	140	87	240	98	93	130
V	96	96	100	93	89	170	140	86	100	100	100	140	79	100
Y	14	24	22	26	25	32	8	24	21	28	24	23	21	23
Zn	11	50	14	76	43	26	180	73	51	24	77	61	24	22
Th	13	16	17	18	19	12	9	17	14	16	12	16	20	30
Yb	2	3	3	3	3	4	1	3	3	4	3	3	3	3

Table 4. Compositions of Clastic Metasedimentary Rocks from the Wyoming Province (Weight Percents)

	Southwest Montana					Wyoming	Worldwide
	1	2	3	4	5	6	7
SiO_2	65.4	59.7	45.2	66.6	66.6	65.6	65.9 + 2.2
TiO_2	.7	.8	1.1	0.5	.5	0.6	0.6 + 0.1
Al_2O_3	14.8	17.5	26.6	13.9	16.0	15.8	14.9 + 1.3
FeO	6.9	8.2	12.9	6.9	7.6	6.0	6.4 + 1.5
MgO	3.3	3.9	6.1	3.2	3.6	3.2	3.6 + 1.0
CaO	1.6	1.9	1.6	1.2	1.1	2.3	3.3 + 1.1
Na_2O	2.0	1.9	1.6	2.1	2.0	3.8	2.9 + 0.5
K_2O	2.6	3.0	6.2	2.5	2.8	2.5	2.2 + 0.3
K_2O/Na_2O	1.3	1.6	3.9	1.5	1.4	0.7	0.76
FeO + MgO	10.2	12.1	19.0	10.1	11.2	9.2	10.0

1. Average of 14 schists, Henrys Lake Mountains, S.Madison Range, Montana (average from Table 3, this study)
2. Average of 3 schists, western South Snowy Block
3. Sample M-10, high-iron mica schist, southern Madison Range (Gibbs et al., 1986)
4. Average of 13 schists, central South Snowy Block, Montana (Thurston, 1986)
5. Average of 6 schists, central South Snowy Block (Gibbs et al., 1986).
6. Average of 23 greywackes, Wind River Mountains, Wyoming (Condie, 1967).
7. Average Archean clastic sedimentary composition +95% confidence limit (Taylor and McLennan, 1985).

95% confidence limits for Archean clastic rocks but are similar to other pelitic schists in the Beartooth Mountains and southern Madison Range (Table 4).

Elevated K_2O and K_2O/Na_2O ratios both fall outside the 95% confidence interval for Archean clastic rocks. These elements resemble average Proterozoic and Phanerozoic signatures (Taylor and McLennan, 1985) and resemble other meta-sedimentary analysis in the northwestern Wyoming Province in Table 4. The geochemical signature for the northwestern Wyoming Province is very consistent and contrasts sharply with the southern Wyoming Province and the worldwide Archean average. This almost singular geochemical signature suggests similar provenance characteristics across the northwestern Wyoming Province.

Trace and Rare Earth Elements

The schists are enriched in several trace elements, particularly Mn (up to 900 ppm), Ba (up to 780 ppm), Cr (up to 300 ppm) and Ni (up to 170 ppm). Six REE elements, La, Ce, Nd, Sm and Yb were successfully analyzed. The general REE pattern in Figure 28A resembles post-Archean signatures (Figure 28B) exhibiting LREE enrichment, and a flat HREE distribution typical of post-Archean greywackes. Sample M-10 (Gibbs et al., 1986) shows a substantial negative Eu-anomaly. Unfortunately, Eu levels were below the detection limit (< 2 ppm) in the present analysis and it is uncertain whether they show a Eu anomaly.

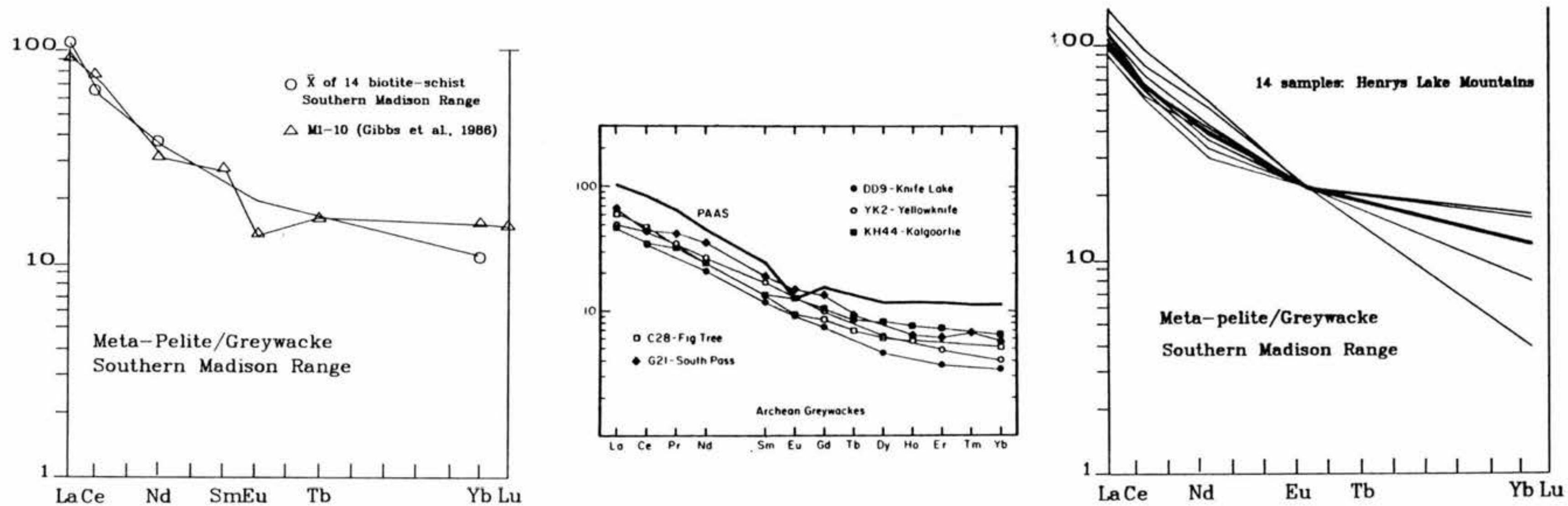


Figure 28. Chondrite normalized rare earth element plots for the meta-pelite/greywackes from the Henrys Lake Mountains. a. The average of 14 samples from the Henrys Lake Mountains and sample M-10 (Gibbs et al., 1986). b. REE plot of selected Archean greywackes and PAAS (Taylor and McLennan, 1985). c. REE plot of all 14 Henrys Lake Mounains samples.

However, the LREE enrichment and flat HREE pattern of M-10 parallels that of the 14 samples.

A plot of the 14 schists (Figure 28C) reveals some variability in the relative LREE enrichment and HREE concentrations exhibiting both steep and flatter slopes. Most samples are enriched in LREE, with an average La concentration (38 ppm) typical of post Archean signatures (eg; 39+3 ppm; Taylor and McLennan, 1985). However, the average La/Yb ratio is 12.6 and falls within the 95% confidence interval for Archean rocks (eg; 11.5 + 2.5; Taylor and McLennan, 1985).

Protolith of the Quartz-Biotite-Plagioclase-Schist

Compositionally, the quartz-biotite schists are characteristic of meta-pelites and greywackes with elevated Al_2O_3 contents (due to aluminous minerals such as garnet and kyanite) and high K_2O/Na_2O ratios. Elevated concentrations of FeO, MgO, Cr, Ni, Ba and Mn, and LREE enrichment (La and Ce) may reflect relative enrichment of these elements in biotite (FeO+MgO, Cr, Ni), feldspar (Ba substitutes for K, Mn for Ca), and heavy minerals.

Lithologic association with thick carbonate sequences also points to a metasedimentary protolith. Additionally, abundant primary sedimentary structures indicate a sedimentary source. Texturally, the schists are characteristic of turbidites with relict Bouma sequences (Bouma, 1962), prevalent graded-bedding, minor scour casts and cross-beds.

Depositional Setting

Deep, quiet water environments such as steep continental rises (Walker, 1979) favor the preservation of thick (100's to 1000's meters) turbidite sequences. Coalescing submarine fans form the continental rise and outer shelf through successive deposition of clastic material by turbidity currents. These areas are characterized by laterally extensive (100's meters), parallel-sided units that vary little in thickness laterally. Based on Bouma divisions, the turbidites in the southern Madison Range are most characteristic of mid - to distal portions of submarine fan complexes.

Other sedimentary rocks occurring with the turbidite successions along continental margins are subaqueous debris flows, or olistostromes, characterized by chaotic matrix-supported pebbly sandstones, and conglomerates with abundant muddy matrix (Walker, 1979). An olistostrome may be the protolith of one unusual biotite-schist unit found in Little Mile Canyon, comprised of non-sorted, non-stratified larger quartz-clasts (up to 25cm) in a dominantly biotite matrix.

Thurston (1986) found that meta-turbidite sequences in the Beartooth Range grade laterally westward into iron formations and thick mudstones or meta-pelites characteristic of the deeper portions of the basin. The metasedimentary sequence in the Henrys Lake Mountains lacks thick iron formations and thick mudstone, is intercalated with thick carbonates, and was probably deposited more proximal to a continental margin.

Provenance and Tectonic Setting

The use of conventional modal analyses to determine provenance and tectonic setting is not applicable due to alteration and recrystallization of greywacke minerals during amphibolite facies metamorphism. Element mobility during metamorphism is still inadequately understood. However, Condie (1983) suggests that it is important to use discrimination models that utilize the immobile trace elements rather than compare abundances of elements known to be mobile during secondary and metamorphic conditions (Si, Ca, Al, Ba, K, U, Rb, Cs). The elements La, Ce, Nd, Y, Th, Zr, Hf, Nb, Ti and Sc are considered the most suitable for provenance and tectonic setting discrimination due to their low mobility during sedimentary, igneous and metamorphic processes (Winchester and Floyd 1977; Bhatia and Crook 1986).

A recent scheme to discriminate the tectonic settings represented by greywacke/turbidite successions has been proposed by Bhatia and Crook (1986) on the basis of trace elements insensitive to alteration. The tectonic setting discrimination plots utilized in their study were developed for continental margin, intracratonic, and ocean basin greywackes.

Figure 29 is a discrimination plot of La versus Th discriminates between oceanic island arc, continental

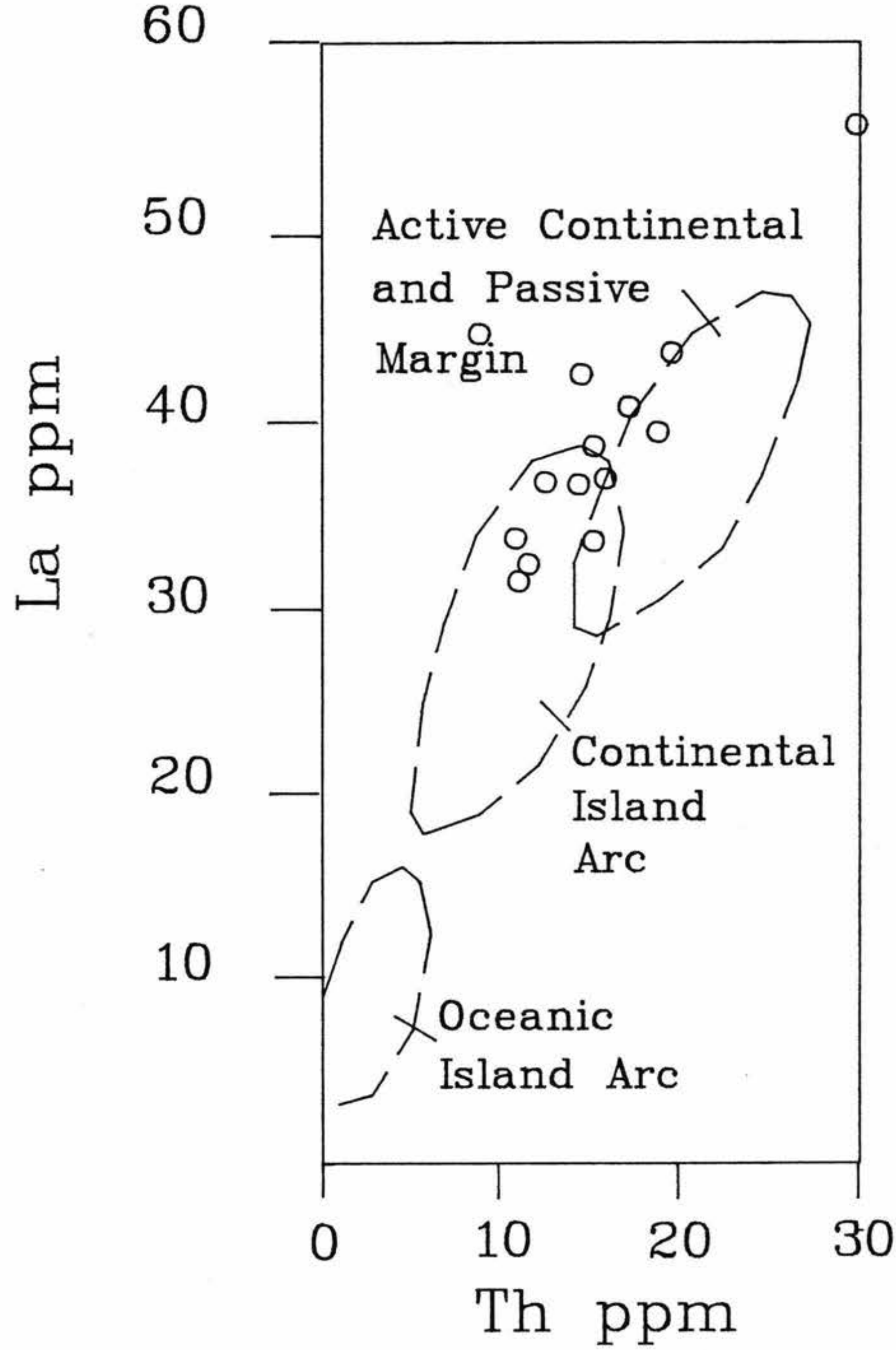


Figure 29. La-Th plot of meta-pelite/greywackes for tectonic discrimination. Dotted lines represent the dominant fields for the various tectonic settings. (DiscrimiNation diagram from Bhatia and Crook, 1986).

island arc and active continental margins. La, a light rare earth element, and Th, a large highly charged cation, behave similarly during sedimentation. La and Th generally increase with silica and compositional maturity and are depleted in mafic rocks (Bhatia and Crook, 1986). Variable La/Th ratios shown in Figure 29 are consistent with either a continental island arc or active continental margin. The average La/Th ratio is 2.7 and is almost equal to the average from continental island arcs (eg; 2.4 = 0.3) and resembles post-Archean sedimentary values (2.8 + .2, Taylor and McGlennan, 1985).

The ternary plot of La, Th and Sc in Figure 30 also discriminates between continental margin, continental island arc and oceanic island arc settings. Sc is a ferromagnesian trace element that resides in mafic volcanics and indicates the relative ferromagnesian component in metasediments (Bhatia and Crook, 1986). In Figure 30, all but one of the pelites plot in a continental island arc field. One of the samples plot in an oceanic island arc field possibly suggesting a limited mafic component in the source.

In a continental island arc setting, the sediments are mainly derived from intermediate volcanic rocks from more mature arcs (or recycled orogens) adjacent to an active continental margin. The sediments are deposited in inter-arc, back-arc/marginal and fore-arc basins (Bhatia and Crook, 1986). Island arcs in this setting are often

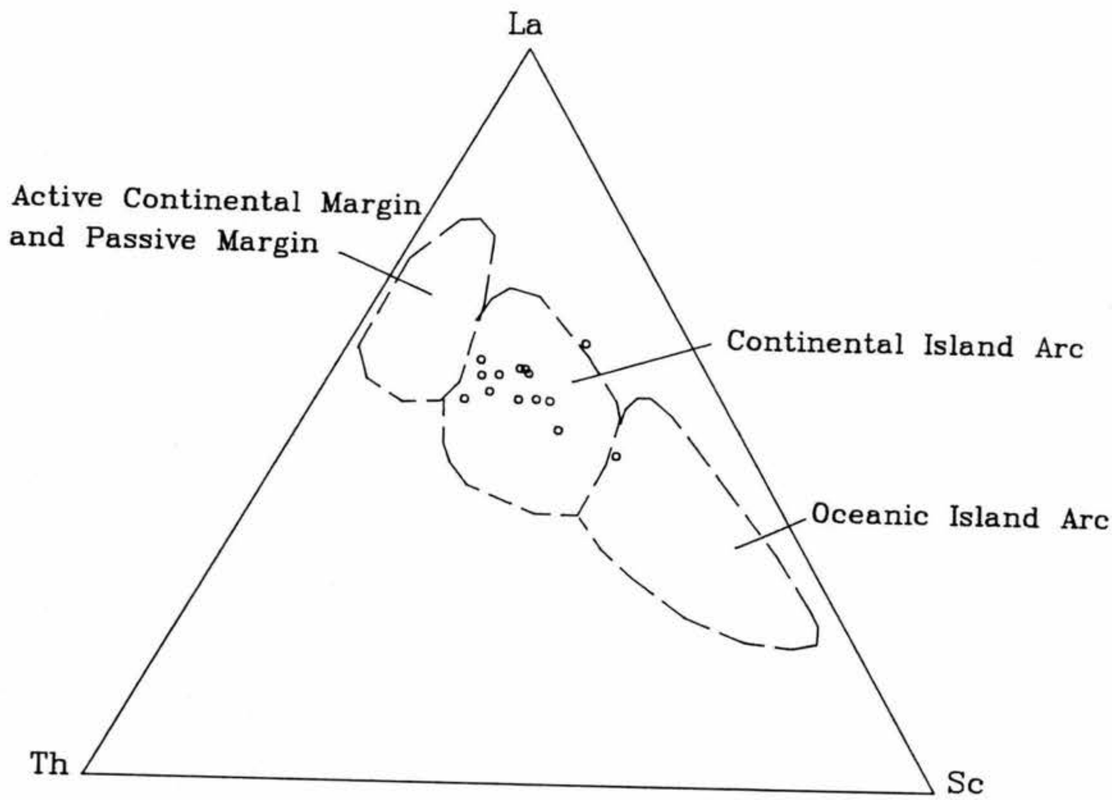


Figure 30. La-Th-Sc plot of meta-pelite/greywackes. Dotted lines represent the dominant fields for the various tectonic settings. (Discrimination diagram from Bhatia and Crook, 1986).

continental fragments detached from the mainland or form on well developed continental crust or on thin continental margins (Bhatia and Crook, 1986). Modern examples of this type of setting include the Sea of Japan style back-arc basins, the Puerto Rico shelf, the Havre Trough, and the Cascades (Bhatia and Crook, 1986).

Elevated K_2O/Na_2O ratios, Ba concentrations (up to 870 ppm) and high La/Yb ratios with a Eu anomaly indicated in sample M-10 all suggest that a K-rich granitic rocks formed part of the source area. High SiO_2 and Al_2O_3 contents along with elevated K_2O/Na_2O ratios and lower Na_2O + CaO contents found in the southern Madison Range greywackes are also consistent with a granitic or felsic volcanic source. The high ferromagnesian component indicated by elevated concentrations of Fe_2O_3 + MgO could be the result of a mafic component in the source area. Iron formations forming proximal to the source region or prolonged weathering and oxidation may also account for the increased ferromagnesian component. Additionally, Archean seawater was probably enriched in Fe^{2+} due to reduced atmospheric conditions during the Archean (Windley, 1984).

<u>Amphibolites</u>

Table 5 presents the geochemical analyses of 5 amphibolites and 1 meta-diabase (C-25). The samples are from massive beds in layered amphibole gneiss sections and a diabase dike (Appendix 2). Textural characteristics, such as layering and size grading in amphibolites (Engle

Table 5. Whole rock and trace element chemistry of amphibolites. U.S. Geological Survey provided whole rock analysis. Trace element neutron activation data provided by New Mexico Institute of Mining and Technology (sample C-21 is U.S.G.S data).

Sample	C-12	C-25	C-31	C-26	C-30	C-21
SiO2	49.6	57.2	50.7	46.5	45.3	50.4
Al2O3	14.2	14.2	14.4	14.7	14.9	13.6
Fe2O3	14	10.9	12.9	16	13.5	14.5
MgO	6.37	3.66	6.21	6.34	10.6	6.68
CaO	10.1	6.86	9.6	11.2	10.7	7.56
Na2O	2.1	3.22	2.69	2.15	1.9	2.6
K2O	0.42	1.64	0.6	0.36	0.25	0.65
Ti2O5	1.34	0.99	1.56	2.11	1.22	1.34
P2O5	0.11	0.16	0.16	0.31	0.11	0.13
MnO	0.23	0.15	0.19	0.23	0.21	0.17
Total	98.47	98.98	99.01	99.9	98.69	97.63
K2O/Na2O	0.2	0.50	0.22	0.16	0.13	0.25
FeO+MgO	20.37	14.56	19.11	22.34	24.1	21.18
Sc	48	24.4	26.78	31.45	36.75	42
Cr	129.8	20.5	102.9	204.4	462	180
Co	70.7	45.4	40.6	50.4	92.1	16
Sb	0.044	0.543	0.07	0.063	0.09	
Ba	160	657	241	107	264	260
U	0.32	3.2	0.48	0.25	0.11	
La	8.4	32.3	17.73	12.12	5.66	10
Ce	19	64.6	40.8	29.2	14.3	16
Nd	13.4	30.1	20.9	18.4	9.5	9
Eu	1.31	1.45	1.58	1.48	1.16	
Tb	0.73	0.82	1.04	0.59	0.473	
Yb	3	2.18	3.29	2.36	1.66	3
Lu	0.462	0.361	0.51	0.359	0.252	
Hf	3.05	4.45	3.95	3.12	1.9	
Ta	0.429	0.71	0.657	0.56	0.308	
Th	1.24	10.52	2.83	0.97	0.41	
Zn	159	128	120	131	143	93
Ni	150	52	84	112	490	61
Cs	0.08	2.42	0.108	0.03	0.03	
Y	22	22	37	24	13	24
Sr	120	280	220	210	180	210

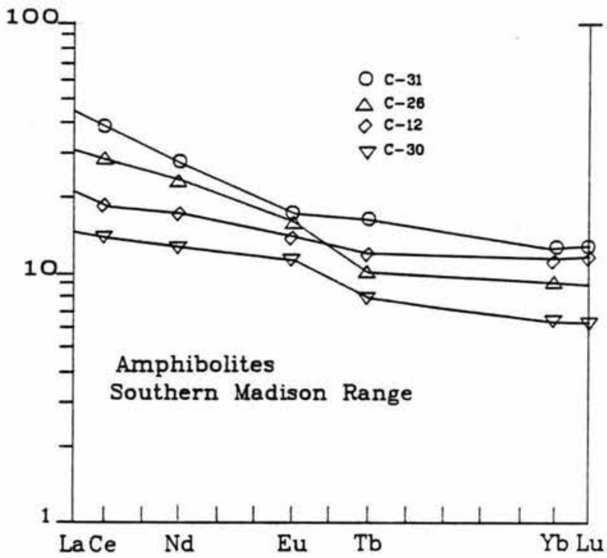
and Engel, 1951; Wilcox and Poldervaart, 1958; Evans et al, 1960) and geochemical signatures (Leake, 1964; Shaw and Kudo, 1965; Gorbachev, 1974) are often used to determine the protolith of amphibolites. This study examines REE patterns, trace element chemistry, and textural characteristics to determine the protolith and tectonic setting of the amphibolites.

The Henrys Lake mountains amphibolites are enriched in Cr, Ni and Ti and this is generally indicative of ortho-amphibolites (Leake 1964; Shaw and Kudo,1965). Additionally, Cr/Ni and Sr/Ba ratios are greater than one suggesting an igneous protolith (Gorbachev, 1973). Relict zoning in some plagioclase (epidote cores with plagioclase and quartz rims) also indicates an igneous source.

<u>Rare Earth Element Distribution</u>

The REE patterns exhibited in Figure 31A lack Eu anomalies, and show variable LREE enrichment. A comparison of 31A with Figure 31B shows that the southern Madison Range amphibolites resemble arc-tholeiites in their REE signature. A ridge tholeiitic basalt (MORB) would plot as a straight line, with REE abundances enriched about ten times over those of chondritic meteorites. Sample C-31, collected from Black Mountain, exhibits the greatest LREE enrichment and the least HREE depletion and is similar to andesitic-tholeiite.

While the amphibolites exhibits relict igneous signatures, texturally some of the amphibolites resemble



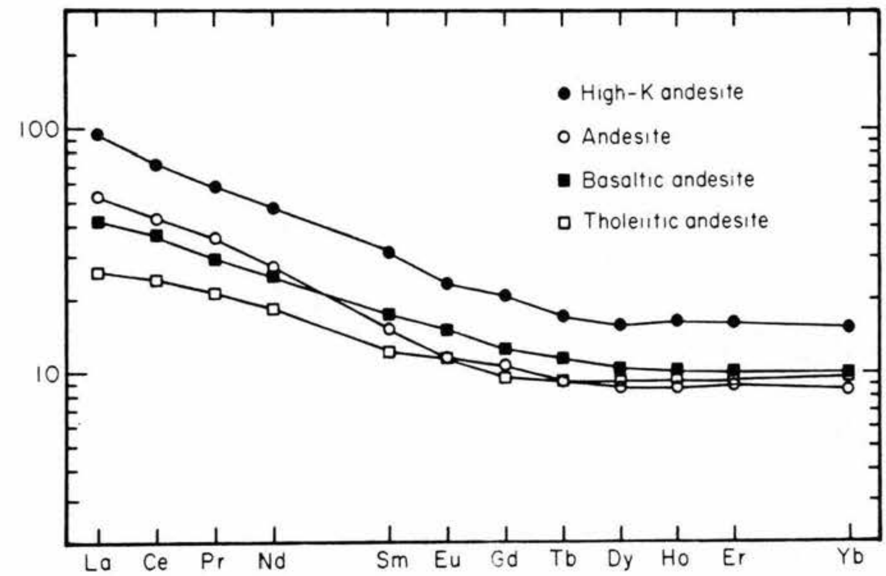


Figure 31. Chondrite normalized REE plots of Henrys Lake amphibolite samples (a) and typical REE patterns for island arc rocks (b) Sundra Arc, Indonesia (Taylor and McLennan, 1986).

sedimentary rocks. For example, the hornblende schists and amphibolites that form the basal portion of the meta-turbidite sequence exhibit interlayering on the millimeter to micrometer scale. Zones of graded plagioclase and quartz blebs (Figure 6) suggest these basal units may represent reworking of flows and ash deposits with mud-stones and greywacke. They may also represent episodic mafic ash accumulation within the turbidites. Bielak (1978) also interpreted some of the Cherry Creek amph-ibolites from the Ruby Range as metasedimentary based on relict pebbles and graded bedding in hornblende schists.

Tectonic Setting

Studies that document the mobility of elements during secondary processes suggest that Ti, Y, Zr, Nb, Ta, Hf, Co, Sc Ce, and REE are elements least susceptible to remobiliz-ation during metamorphic processes (Winchester and Flyod 1979; Condie, 1983). Consequently, Wood and others (1979) developed a ternary discrimination diagram utilizing the immobile trace elements Hf, Ta, and Th concentrations to distinguish magma types erupted in various plate tectonic settings: within-plate basalts, mid-ocean ridge basalts, and basalts formed at converging plate margins. Figure 32 exhibits data for the 4 amphibolite samples analyzed by neutron activation. Two of the samples plot in the E-morb field representing enriched basalts produced in marginal basin or back-arc basalts. Two of the samples

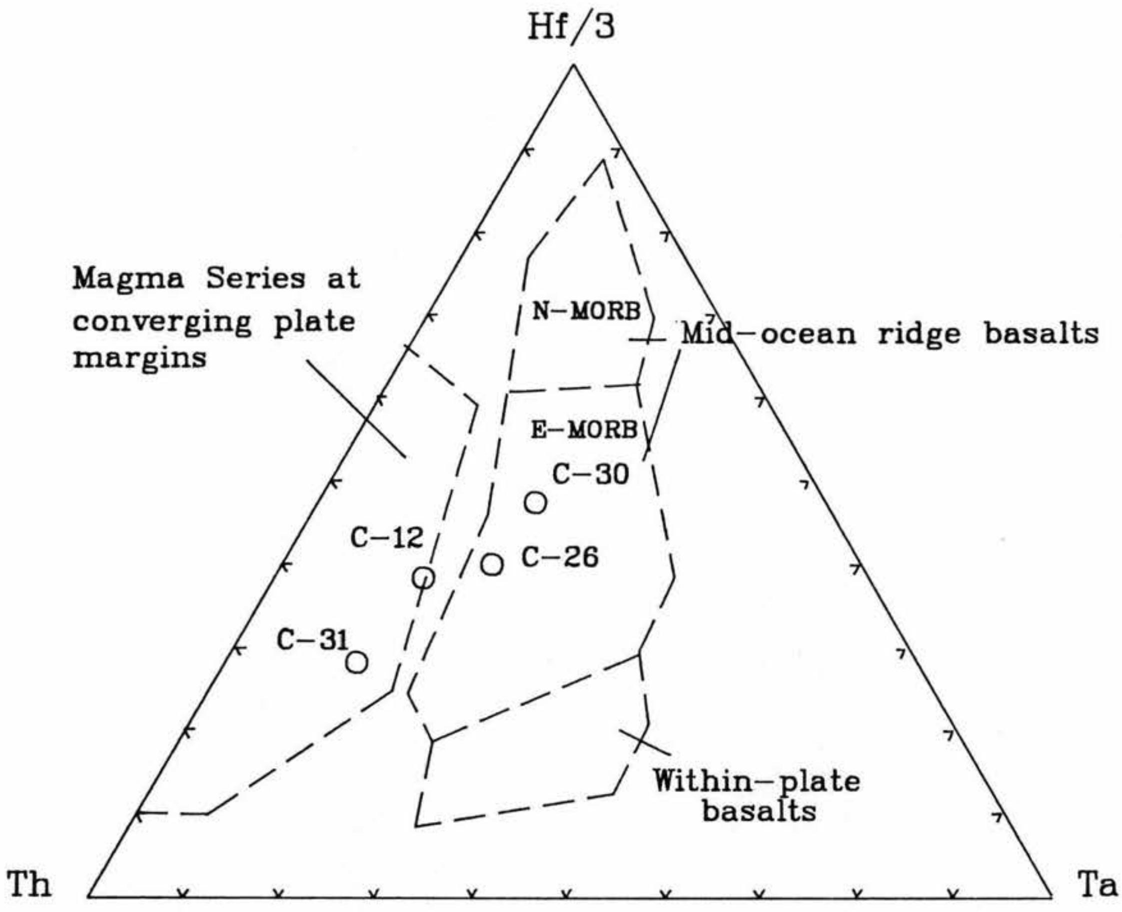


Figure 32. Th-Hf-Ta discrimination diagram with the fields of magma composition erupted in different tectonic environments outlined. (Discrimination diagram from Wood, 1979).

plot in the island arc basalt field representative of magmas erupting at converging plate margins.

Chayes (1965) found that concentrations of TiO_2 less than 2 weight percent characterize volcanic arc basalts while intraplate and MORB concentrations averages are greater than 2 weight percent. This scheme would also place the Henrys Lake amphibolites in a volcanic arc setting.

The meta-basalts are peraluminous, with average Al_2O_3 (14%) greater than CaO+NaO. Relatively high Al_2O_3, Fe enrichment, low alkali and higher Ba concentrations are suggestive of arc-tholeiites (Condie, 1983). Additionally, light REE enrichment patterns like that in Figure 25A are more typical of arc-tholeiites than ridge-tholeiites. High concentrations of Cr and Ni may indicate a high degree of partial melting of the mantle source area (Condie, 1983). The major and trace element geochemistry suggest the amphibolites represent meta-basalts, possibly arc-tholeiite that formed in an arc or back-arc marginal basin adjacent to a convergent plate setting.

CHAPTER 8

TECTONIC INTERPRETATIONS

Introduction

Recent advances in Phanerozoic tectonics have led to a plethora of plate tectonic models for the Archean basement of southwest Montana. The application of Phanerozoic tectonic models to Archean petrogenetic environments remains controversial because of an average heat flow up to 5 times that of the present may have modified tectonic processes (Abbott and Hoffman, 1984). Additionally, Archean petrogenetic environments tend to lack clear evidence of blueschist facies assemblages, chaotic melange terrains, clear cut paired metamorphic belts and andesitic rocks. The general absence or obscurity of sequential petrotectonic assemblages from trench, arc-trench gap and back-arc basin have led to uncertainty in Archean tectonic models.

Abbott and Hoffman (1984) and Condie (1983) argue that Archean and Phanerozoic tectonic regimes differ only in degree and not fundamentally in nature. They postulate increased subduction rates of hotter oceanic crust along shallower Benioff zones. Pioneering studies (Hoffman, 1980; 1984; 1988) in the Canadian shield have extended modern tectonic regimes to the Precambrian. Evidence suggests either the opening and closing of an ocean basin (Hoffman, 1980) or back arc basin (Hoffman, 1988) for the deposition of the Coronation Supergroup. Similarly, evidence for an early Proterozoic volcanic arc succession, rifting, and arc-continent collision is suggested by several workers along the Cheyenne Belt in the southern Wyoming Province (Karlstrom et al., 1984; Condie, 1982) The extension of plate tectonics into the Precambrian is probably viable; however, rarely do natural geologic features reflect the ideal tectonic setting due to changes in tectonic regime through time.

Very few tectonic analogs have been developed for Archean carbonate bearing shelf associations within gneiss belts. The stratigraphy and the structural relationships of the carbonate bearing Cherry Creek Metamorphic Suite in the Southern Madison Range provides important constraints on the framework of Archean tectonic regimes in the northwestern Wyoming Province.

Previous Tectonic Interpretations of Southwest Montana

Fountain and Desmarais (1980) suggested that a major continental suture zone should be apparent in the pre-Belt of southwest Montana based on extrapolation from the Wabowden terrane of Manitoba. Erslev (1981) hypothesized that the Madison Mylonite Zones may be similar to the structural boundary between the Superior and Churchill Provinces based on similar metamorphic conditions between the Superior-Churchill boundary. He suggested (Erslev, 1981) that the boundary between the Churchill and Superior Provinces must be limited to the subsurface northwest of the Madison Mylonite Zone if it crosses Montana. Erslev (1982) concluded that the Madison Mylonite Zone does not represent a major continental suture because metasediments can be correlated across the shear zone.

Wilson (1981) proposed that the mixed lithologies of the Cherry Creek Metamorphic Suite in the Tobacco Root and Ruby Ranges represent an accretionary prism and trench-fore-arc environment analogous to the Mesozoic Franciscan Formation and Jurassic Great Valley Sequence respectively. Wilson does not explain why chaotic melange (composed of ophiolitic slices, exotic blue schist pods, and other dismembered trench sediments), which is so characteristic of accretionary prisms (e.g., Franciscan Formation; Aalto, 1982; Blake, 1974; Cowen et al., 1971), is missing in the Cherry Creek sequence. Additionally, fore-arc sediments are typically deposited on an ophiolitic basement (Dickenson and Seely, 1979) and there no evidence for ophiolites in the Cherry Creek Metamorphic Suite sequence.

To the contrary, evidence suggests that the Cherry Creek Metamorphic Suite rests unconformably on the granitic Pre-Cherry Creek Metamorphic Complex (Erslev, 1983). Shelf deposits are rarely deposited directly on pre-existing continental basement in fore-arc settings. However, in equatorial positions, carbonate and non-volcanic sediments may be deposited directly on evolved arc massifs in marginal re-entrant regions (e.g., Mentawai Trough, Dickenson and Seely, 1979).

Thurston (1986) proposed a suspect terrane model (Coney et al, 1980) for the Beartooth Range for metasediments with geochemical affinity with the Cherry Creek Metamorphic Suite meta-turbidites (Table 4). Thurston suggested that differences in major element and trace element signatures and structural style (Mogk, 1984) between the South and North Snowy blocks as evidence for the suspect terrane model. The South Snowy block chemistry is very similar with the eastern Beartooth metasediments; however, Thurston suggests these similarities are "coincidental". In contrast to Thurston's hypothesis, regional geochemical correlation in Table 4 demonstrates that there are more similarities than differences in metasediment geochemistry across the northwestern Wyoming Province. The almost singular major element geochemical signature of metasediments with Cherry Creek affinity (Table 4) argues against a suspect terrane model.

Additionally, differences in metamorphic grade and structural style do not necessarily lend support to a suspect terrane model. Differing metamorphic conditions, changes in depositional environment, and differing structural styles are diachronous and complex across an orogen as is documented in the Klamath Mountain Orogeny in California (Davis et. al., 1965; Worrall, 1981).

Several workers propose collisional and accretionary events in the northwestern part of the Wyoming Province during the Late Archean (Mogk et al., 1988; Mueller, 1985). Mogk and others (1988) suggest that the Beartooth Mountains and probably all the northern Wyoming province, was the site of a Late Archean collisional orogeny that occurred along the margin of an older continent (3.4-3.2 Ga).

Mogk and others (1988) suggest the aggregation of seven major lithologic units in the North Snowy Block after the separate, main-stage metamorphic and/or deformational events that affected each unit. All the units are Archean in age and they suggest the terrane aggregated between 2.74 and 2.56 Ga ago. They conclude that the North Snowy block represents the major suture zone between two fundamentally distinct terranes, a younger plutonic terrane (Beartooth Arc) versus an older supracrustal terrane. However, the metasediments in the Snowy Block of the Beartooth Mountains and the southern Madison Range suggest the metasediments can be correlated across the shear zone making it unlikely that this area represents a major suture zone.

Tectonic Setting and Depositional Environment

Based on the vertical stratigraphic sequence, (Figure 4) regional stratigraphic correlation (Figure 33), and lateral facies transitions (Erslev, in press), I propose that the Cherry Creek sequence is most consistent with a

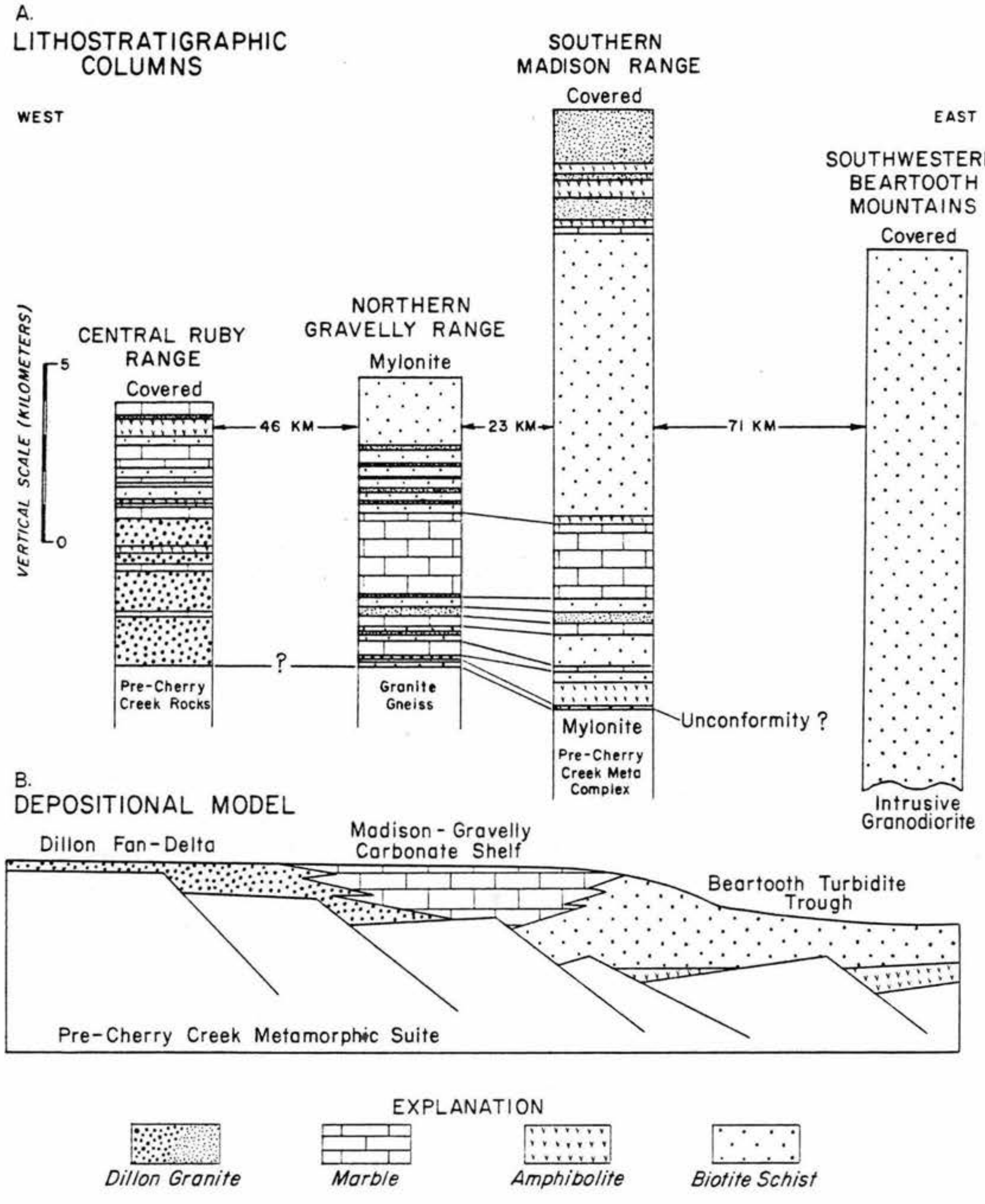


Figure 33. Regional lithostratigraphic correlation and depositional model of the Cherry Creek Metamorphic Suite. (From Erslev, in press).

back-arc basin depositional setting (e.g., Sea of Japan marginal basin; Figure 34). A narrow marginal basin between an arc and continental margin (ie. Sea of Japan) is one environment where miogeoclinal shelf associations dominate the continental side of the basin and merges laterally with turbidites and volcaniclastic sediments toward the arc. The lithologic sequence in shelf association depends on the size of the marginal sea (Condie, 1983), the rate of subsidence, latitude, the lithology of the adjacent continental crust, and relative influence of arc sedimentation (Karig and Moore, 1975).

Sedimentation in basins adjacent to continents or to very large evolved arcs is strongly affected by continental terrigenous sources (Karig and Moore, 1975). High K_2O/Na_2O ratios and an apparent Eu anomaly (sample M-10) are consistent with a K-rich granite in the source area, or evolved continental crust. Additionally, the conglomerate at the base of the Cherry Creek Metamorphic Suite contains clasts of the Pre-Cherry Creek Metamorphic Complex (Erslev, 1983), directly supporting deposition of the Cherry Creek Metamorphic Suite on an older basement complex. Trace element geochemistry of the meta-turbidites suggests they were deposited in a continental island arc setting, with felsic volcanics also in the source area (Bhatia and Crook, 1986).

The vertical sequence of the Cherry Creek Metamorphic Suite, based on regional stratigraphy and stratigraphic

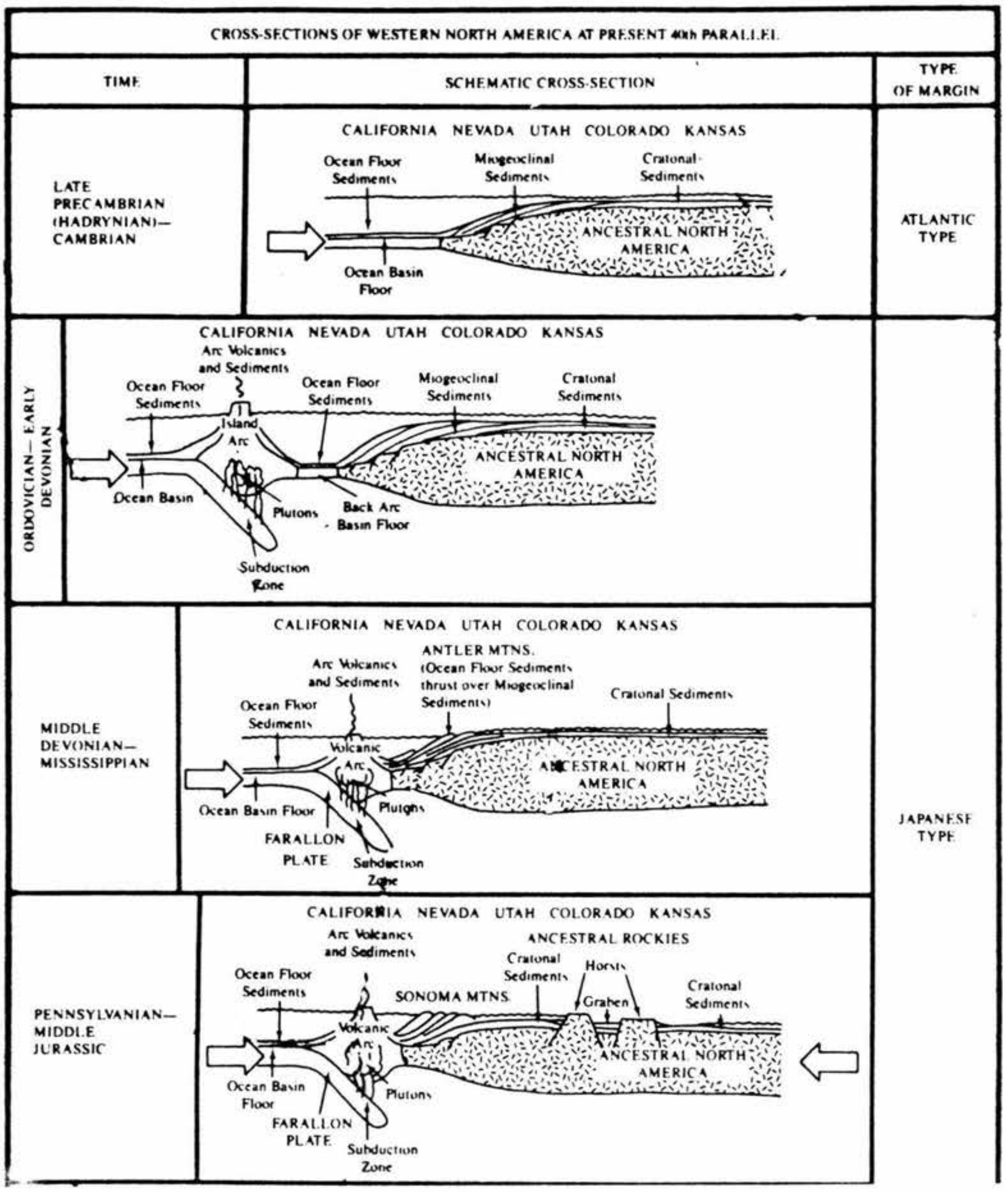


Figure 34. Sea of Japan style continental island-arc. Cross-sections illustrating the geologic history of the southwest margin of the Cordilleran. Note the progressive closing of the marginal sea from the Devonian through the Middle Cretaceous. (From Mintz, 1981).

tops in the Henrys Lake Mountains, reflects a subsiding basin, or transgressive assemblage, where turbidites and volcaniclastics overlie carbonates (Figure 35). Laterally facies changes indicate an increase in turbidite thickness and iron-formations toward the east in the Beartooth Mountains (Thurston, 1987; Erslev, in prep.). This may suggest the basin increased in depth toward the southeast.

The regional structural model (Fig 26) suggests tectonic thickening along imbricate thrusts with vergence toward the northwest. Thus, the increase in offshore facies up section may be both structurally and stratigraphically controlled.

Late Archean deformation and shortening of the Cherry Creek is most likely related to some form of accretionary tectonics such as the closing of the marginal basin and associated collisionary tectonics (Figure 36). An ancient analog of this would be the closing of the Ordovician-Early Devonian marginal sea along western North America during the Antler Orogeny (Figure 34). Later during the Nevadan Orogeny (Jurassic), the back-arc marginal sea basin finally closed and eugeoclinal sediments were thrust over thick carbonate bearing miogeoclinal sediments with vergence toward the foreland or continental interior (Dickenson and Seely, 1979; Burchfiel and Davis, 1975; Schweickert, 1981). This may be analogous with the thrusting of the Cherry

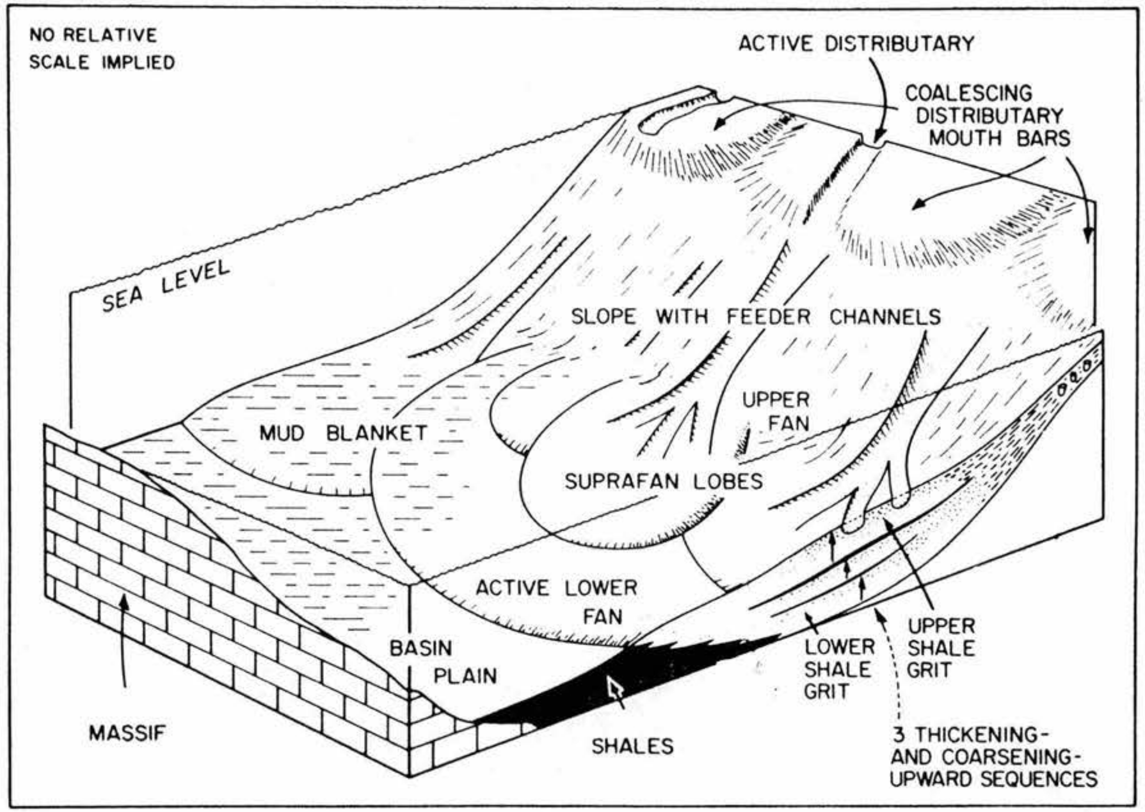


Figure 35. Schematic block diagram showing depositional relationship of different sedimentary units along turbidite troughs. (From Walker, 1978).

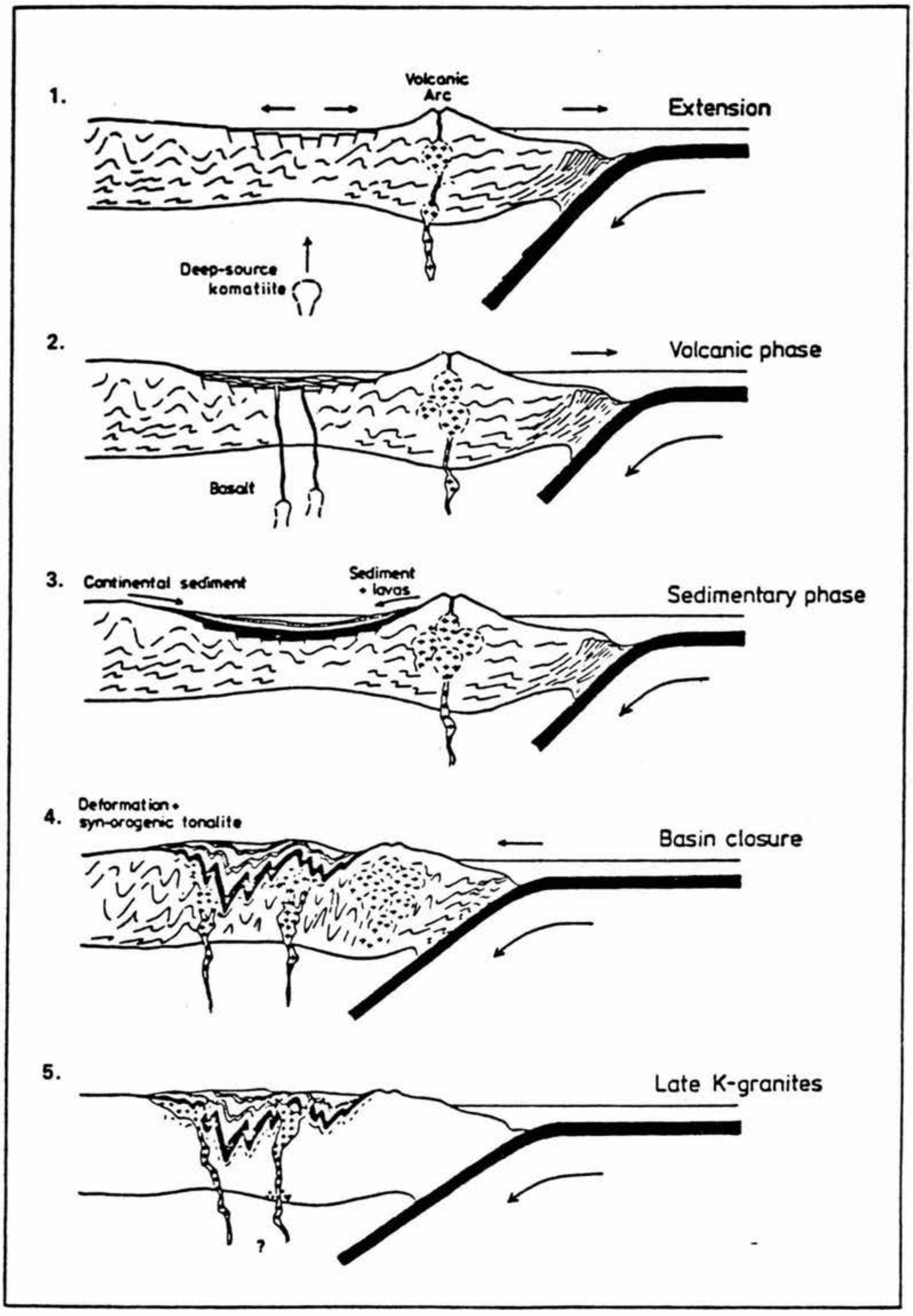


Figure 36. Evolutionary development and deformation associated with a back-arc basin tectonic setting. (From Tarney et al., 1976).

Creek Metamorphic Suite toward the Pre-Cherry Creek continental margin to the northwest.

Although marginal basins are initially zones of extension and sediment accumulation, the evolution of most of these zones suggest later contractional deformation along fold-thrust belts due to migration of the arc-subduction complex (Dickenson and Seely, 1979; Hoffman, in prep.; Burchfiel and Davis, 1975; Schweickert, 1981). Hoffman (in prep.) proposes that Walther's law may apply to active continental margins and the associated igneous rocks. He proposes that long accretionary progradation or outbuilding of a fore-arc region will ultimately cause magmatic intrusions (prograding-arc material) into fore-arc sediments. With continued progradation, accretion, and the closing of the marginal basin both fore-arc and back-arc regions may be variably effected by magmatism and intrusion.

The Cherry Creek Metamorphic Suite then, may be interpreted as a continental or evolved arc margin suite that has undergone significant crustal shortening akin to foreland fold and thrust belt development. The closing of a marginal basin, with thrusting of shelf/continental margin along a pre-Cherry Creek margin during the Beartooth Orogeny (2.7 Ga) may explain the structural geometry found in the Henrys Lake Mountains portion of the Southern Madison Range.

CHAPTER 9

GEOLOGIC HISTORY AND CONCLUSIONS

Geologic History

The following geologic history is based on structural data from this study and previous work, geochemistry, and recent age determination. In outline form, the chronology is as follows:

1. Deposition of the Cherry Creek sediments, a dolomite-quartzite-greywacke-volcaniclastic assemblage, adjacent to a continental margin in a back-arc basin. Preliminary analysis of detrital zircons in Cherry Creek quartzites suggests an aggregate provenance age greater than 3.0 Ga (Mueller, 1987, personal com.).

2. Deformation of the meta-sedimentary assemblage during a compressional orogenic event associated with an actively converging plate margin. Bulk shortening and tectonic thickening of the Cherry Creek Metamorphic Suite was accommodated by thrust imbrication and duplex stacking. A 2.7 Ga minimum metamorphic age for an early thermal event is indicated by ^{40}Ar-^{39}Ar (Erslev and Sutter, in prep.). This Late-Archean thermal event is synkinematic with early shear zone development. The term Beartooth orogeny has been tentatively applied to a similar Late-Archean event in

southwest Montana (Skinner et al., 1969; James and Hedge, 1980) and may be applicable for this deformation event.

3. Intrusion of granodioritic sills (2.58 Ga Ub-Pb zircon analyses; Shuster and others, 1987) occurred late to syn-kinematically with middle amphibolite facies metamorphism.

4. Proterozoic deformation is characterized by the development of retrograde, epidote-amphibolite facies assemblages along reactivated shear planes, with overall southeast vergence suggested by fabric data from the Madison mylonite zone (Erslev, 1983). Thrusting of the Pre-Cherry Creek Metamorphic Complex over the Cherry Creek Metamorphic Suite occurred along a northwest dipping shear zone that represents a major non-conformable tectonic contact of Early-Proterozoic age (Erslev, 1981). Intrusion of diabase dikes may have occurred at this time.

5. Intrusion of diabase dikes and sills between 1.45 Ga and 1.12 Ga (Wooden et al, 1978) occurred with many of the sills intruding parallel to northeast trending shear zones. Lack of penetrative fabric in the diabase dikes and sills suggests relative stability of the terrain by the Late-Proterozoic.

<u>Conclusions</u>

1. This study documents the earliest stage of deformation in the Cherry Creek Metamorphic Suite during 2.7 Ga middle-amphibolite facies metamorphism. The complex

map pattern is partially the result of a tectonic duplication. Duplication of Cherry Creek lithologies toward the southwest is the result of Archean thin-skinned thrusting along a series of concordant, generally southeast-dipping mylonites zones. Increases in individual unit bulk thickness in the northeastern units is the result of intraformational fold thickening, forming zones of opposing facing directions and isoclinal folding.

Strain analysis of psammitic portions of meta-turbidites indicates largely flattening strains and bulk shortening of the Cherry Creek Metamorphic Suite. However, mylonitic zones contain plane strain fabrics consistent with ductile shearing. Fabric asymmetries reveal reverse (high-angle thrust) motion along these southeast-dipping mylonite zones with northwest tectonic transport. Prograde mineral growth lineations parallel fold axes in zones of shear folding and suggest mineral growth (middle-amphibolite facies metamorphism) concurrent with deformation.

2. Based on relict sedimentary textures, lithologic associations and geochemical signatures the tectonic environment and depositional setting of the Cherry Creek Metamorphic Suite is most consistent with a continental island arc setting (e.g., Sea of Japan). The Cherry Creek sediments were most likely deposited in a shelf setting on an older basement along a continental margin. Terrigenous input is dominantly felsic, with a K-rich granitic sources.

3. This study has important implications for crustal development of the northwestern Wyoming Province. This study supports the idea that southwest Montana accreted to the Wyoming Province during the 2.7 Ga Beartooth Orogeny. The Cherry Creek Metamorphic Suite has undergone significant crustal shortening and tectonic thickening by thrust imbrication and duplex stacking. This thin-skin deformation is closely analogous to many post-Archean convergent belts suggesting similar tectonic processes during the Archean.

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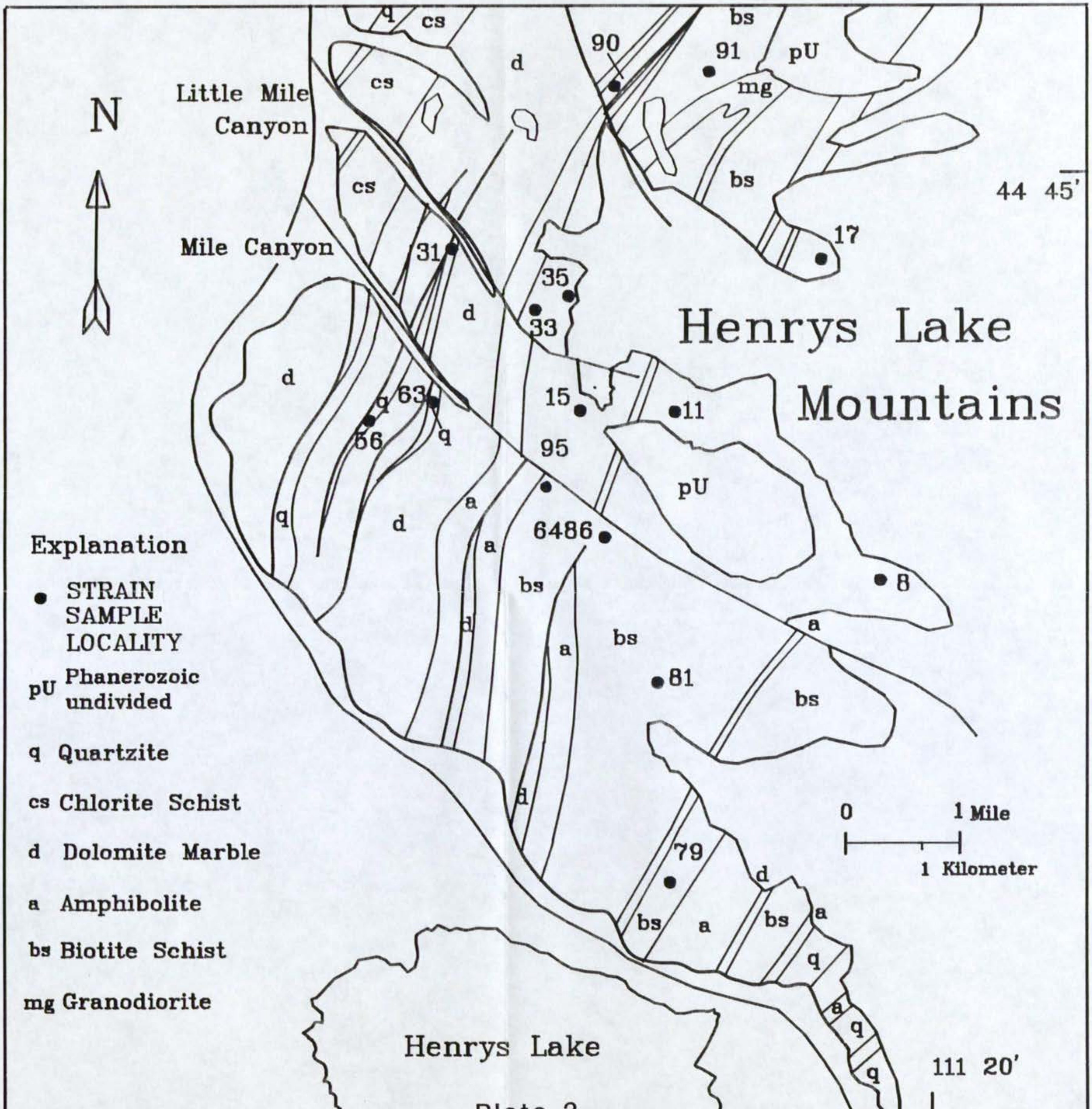
Geologic Map of the Archean Cherry Creek Metamorphic Suite in the Henrys Lake Mountains, Southern Madison Range
Wendy Sumner
Modified from Witkind, 1979 and Erslev, 1983
Scale
1:24,000
EXPLANATION
Q Quaternary Sediments
Ph Phanerozoic undivided
Precambrian units
(Sequence does not necessarily indicate age relationships)
di Diabase dikes and sills
mg Meta-granodiorite
bs Biotite-Schist (compositional changes indicated within unit on map)
a Amphibolite
d Dolomite Marble
cs Chlorite-Hornblende Schist
q Quartzite
Structural Symbols
Contact; dashed where inferred; Quaternary contacts smaller
High angle fault
Mylonitic thrust
Strike and dip of foliation
Small scale fold
Numerous minor folds and style indicated
Hebgen Dam Quadrangle
Henrys Lake Quadrangle
MADISON RANGE FAULT
HENRYS LAKE
SPILLWAY ELEVATION 6472
Sheep Mtn
Coffin Mtn
Coffin Lakes
Targhee Peak
Black Mtn
Raynolds Pass
Clark Lake
Edwards Lake
Bald Peak
MONTANA
IDAHO
TARGHEE NATIONAL FOREST
44°45'
111°20'

Plate 1


Little Mile
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1 Mile
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81
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cs
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bs
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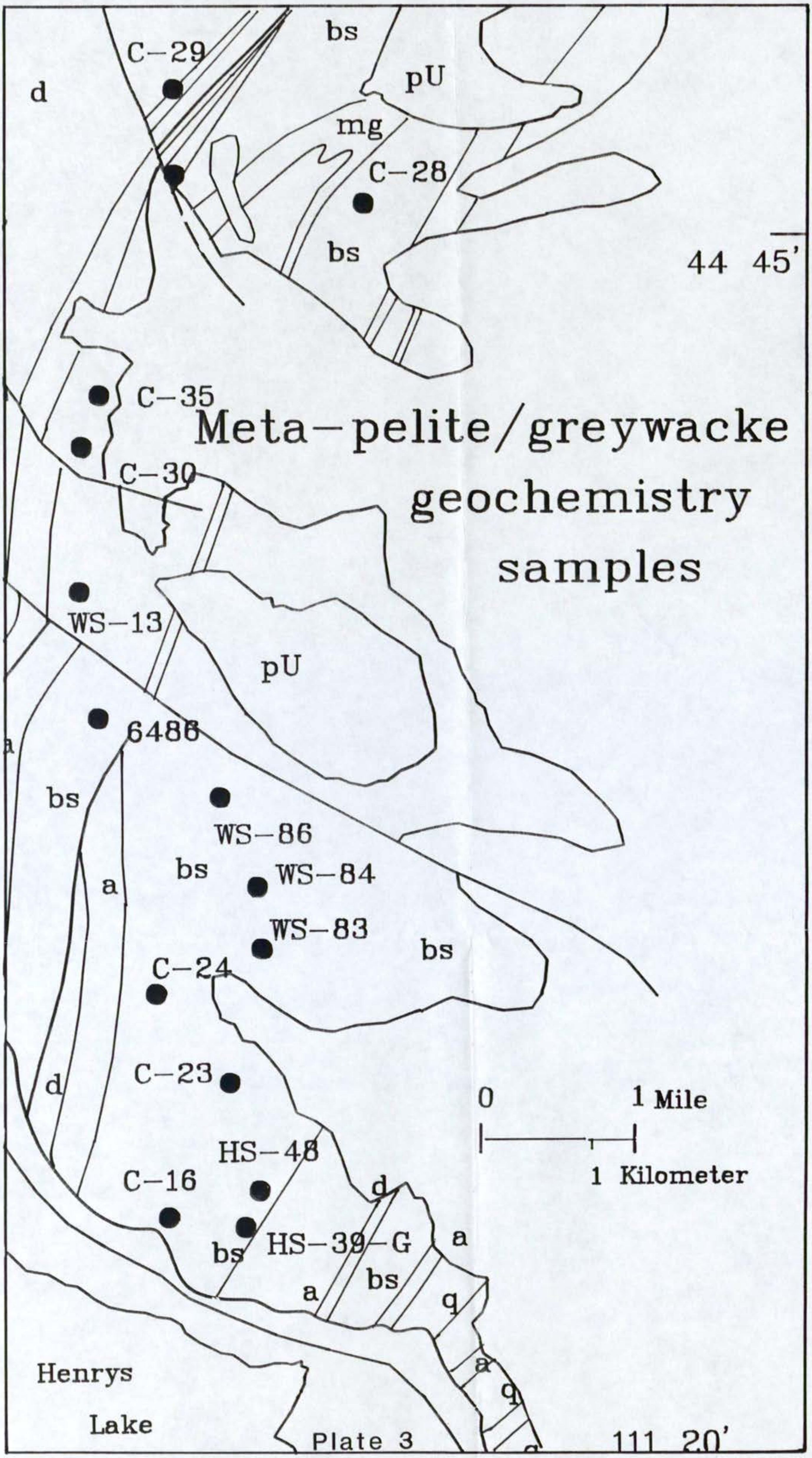
a
Explanation
STRAIN
SAMPLE
LOCALITY
pU Phanerozoic
undivided
q Quartzite
cs Chlorite Schist
d Dolomite Marble
a Amphibolite
bs Biotite Schist
mg Granodiorite

Plate 2


Meta-pelite/greywacke geochemistry samples
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WS-13
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6486
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a
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bs
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0
1 Mile
1 Kilometer
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Henrys
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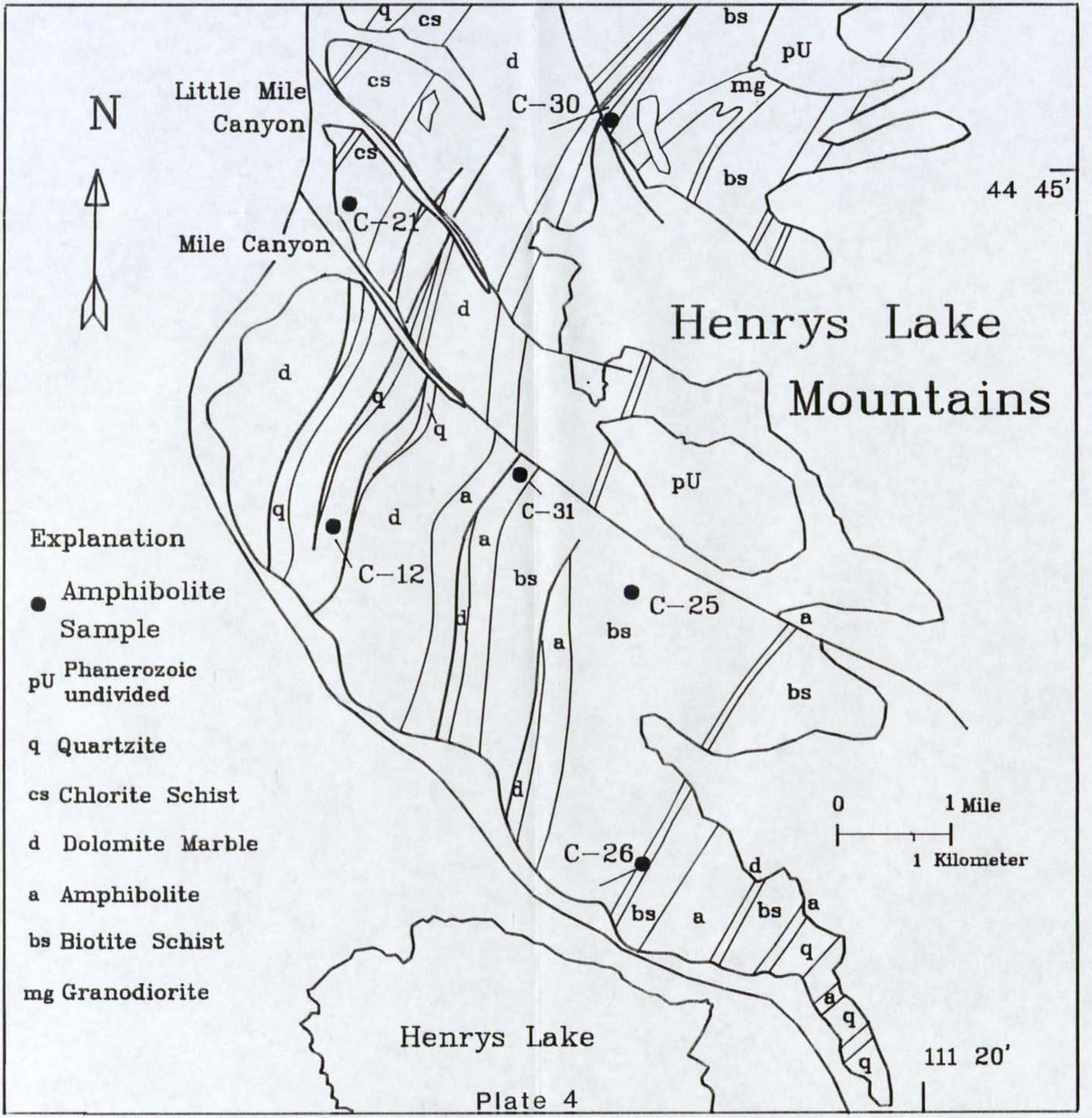
Plate 3
111 20'



N
Little Mile Canyon
Mile Canyon
Henrys Lake Mountains
Henrys Lake
C-30
C-21
C-31
C-12
C-25
C-26
44 45'
111 20'
0
1 Mile
1 Kilometer
q
cs
d
bs
pU
mg
a
Explanation
Amphibolite Sample
pU Phanerozoic undivided
q Quartzite
cs Chlorite Schist
d Dolomite Marble
a Amphibolite
bs Biotite Schist
mg Granodiorite

Plate 4