INTRODUCTION

Laramide uplift of the southern Gravelly Range of southwestern Montana exposed anomalously low-grade Precambrian metamorphic rocks. In the central Gravelly Range metamorphism ranges from greenschist to lower amphibolite facies, while basement rocks in adjacent Laramide uplifts to the north and west have been metamorphosed to upper amphibolite and granulite facies (O’Neill, et al., 1988; Cheney et al., 2004; Brady et al., 2004; Vargo, 1990; Erslev and Sutter, 1990) (Fig. 1). Within the Gravelly Range, the low grade metamorphic rocks abut sillimanite schists to the north and staurolite schist to the south (Vargo, 1990). This work uses structural style, petrography, and field relationships to constrain possible protoliths and tectonic settings of the rocks of the central Gravelly Range. In doing so, it puts the central Gravelly Range in context with models for the Big Sky orogeny as defined by Harms et al. (2004).

PETROGRAPHY AND POSSIBLE PROTOILITHS

The rocks of the central Gravelly Range are metasedimentary and meta-igneous. Petrography was determined by analyzing thirty thin sections with a petrographic microscope, and five with a scanning electron microscope, as well as from field observations. There are four major rock groups:

1) Metasedimentary, non-volcaniclastic rocks, predominately meta-banded iron formation, quartzite, black phyllite, and minor muscovite-chlorite-biotite schists. The meta-banded iron formation is distinguished by laterally continuous outcrops up to ten of meters thick with parallel 1-10 cm thick layers of alternating aphanitic magnetite rich rock and quartz rich rock. Quartzite consists of 70-90% quartz with 10-20% biotite and/or muscovite, +/- plagioclase, +/- microcline. Polycrystalline
quartz grains are common and accessory minerals include ilmenite, zircon, and monazite. Hand samples range from grayish white in less-deformed rocks to emerald green in shear zones. Original crossbedding is preserved locally. Phyllite outcrops in the central study area primarily as one continuous sequence (Fig. 2). It varies in color from dull dark brown to dark green to black. The fabric is defined by aligned fine grained micas less than 0.01 mm in diameter that are difficult to resolve even with the scanning electron microscope. Asymmetric biotite and chlorite porphyroblasts are common as are elongate grains of rutile.

Muscovite-chlorite-biotite schists are the least abundant unit, and occur structurally directly above and below the northern mafic body (Fig. 2). They are characterized by medium brown color and muscovite and/or chlorite flakes easily visible in hand sample. The muscovite and/or chlorite porphyroblasts overprint strong fabric defined by biotite and/or chlorite. These porphyroblasts are most likely the result of the retrograde reaction: biotite + water ⊆ muscovite + chlorite (Spear, 1993). The most likely protoliths for the metasedimentary sequence are iron formation, sandstone, mudstone, and greywacke or paleosol.

2) Actinolite-chlorite-quartz schist, consisting primarily of quartz (50-70%) and strongly aligned chlorite (30-50%), with varying amounts of actinolite and minor albite. Compositional banding is poor; quartz and chlorite are close to evenly distributed. Actinolite occurs in bundles of radiating acicular grains subparallel to foliation. Average grain size is 0.1-0.5 mm. The greenschist has several possible protoliths, including altered basalt, epiclastic deposits, or calcareous shale.

3) Fine grained massive zoisite amphibolite, consisting of 30-60% actinolite, up to half now altered to biotite, 20-50% plagioclase, and <5-40% zoisite. These rocks occur as discontinuous pods less than 5 m across in the phyllite of the

Figure 2. Schematic map representation of study area showing location of northern, central, and southern areas, as well as distribution of rock types, and local structural features.
central study area, and as laterally continuous units surrounding the northern mafic body (Fig. 2). The size, shape of the outcrops, and massive fabric are all suggestive of shallow intrusive origins. Whole rock geochemical analyses from the central study area demonstrate that the protolith has a tholeiitic basaltic andesite composition (Siegel, this volume).

4) **Heterogeneous amphibolite** with variation in grain size, mineral assemblage, and fabric along and across strike over distances of less than ten meters. Mineral assemblages range from garnet + ferrotetchmakite, to biotite + actinolite, to zoisite + actinolite. The greatest variation occurs in the zoisite + actinolite rocks where actinolite ranges from 15-80%, grain size ranges from 0.01 to 2 mm, and fabric ranges from mylonitic to massive. There are several possible protoliths. These include volcaniclastic deposits, variably metamorphosed intrusive bodies, or multiple generations of intrusion and/or volcaniclastic deposits.

**FIELD RELATIONSHIPS**

The study area can be broadly divided into three lithologically distinct regions (Fig. 2). In the northern area there are approximately equal amounts of banded iron formation, quartzite, and amphibolite, with lesser amounts of phyllite and muscovite-chlorite-biotite schist. Amphibolite occurs primarily as one horizon that outcrops discontinuously across strike for 200 m. The upper and lower contacts are fine grained and massive, and amphibolite toward the center of the unit varies greatly in grain size and fabric. The central area is predominantly phyllite with minor amounts of quartzite and isolated pods of fine grained massive amphibolite. The southern area is predominately amphibolite with smaller amounts of actinolite-chlorite-quartz schist. The largest and most heterogeneous mafic body is in the southern section, extending at least one km across strike. Actinolite-chlorite-quartz schist is found structurally between the phyllite of the central section and the larger mafic body.

Extent of recrystallization is lowest in the north and greatest to the SE. In the north crossbedding in quartzite and pillows in metabasalt are preserved. In the actinolite chlorite quartz schist and the phyllite farthest to the southeast, there are multiple crenulation cleavages and doubly folded open folds. There is also a gradational increase in actinolite growth in the actinolite chlorite quartz schist to the southeast.

**STRUCTURAL ANALYSES**

The rocks of the central Gravelly Range are a northwest dipping homoclinal sequence (Fig. 3). Crossbedding in the northern and central area is all right side up, suggesting that isoclinal folding, if present, is not extensive. These results are consistent with the work of Vargo (1990). Broad open sinusoidal folds with wavelengths up to ten times amplitude are common, ranging in scale from 1-30 m in wavelength. There are at least two nearly perpendicular fold axes that create 0.5 to 1 m dome-shaped interference patterns and occur in conjunction with multiple overlapping crenulation cleavages. These were primarily observed in the phyllite farthest to the southeast and in the actinolite-chlorite-quartz schist (Fig. 2). In some banded iron formation outcrops in the north there are at least two crenulation cleavages, and compositional banding is folded into tight overturned similar folds.

Shear zones occur in discontinuous bands throughout the study area and are seen in all rock types. These are recognized in the field by increased mineral lineations, increased quartz veins, asymmetric foliations, visible augen, and/or elongate quartz pencils. Throughout the study area mineral lineation trends to the northwest (Fig. 4a). Five oriented thin sections were cut perpendicular to foliation and parallel to lineation and analyzed for kinematic
indicators. S-C fabrics were found in quartzite, and asymmetrically mantled porphyroblasts in phyllite. Four of the five thin sections studied indicate reverse sense of shear. These results are consistent with the work of Vargo (1990).

**DISCUSSION AND TECTONIC SETTING**

Following O’Neill (1998), this study concludes that the most likely original tectonic setting for the central Gravelly Range is a foreland basin. O’Neill (1998) recognized similarities between the low grade rocks of the Gravelly Range and Proterozoic foreland basins of the Canadian Shield, described in detail by Hoffman (1987). Proterozoic foreland basin deposits are fundamentally different from their modern equivalents in two ways: they are characterized by outer ramp deposition of banded iron formation and there is abundant mafic magmatism (Hoffman, 1987).

![Figure 3](image3.png) Equal area lower hemisphere stereoplot of poles to foliation showing northwest dipping homoclinal sequence. N=83. Mean foliation is 230/54 and is shown by dashed great circle.

![Figure 4](image4.png) A. Equal area lower hemisphere stereoplot of mineral lineations throughout study area. N=43. Mean lineation is 54/306. B. S and C fabric in deformed quartzite. Both fabrics are defined by concentrations of aligned biotite. Biotite in the C fabric is slightly darker and the alignment is discontinuous. The S fabric occurs is more penetrative and is parallel to the long axes of stretched quartz. C. Asymmetric quartz pressure shadows on opaque minerals in deformed phyllite suggest clockwise rotation.
The banded iron formation, black phyllite, and quartzite observed in this study are consistent with a sediment starved basin receiving moderate amounts of mature clastic sediment. Amphibolite bodies in the north and central study area are interpreted to be gabbroic sills, and meta-pillow basalt in the north to be the associated submarine volcanics. Reverse faulting documented here and by Vargo (1990) are interpreted to be the result of the progradational nature of thrust-belts that incorporate their own foreland deposits as they advance. Multiple crenulation cleavages and fold axes indicate an ongoing metamorphic history that could have occurred as the foreland basin became involved in collision.

REFERENCES CITED

Brady, J.B., et al., 2004, \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of metamorphic rocks from the Tobacco Root Mountains region, Montana, in, Brady, J.B., et al., eds., Precambrian Geology of the Tobacco Root Mountains, Montana: Geological Society of America Special Paper 337, p. 131-149.


