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INTRODUCTION

Through collaborative field and lab work, the 2010-2011 Montana Big Sky Keck Project hopes to discover a better understanding of the metamorphic, structural and geochronologic histories of the Precambrian metamorphic rocks that make up the field area in the Henrys Lake Mountains as they evolved through the late history of the Wyoming province. In doing so, the project seeks to understand if, and how, these histories vary across the field area and how they fit into a regional context. Erslev and Sutter (1990) studied the metamorphic and structural history of the Madison mylonite zone outside of the Keck field area to the northeast. Similar mylonites along strike in the Keck field area, both within and beyond the areas mapped as Madison mylonite zone, have not been studied in detail. Through kinematic analysis, this project hopes to determine whether these mylonites have or have not experienced the same history as the mylonites of the Madison mylonite zone.

Many questions can be asked about the specific histories of the mylonites within the field area. These include: Do the mylonites vary across the field area and if so, how? Are all the mylonites of the study area related to the Madison mylonite zone, or are some related to a different phase of deformation? What do mylonite mineral assemblages tell us about the pressures and temperatures the mylonites experienced at the time of formation? What large and small scale structures exist in the field area? How do these same structures fit within the regional geologic history of the study area? What is the sense of shear in the mylonite zones and what is the regional transport direction? From what protolith did these mylonites form?

METHODS

During a four week field season, oriented mylonitic rock samples were collected from a wide range of locations within the study area (Fig. 1). In addition to samples, foliation and lineation measurements from the mylonites, were collected in the field. Data from kinematic indicators were collected wherever possible.

Upon returning to Smith College, lineation-parallel, foliation-perpendicular thin sections were cut from all 24 samples. Using a polarizing light microscope, optical techniques were used to identify mineralogy and any kinematic indicators present in the sample suite. In addition, some work was done on the Scanning Electron Microscope (SEM) to determine more precise mineral compositions. Once kinematics were determined in thin sections, the samples were reoriented and shear sense was determined in real space.

PETROGRAPHIC AND PETROLOGIC RESULTS

A range of textures occurs in the study samples, therefore textures have been ranked (Fig. 1) from 1, highly brittle cataclasites, to 2, protomylonites to 3, ductile mylonites. Rocks with cataclasitic textures, ranked with a degree of deformation of 1 (Fig. 1, Sample 10-AW-23B), are composed of a complex of altered, broken grains of mafic minerals, feldspar, and quartz, in a matrix of chlorite, biotite and other alteration minerals. These rocks contain few to no kinematic indicators. More of these rocks were found in the southwestern field area (Figure 1: stations 13 and 23). In other cases, such as, but not unique to, station 3, samples with brittle textures (such as 10-AW-3C) appear to represent the edge of a shear zone. More
Figure 1. Study area sample location map, showing the degree of deformation denoted on a scale of 1 to 3, and lineation orientation of each sample. Each diagnostic sample is accompanied with a D for top down or U for top up sense of shear determined from each sample. Photomicrographs show examples of each grade of deformation. Based on USGS 3D scaled topographic quadrangle maps: Earthquake Lake, Cliff Lake, Hidden Lake Bench, Targhee Peak, Targhee Pass, Mount Jefferson, Sawtelle from http://www.arcgis.com/home/ with a scale of 1:86,439.
ductilely deformed samples (such as 10-AW-3A and 10-AW-3B) also occur.

Rocks that represent the mylonitic end member, Texture 3, are found in the centers of shear zones. These rocks range in composition, but are predominantly quartzofeldspathic rocks with muscovite, biotite, some chlorite and some small percentage of mafic minerals. They have well developed foliations and shear bands and can contain diagnostic kinematic indicators. Pressures and temperatures in these rocks were such that quartz was able to flow and dynamically recrystallize, but feldspar was left undeformed or broken in response to strain. In many of these rocks there are particles with multiple mineral grains, possibly once representing lithic fragments, here referred to as lithoclasts, commonly with well formed tails and surrounded by comparatively fine grained micaceous matrix. These lithoclasts commonly contain large amounts of symplectite. In contrast to the quartzofeldspathic rocks, some of the mylonites in the field area have low silica content and are predominantly composed of mafic minerals (Samples 10-AW-17 and 10-AW-21).

Yet a third group of protomylonitic like rocks occur within the field area, and are ranked with a degree of deformation of 2 (Fig. 1, Sample 10-AW-1A). These intermediate rocks show both brittle and ductile characteristics. In these rocks, S-fabrics are generally better developed than C-fabrics. Grains are generally angular and rotated into alignment with the shear fabric. Lithoclasts and strain shadow tails are poorly formed. These rocks can be highly altered and contain a higher percentage of mafic minerals forming lithoclasts and matrix than in the more ductile rocks. Distribution of the cataclasites, mylonites, and protomylonites can be seen in Figure 1.

Symplectic texture of quartz intergrown with perthite, composed of orthoclase and pure albite (Fig. 2B) is very prevalent in quartzofeldspathic mylonites studied. In almost all cases where symplectite is absent, quartz and plagioclase are not present or are in very low abundance within the rock. Although this intergrowth can only be seen at thin section scale, it represents up to 80 percent of lithoclast composition in the mylonites, but it is not present in the matrix. It is proposed that symplectite grew as a result of shearing because the symplectite fabric is systematically aligned with relation to orientation with respect to the shear fabric. Although variation in texture exists, wavy lamellae within the symplectite are perpendicular or at high angle to the principal mylonitic foliation. In many cases, entire lithoclasts are formed of individual grains, each made up of symplectite, in which case the symplectite intergrowth is coarser grained at lithoclast boundaries than at the interior of the grain. In cases where only part of a lithoclast has symplectic texture, symplectite is present in all cases at the edge of the lithoclast and not in the center (Fig. 2D, 2E). In many cases, symplectite textures can be seen to curve from high angle to the C-fabric to parallel to the C-fabric the closer to the margin of the lithoclast. As temperatures were not sufficient to allow feldspar to bend or ductilely deform, symplectite must have grown while mylonites were being sheared. In lithoclasts only partially composed of symplectite, symplectite growth typically exists on grain edges that are parallel to the S-fabric, and is not present in the tails of the lithoclast (Fig. 2D, 2E). This pattern of growth (Fig. 2D) with a principal alignment of symplectite wavy lamellae along foliation parallel edges of lithoclasts is believed to result from shearing because the replacement of K-feldspar by symplectite leads to volume reduction in the rock (Simpson and Wintsch, 1987).

In all locations where intermediate intrusives are present, mylonites are also found in localized shear zones. As at Station 3 (fig. 1), a gradual transition within intrusive bodies from mylonite (10-AW-3A) in the center of the zone, to remnant primary igneous texture (10-AW-3C), to apparently intact igneous rock was typical. Where shear zones are present in metagneous bodies, the grain size of the mylonites is always larger than the surrounding metagneous rock.

It is not known whether the same brittle to ductile transition exists for other potential protoliths. Other mylonites are so intensely strained or were initially so fine grained that no obvious protolith could be determined in the field. Despite mylonites’ sometimes quite close proximity to metasedimentary rocks, a gradational transition from metasedimentary rock to mylonites was never observed.
formation. The ductile behavior of quartz accompanied by the brittle behavior of feldspar in quartz-ofeldspathic mylonites also supports this conclusion.

A method of phengite geobarometry, described in Massonne and Schreyer (1987), was applied to Sample 10-AW-1B. As a chemical equilibrium with phengite and the correct limiting mineral assemblage of quartz, K-feldspar and phlogopite is present in the rock (Fig. 2A, 2B), a ratio of 3.2 to 3.3 silicon per formula unit in phengite is interpreted based on the model (Fig. 2C) to give pressure for these rocks of 5 kb (0.5 GPa). This is considered a minimum pressure because of uncertainty about the temperature at the time of shearing. As phengite was identified in symplectite (Fig. 2A) that likely grew during shear, this pressure applies to the time when rocks in Antelope Basin (Fig. 1) were actively accommodating large amounts of strain.

**STRUCTURAL RESULTS**

Several structural trends are clear from analysis of mylonite field data. Mylonitic foliation is closely clustered around a mean of 237/38 (Fig. 3A). Only three measurements do not follow this trend, and those were all taken on the far eastern side of the field area (Fig. 3). If this indicates some large scale overturning or folding within the field area, insufficient data exist to support that conclusion. The NE trending, NW dipping mylonitic foliation in the Madison mylonite zone of the southern Madison Range (Fig 3C) (Erslev and Sutter, 1990) is parallel to mylonitic foliation in the Henrys Lake Mountains (Fig 3A). Mylonitic Lineations are not as closely clustered as foliations, but show a mean vector of 47/304, very similar to that in the Madison mylonite zone (Fig. 4A). In general, lineations are parallel, or close to parallel, to the dip of foliation. Lineations measured in the field were typically white minerals, possibly quartz or feldspar, and elongate black mafic minerals. Plotted separately, (Fig. 4D) both lineation types show similar means. There is little meaningful variation across the field area. For this reason it is believed that all mylonites in the field area are related to the Madison mylonite zone.
KINEMATIC RESULTS

Although variation exists in the data set, kinematic indicators around the field area give a principal transport direction verging to the SE (Fig. 1) or updip (Fig. 3A). Exceptions to this general trend are three samples at station 3 (10-AW-A, 10-AW-B, and 10-AW-C) in the north part of the field area, as well as sample 10-AW-5 to the south (Fig. 1). Further work is being done to understand the reason for exceptions in the results.

For the range of brittle to ductile textures observed, kinematics were determined in different ways. In rocks with cataclastic texture (1, Fig. 1), no diagnostic kinematic indicators were found. These rocks show brittle offsets in grains, but a consistent pattern of offsets was not found to give a sense of shear for the rocks. Protomylonites (2, Fig. 1) typically yielded indicators. In these rocks, S-C fabrics are commonly good to poor. Although the rocks do commonly contain lithoclasts with sigmoidal tails, most lithoclasts have tails with no clear asymmetry due to the...
angular form of the lithoclasts. Mylonites (3, Fig. 1) yield the most diagnostic indicators. S-C fabrics are well formed, lithoclasts have well formed sigmoidal tails and rotated grains are not uncommon (Fig. 5). In many cases, tail composition is different from the composition of the center of the lithoclast, and so was classified as strain shadows. As the orientation of shear zone boundaries are not known for any of the samples, all potential S-C’ fabrics are here described as S-C fabrics.

CONCLUSION

Mylonites in the Henrys Lake Mountains are present in a range of textures and compositions. Textural differences in these mylonites are interpreted as a result of difference in protolith as well as difference in the degree of deformation as a result of distance from the shear zone centers. Although symplectite may have been present in the protolith, symplectite has grown during shear, potentially as a means for volume reduction (Simpson and Wintsch, 1989). Mineral assemblages typical of greenschist facies and phengite equilibrium with K-feldspar, quartz and phlogopite suggests a minimum pressure during mylonite formation of 5kb (0.5 GPa) (Fig. 2). Mylonites are present in NE trending, NW dipping, SE verging shear zones parallel to those in the Southern Madison Range, dated by Erslev and Sutter (1990) at 1.8 Ga, and believed here to be the result of the Big Sky orogeny.

REFERENCES


Figure 5. Photomicrographs of three mylonite samples from different locations in the field area in plain polarized light showing shear sense determinations and orientations of well formed S-C fabrics.