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SHEARING IN THE MYLONITES OF THE MCATEE BRIDGE RIDGE, MONTANA, USA: COMPRESSIONAL SHEARING IN THE BIG SKY OROGENY

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INTRODUCTION

At the same time as the metamorphism documented by previous Keck projects in the Tobacco Root Mountains, and explained by Harms et al. (this volume), rocks in the Southern Madison and Gravelly Ranges were sheared into mylonites at temperatures between 350 and 500ºC (Erslev and Sutter, 1990). The mineral foliation in these mylonites strikes in the same direction as in the Tobacco Root Mountains (Harms et al., 2004) and the mylonites may be interpreted as foreland thrusts associated with crustal compression during the Big Sky Orogeny (O'Neill, 1998).

Between the Gravelly and Southern Madison Ranges in southwest Montana, just to the south of the McAtee Bridge on the west side of the Madison River, three large outcrops of granitic mylonite protrude from the Quaternary gravel terraces and alluvium, which I have named the McAtee Bridge Ridge, or the MBR. This study includes the southern and middle exposures of the three sections in the MBR. The northern outcrop was not studied due to land ownership.

These rocks are uniquely placed to aid in understanding the Gravelly and Southern Madison Ranges. The shear sense and metamorphic history seen in the MBR show that the Madison Mylonite Zone (MMZ) described by Erslev and Sutter (1990) extends into the Madison River valley. These findings reinforce the character of the Big Sky orogeny (Brady et al., 2004) by adding additional evidence for large-scale continental accretion.

UNIT DESCRIPTIONS

The MBR outcrops are composed of four lithologic units, the most common of which is a granitic mylonite. There are also aplite and pegmatite units, which appear to be younger than the meta-granite and co-genetic; they crosscut it and each other. Finally, there is a biotite-rich quartzofeldspathic gneiss that is cut by all three of the other units (Fig. 1). All four show foliation, mainly defined by micas, and lineation, mainly defined by quartz ribbons.

Figure 1. The gneiss unit (gray) cut by pegmatite veins.

The mineralogy of the meta-granite, aplite, and pegmatite units are very similar. They are all over 90 percent quartz and feldspar with minor biotite, muscovite, and epidote. About two thirds of the samples contain oxides and one aplite sample has two small garnets. No pegmatite thin sections contained garnet but it was commonly observed in this unit in the field. The only large-scale difference between these rock types lies in their grain sizes – the aplite has much smaller feldspar porphyroclasts on average than the meta-granite (~0.6 mm) or pegmatite (~2.75 mm). Pegmatite samples were from relatively fine-grained sections of the unit so that the kinematic indicators fit in handsample and thin section. Larger grains, up to 10 cm are present in the pegmatite unit in the field.

The gneiss unit contains much less quartz and feldspar and more biotite and epidote. Feldspar porphyroclasts are smaller on average than in the meta-granite and pegmatite units, 1.4 mm compared to 2.7 mm and 2.8 mm respectively.

The rocks have almost certainly been significantly recrystallized both during and after deformation. Microcline is commonly found in the matrix and in feldspar porphyroclast tails, as crystals elongate in the direction of foliation. Additionally, the lineation parallel quartz ribbons are almost always polycrystalline and individual crystals have random orientations, which could not be solely the result of crystal slip during shearing.

The fabric in all of the units is similar. The average foliation orientation is 205/45N, n=50, while for lineations it is 295/44N, n=49. Both foliations and lineations are strongly clustered (Fig. 2).

GEOCHEMICAL RESULTS

Three samples – one meta-granite, one pegmatite, and one aplite – were analyzed for major and trace element chemistry. The oxide compositions of these samples are nearly identical and trace element composition is generally within an order of magnitude. Samples have similar slopes on a chondrite normalized rare earth element diagram (Fig. 3a). The meta-granite displays a positive europium anomaly while the aplite and pegmatite show negative europium anomalies. The meta-granite also displays a positive cerium anomaly but the other samples do not have corresponding negative anomalies. A spider diagram of trace elements, normalized to NMORB has a saw-toothed pattern but the lines are semi-parallel between samples (Fig. 3b).

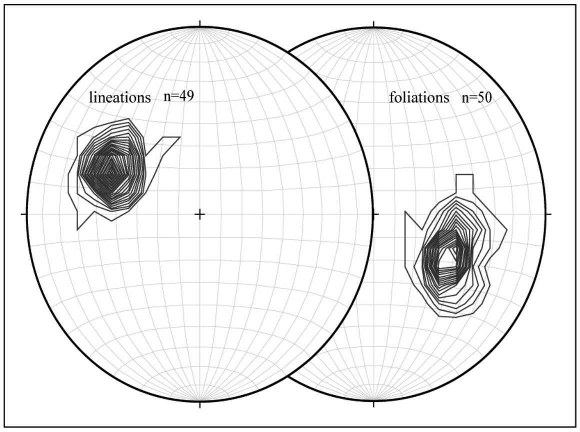

Figure 2. One percent area contours of lineations and foliations (poles to planes) measured in the field. The stereonets are equal area projections. The contour interval is one.

Whole rock major and trace element geochemistry was determined by ICP-MS and ICP-ES analysis by ACME Analytical Laboratories Ltd.

KINEMATIC INDICATORS

The features that are most useful in determining shear sense in these rocks are asymmetric shapes created by brittle feldspar deformation during non-coaxial shear and the quartz and feldspar immediately around porphyroclasts as well as S-C fabrics and mica fish**.**

Quartz – exhibits ductile deformation. It occurs in the matrix, as well as in elongate multi-crystalline ribbons. Ribbons mainly form linear

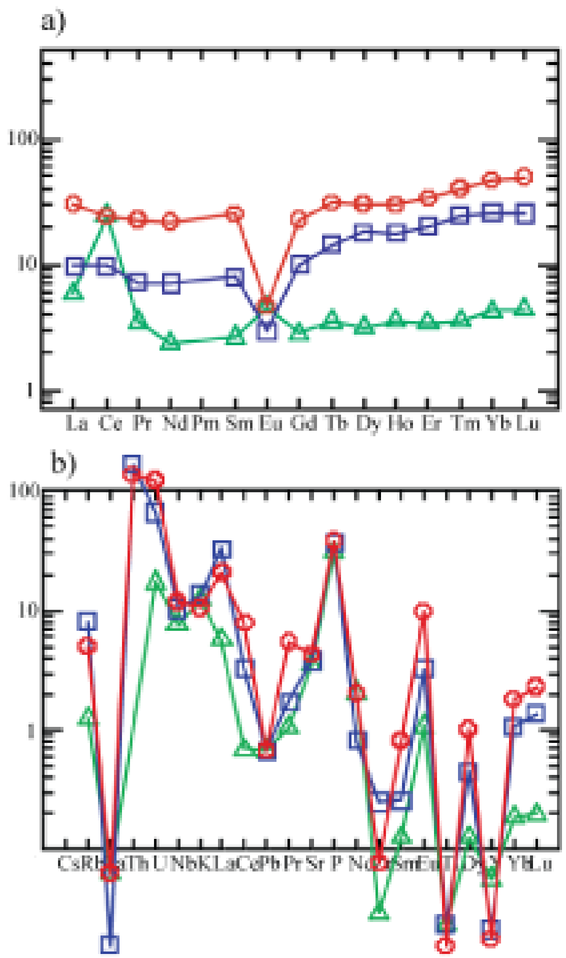

Figure 3. a) Rare earth element compositions normalized to chondrite and b) trace element compositions normalized to NMORB using the Sun and McDonough (1989) calibration of meta-granite (triangles), aplite (squares), and pegmatite (circles).

shapes that indicate overall fabric and not sense of shear.

Feldspar – exhibits almost entirely brittle deformation. Grains in close proximity may show nearly identical patterns of weathering and twinning, as well very similar orientation. These grains could be the result of brittle destruction of larger phenocrysts during shear.

The asymmetries seen in feldspar porphyroclast tails are very important kinematic indicators in these rocks (Fig. 4). Sigma shapes are the most common but delta types are present as well. Due to the recrystallized nature of the minerals, it can difficult to distinguish a sigma indicator from a delta indicator showing opposite sense of shear. All six of the convincing porphyroclasts indicate updip motion to the southeast.

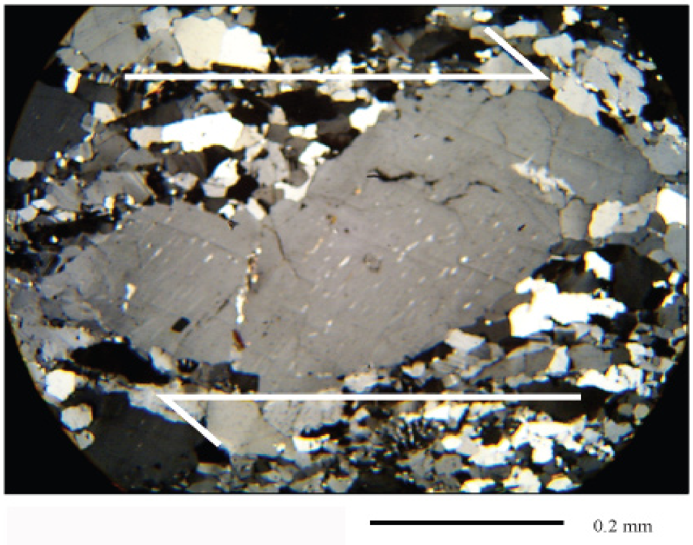

Figure 4. Sigma-type porphyroblast indicating top-to-the-right movement. Photomicrograph under crossed polars.

Myrmekite – occurs mainly as inclusions in large feldspars and rarely as an element of the matrix. In some cases the inclusions are asymmetric quarter structures and reinforce the sense of shear indicated by feldspar tails. These quarter structures also demonstrate that recrystallization happened during the shear.

Micas – biotite is generally elongate in the direction of foliation while muscovite is more commonly seen as large, relatively equidimensional crystals and as alterations in feldspar. Micas can show shear sense well but are more important in the MBR as indicators of the overall foliation. The micas exhibit both brittle and ductile deformation. In one grain the asymmetries point to updip motion to the southeast.

S-C fabrics – occur in thin sections from the meta-granite, aplite, and gneiss units. The S direction is seen in the mineral foliation and the

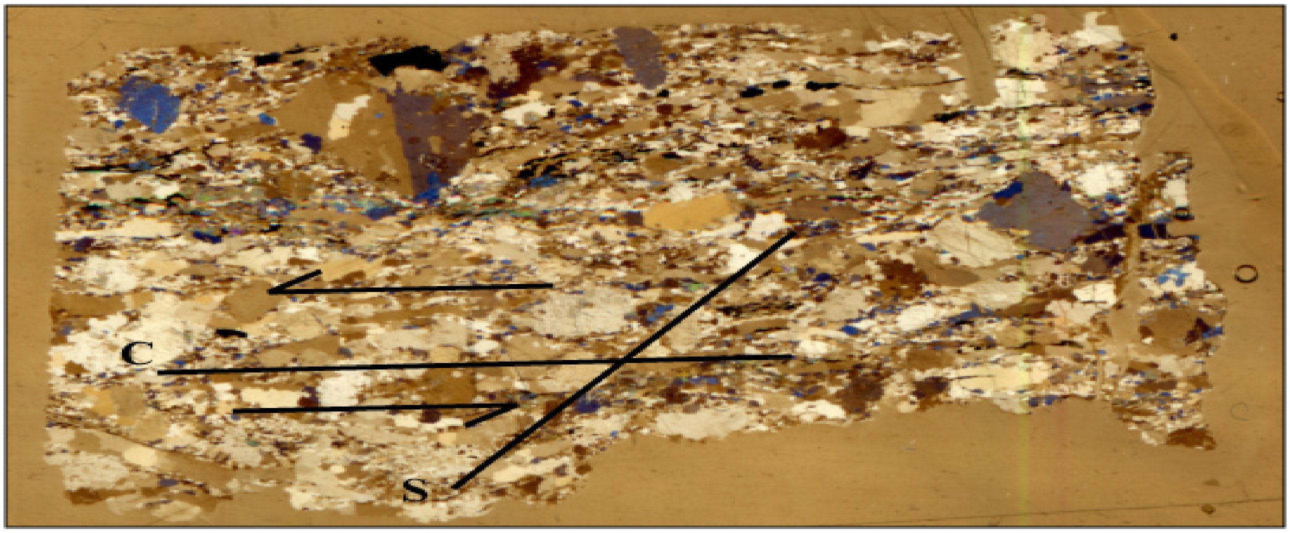

Figure 5. S-C fabrics in meta-granite. It indicates top-to-the-left movement. Field of view is 35 mm.

C fabric appears as spaced microfaults indicated by grain size reduction (Fig. 5). Where visible, they are very good shear sense indicators and show updip motion two to one over downdip.

Indicators suggest both updip and downdip motion. However, the preponderance of the evidence points to updip to the southeast shear. Not only do the majority of features show this but also where multiple indicators occur together in a sample they agree and indicate updip motion.

DISCUSSION AND CONCLUSIONS

The measured properties of the McAtee Bridge Ridge (MBR) each illuminate a different perspective on their history. The most important of these characteristics are elemental composition, mineralogy, and kinematic indicators and mineral fabric, which constrain genetic relationships, metamorphic grade, and sense of shear, respectively.

The parallel nature of the REE and spider diagrams (Fig. 3) suggests that the meta-granite, aplite, and pegmatite units are genetically related. The positive europium anomaly of the meta-granite is accompanied by negative europium anomalies in the later forming aplite and pegmatite units. The larger, positive cerium anomaly in the meta-granite, but not found in the other samples, may be the result of the fluid oxidization of Cerium and subsequent differencial weathering (Taunton et al., 1998) and not indicative of magmatic REE differences. The relationship of the gneiss unit to the other three is not known. Field relationships demonstrate that it is the oldest. It is probably country rock included in the pluton. Erslev and Sutter (1990) describe similar granite/gneiss lithologies of metasomatic origin in the Madison Mylonite Zone (MMZ) to the east, but the pegmatite veins that crosscut the gneiss mean that if there was metasomatism, it was before intrusion of the pegmatite and aplite units.

The metamorphic grade of the MBR is constrained by mineral composition and mode of deformation. Most of the minerals are stable over a large range of pressures and temperatures. However, the presence of epidote, biotite, and muscovite in the assemblage point to greenschist or amphibolite facies. The ductile nature of quartz deformation combined with recrystallization, especially of feldspars into microcline, and the occurrence of myrmekite in feldspars suggest shearing took place at low to medium grade conditions of 400-500°C (Passchier and Trouw, 1996). This places the MBR in greenschist facies, within the range of grades observed in the MMZ (Erslev and Sutter, 1990).

In the MBR the overall fabric shows that the movement across this mylonite zone was predominantly dip-slip in the northwest/southeast direction (Fig. 2). The consistent orientation of the fabric suggests that the orientation of shear did not change significantly during metamorphism and makes it very unlikely that the MBR experienced multiple phases of deformation. The MMZ has a wider range of foliations (Erslev and Sutter, 1990), possibly since it is larger, but this range is inclusive of the fabric in the MBR.

While the kinematic indicators in the MBR show both updip and downdip motion, most of the well-defined structures indicate updip to the southeast. Clearly asymmetrical feldspar and mica porphyroclasts indicate exclusively updip motion and S-C fabrics indicate updip motion by a margin of nearly two to one. Downdip indicators could be shapes produced by localized stresses.

Many characteristics ally the MBR and the MMZ; metamorphic grade, fabric, sense of shear, and location all suggest a close relationship between them. This genetic relationship of the MBR and MMZ would give the MBR rocks a metamorphic age of 1.80 - 1.90 Ga (Erslev and Sutter, 1990) and relate them to the 1.78 - 1.71 Ga Big Sky orogeny in the Tobacco Root Mountains (Harms et al., 2004). While placing the MBR in the MMZ does not enlighten the character of the Big Sky orogeny, it supports its proposed scale and location.

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