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NEW EVIDENCE FOR THE PROTEROZOIC BIG SKY OROGENY RECORDED IN BIOTITE-GARNET-SILLIMANITE GNEISSES FROM MYLONITIC ZONES IN THE HIGHLAND MOUNTAINS, MONTANA

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INTRODUCTION

Precambrian gneisses in the Highland Mountains of SW Montana hold information about the regional extent and effects of the Big Sky Orogeny, an upper-amphibolite grade tectonic event at ~1.77 Ga (Harms et al., 2004). Dynamic fabrics in high-temperature mylonitic rocks at Camp Creek and other sites offer the means to assess metamorphic conditions and kinematic shear sense during tectonism. Garnet, K-feldspar and aligned prismatic sillimanite suggest temperatures in excess of 650ºC at Camp Creek. Dynamic fabrics are overprinted by randomly oriented prismatic sillimanite and muscovite, suggesting that metamorphism at moderate temperature outlasted deformation. Investigation of the textures may be used to test the applicability of the Big Sky orogeny pressure-temperature path formulated for the neighboring Tobacco Root Mountains (Cheney et al., 2004).

The Highland Mountains form a NNW-trending, eastward-tilted block uplift bounded on the west by the Melrose-Divide valley and on the east by the Jefferson-Big Hole River Valley (O'Neill et al., 1986). In the southeastern part of the range, the dominant structure in the Precambrian rocks is an elongate dome of quartzofeldspathic gneiss that forms a NE- to E-trending, doubly plunging antiform (Fig. 1) (O'Neill et al., 1988). A U-Pb monazite age of 1.77 Ga for leucogranite in the dome is interpreted as the time of partial melting and emplacement of the gneiss dome (Mueller et al., 2005), suggesting that the feature formed during the Big Sky orogeny. The focus of the present study is high strain, garnet-sillimanite-bearing zones within the quartz-feldspar-biotite gneiss and mylonitic biotite gneiss mantling the dome. These areas contain information about the P-T conditions in effect during the orogeny and the manner of exhumation of mid-crustal rocks now exposed in the dome. O'Neill et al. (1988) interpreted the thick mylonitic zone as a detachment along which rocks slid off the axis of the dome orthogonally, toward the NW. The mylonitic foliation in this unit strikes NE and dips gently to the SE and NW (O'Neill et al., 1988).

FIELD LOCATIONS AND METHODS

The present study focuses on a zone of sheared rocks at Camp Creek, along the northern edge of the 3-km wide zone of mylonitized biotite gneisses that mantle the Highland Mountain dome on its northwest flank (Fig. 1). Sampling of mylonitic biotite-garnet-sillimanite gneisses was carried out along strike of the ENE-striking, gently south-dipping zone. Mylonitic gneisses from a second site on the more steeply dipping southeastern margin of the dome, informally named "O'Neill's Gulch", were sampled across strike from west to east.

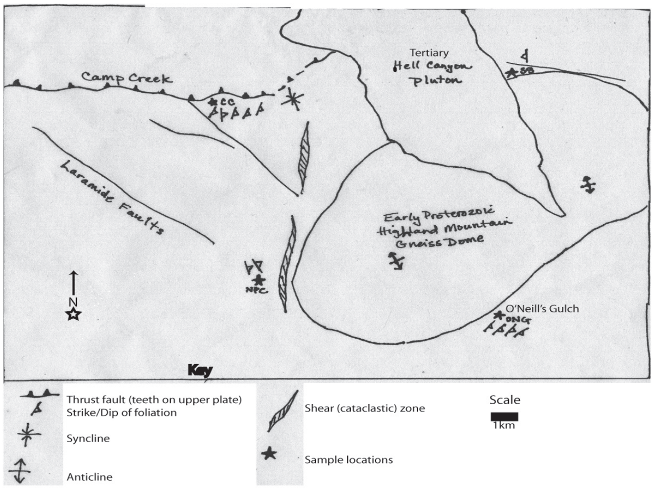

Figure 1. Generalized map of the Highland Mountains including important structural features and sample locations (after O'Neill et al., 1988).

PETROGRAPHY

Fabrics in mylonitic rocks from Camp Creek are expressed at hand-sample and microscopic scale by C-S fabrics, quartz ribbons, biotite pressure shadows surrounding garnet porphyroblasts, segregation into bands of leucosome and melanosome, decussate texture of micas, kink bands and deformation twinning in feldspar, and dynamic sillimanite textures.

Aligned, prismatic sillimanite exhibits xenoblastic to hypidioblastic textures. Porphyroblasts range from 0.5 to 3 millimeters in length, making them readily visible in hand sample. The long axes of grains that define a clear mineral lineation are parallel to foliation within continuous, anastomosing bands. A second generation of variably oriented sillimanite radiates out in concentrations or small pods within the plane of foliation and in some cases also crosscuts it (Fig. 2). Resistant garnet porphyroblasts have strain shadows, or low-pressure zones, where biotite and sillimanite are commonly present.

Overprinting, retrograde textures include sillimanite grains surrounded by both similarly aligned and/or randomly-oriented muscovite. Elongate sillimanite regularly forms aggregates or eye-shaped clusters of bent and warped grains, and exhibits skeletal structures defined by muscovite-filled cracks.

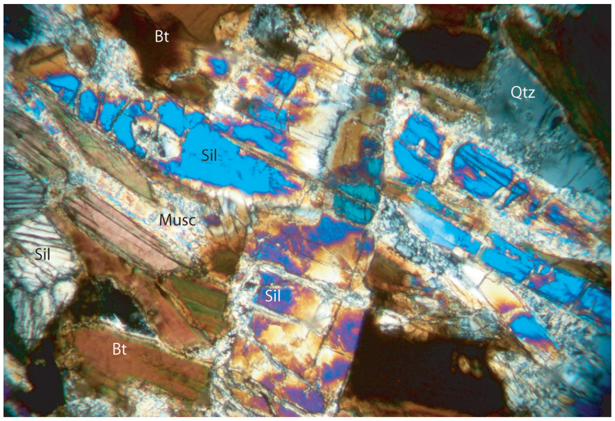

Figure 2. Elongate, xenoblastic sillimanite porphyroclasts at random orientations with embayments filled with retrograde muscovite. Diamond-shaped prismatic sillimanite grains are present in the middle-left with interstitial biotite and quartz. Sample JEL-11H from Camp Creek. Crossed nichols. Width of view is 1mm.

DYNAMIC FABRICS

Sheared rocks at Camp Creek, on the northern edge of Precambrian crystalline rocks in the Highland Mountains, exhibit gently folded, NNW- to NE- striking, shallowly SE-dipping foliations and strike-parallel mineral lineations (Fig. 3). Most samples display distinct C-S

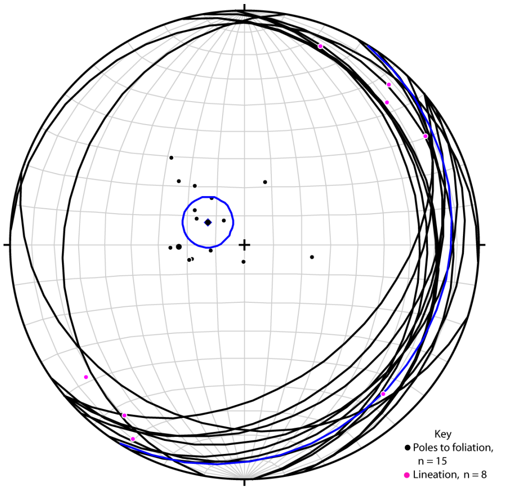

Figure 3. Structural data for Camp Creek, presented in an equal area stereographic projection. Foliation planes are black great circles; mean poles and planes are in blue.

fabrics which together represent conditions of non-coaxial deformation. In thin section, the S-fabric is defined by optically aligned, anastomosing biotite and quartz while the C-fabric forms throughgoing shear planes oblique to the S-fabric. Discrete shear bands oriented obliquely to the S and C fabrics are also present (Fig. 4). Both δ-type and δ-type porphyroclasts are present, including subhedral garnet with wedge-shaped biotite pressure shadows and "bookshelf" plagioclase textures with asymmetric tails (Fig. 4). The prevalent kinematic sense interpreted from asymmetric textures is top-to-NE. Indicators for the opposite shear sense are also observed; however in some cases these cross-cut top-to-NE textures.

On the SE flank of the Highland Mountains along "O'Neill's Gulch", sheared rocks contain NE-striking, steeply SE-dipping foliations with down-dip mineral lineations defined by aligned, elongate sillimanite grains (Fig. 5). Kinematic shear sense interpreted from asymmetric fabrics in this study area is consistently top-to-SE.

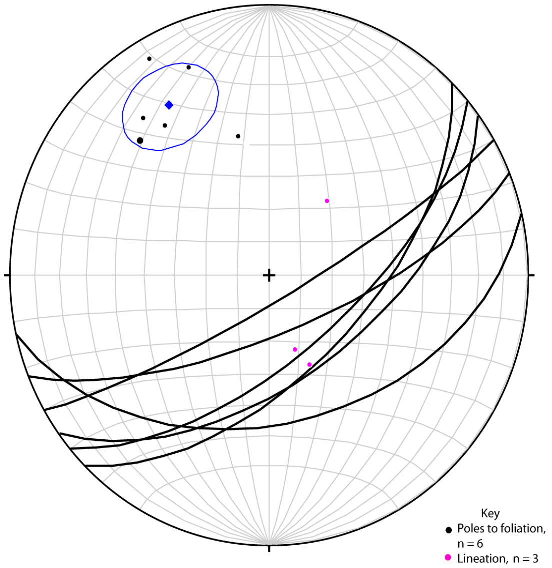

Figure 5. Equal area stereographic projection of structural data for O'Neill's Gulch.

SEM RESULTS

Garnet, biotite and plagioclase from Camp Creek were chosen for geothermobarometry using the garnet-biotite and GASP systems (Holdaway, 2001; Hodges and Spear, 1982). BSE image examination and SEM analysis shows that garnet porphyroblasts are moderately zoned in the eastern part of the study site but lack zoning in the west, with zoning gradually diminishing along the area. Garnet is almandine (Fe-rich phase) in composition; and where zoned, has more magnesium-rich cores and manganese-rich rims. This may suggest re-equilibration at lower temperatures during late-stage (isobaric) cooling or partial melting during their formation (Spear, 1993).

Temperatures calculated using garnet cores and matrix biotite are unreasonable (>1000ºC), indicating that the two mineral phases equilibrated at different times during metamorphism. The strong mineral preferred

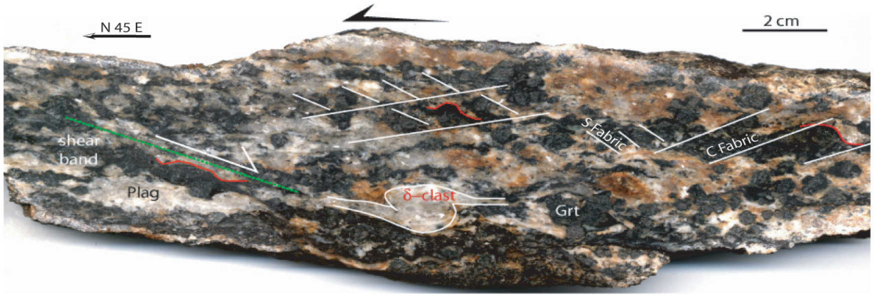

Figure 4. C-S fabric and sigma clasts, together with one large delta-clast, show top-to-NE kinematic shear sense. A cross cutting shear band shows down-to-SW (normal sense) kinematics. View is parallel to lineation, normal to foliation. Sample JEL-04 from Camp Creek.

orientation of biotite and mica foliation wrapping around garnet porphyroblasts suggests that biotite underwent continual dynamic recrystallization during mylonitization but that garnet resisted deformation and strain-induced recrystallization did not affect core domains. Temperatures calculated from compositions of points on garnet rims and touching biotite yield temperatures of 450-550ºC, consistent with the mixed brittle-ductile textures observed in the mylonitic samples. Evidently, garnet rims did re-equilibrate with biotite via Fe-Mg exchange at successively lower temperatures during mylonitization. Quantitative SEM analyses reveal the anorthite content of plagioclase (An_{30}) and grossular content of garnet (Gr_{03}), too low for the GASP geobarometer to be applied reliably (Todd, 1998). The mineral assemblages in the samples did not offer alternative geobarometers.

DISCUSSION/ CONCLUSIONS

SEM discussion: garnet diffusion

The presence of zoning in garnets has several implications about the history of metamorphism and garnet growth in this area. A possible explanation for the trend observed is diffusion zoning, or the modification of preexisting garnet compositions by volume diffusion processes such as exchange reactions with nearby minerals. The garnet zoning net transfer reaction (involving Fe-Mg exchange) (Spear, 1993) likely is:

$$\text{Garnet} + \text{K-feldspar} + H_2O = \text{Sillimanite} + \text{Biotite} + \text{Quartz}$$

BSE images show zoning upon garnet rims and bordering fractures in eastern Camp Creek samples, which suggests that sufficient temperatures were reached for diffusion to be pervasive subsequent to fracturing.

Evolution of mylonitic gneisses at Camp Creek: Temperature implications

Along Camp Creek, prismatic sillimanite grains are commonly aligned in the plane of foliation and define the lineation. A later generation of sillimanite crosscuts dynamic fabrics, suggesting that mineral growth at elevated temperature outlasted deformation. Brittlely fractured and kinked grains of albite and K-feldspar in equilibrium with quartz ribbons are evidence of temperatures within the mixed brittle-plastic transition (450-550°C) (Passchier and Trouw, 1996). Temperatures obtained from garnet rims-touching biotite of ~450°C are consistent with this observation. Syn-kinematic, aligned sillimanite overprinted by decussate muscovite suggest a temperature decrease during dynamic recrystallization. The lineated sillimanite (T>550°C at time of crystallization) is not in textural equilibrium, but shows textures indicative of sillimanite + K-feldspar breakdown to muscovite + quartz. According to these observations, it is likely that the translation of the shear zone from deeper crustal levels to shallower, cooler levels caused re-equilibration and the mineral assemblage seen today.

Fabrics Analysis

The progression of higher-temperature mineral assemblages to moderate-temperature, mixed brittle-ductile fabrics is consistent with translation of Highland Mountains gneisses from deeper toward shallower crustal levels. At Camp Creek, *C-S* fabrics and rotated sigma and delta porphyroblasts show top-to-NE kinematic sense with normal dextral-oblique movement at an angle to the northwestern margin of the Highland Mountains dome. The finding contrasts with O'Neill et al.'s interpretation (1988) of normal-sense of motion due to orthogonal extension and suggests a degree of transcurrent motion in mylonitized gneisses at Camp Creek. At O'Neill's Gulch on the SE flank of the dome, rotated sigma-type porphyroblasts on more-steeply dipping fabrics indicate that tectonic transport was normal-oblique to the southeast, subparallel to but opposite in sense from the direction determined at Camp Creek on the opposite side of the dome. The evidence from these two areas suggests a NE-SW maximum principle strain axis of orientation, rather than the NW-SE direction interpreted by O'Neill et al. (1988). This new interpretation is consistent with the proposed maximum principle strain axis of the Big Sky orogen (Harms et al., 2004).

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