Kinematic Analysis of Mylonitic Rocks, Southern Ruby Mountains, SW Montana: Evidence for Proterozoic Orogenic Crustal Thickening and Topographic Collapse

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Jessica is a senior Earth Science major who conducted her research under the mentorship of Dr. Michael Krol with funding from an Adrian Tinsley program summer grant.

Abstract

Mylonitic granitic rocks from a large shear zone within the southern Ruby Mountains in southwest Montana record evidence for a multiple tectonic movement history. The shear zone is 500 meters thick with ductile shear fabrics generally striking northeast and dipping to the northwest. Foliations in the adjacent country rocks are sub-parallel to the foliations within the mylonites suggesting shear zone development was contemporaneous with the regional deformation and metamorphism of the country rock. A well-developed mineral stretching lineation, defined by aligned sillimanite crystals, records predominantly dip-slip movement, but locally, oblique-slip is also preserved. Sheath-type folds developed in thin calc-silicate layers in calcitic marble have axial orientations similar to the down-dip mineral stretching lineations of the shear zones.

Mesoscopic and microscopic analysis of the mylonites reveals the presence of asymmetric kinematic indicators that record a strong top-to-the-south sense of shear associated with regional compression, thrusting, and crustal thickening. However, in places an opposite shear sense can be identified indicating a period of top-to-the-north sense of shear corresponding with extension, normal faulting, and crustal thinning. The thrust episode is consistent with tectonic shortening and associated high-grade metamorphism reaching 750-800°C and 7-11 kb. Normal movement appears to postdate thrusting, suggesting either a period of post-orogenic collapse due to topographic collapse resulting from an overthickened metamorphic pile (which can be seen today in the Himalayas) or a discretely younger tectonic event. However, the high temperature minerals that define the mineral lineation suggest they were closely related temporally. The timing of deformation, metamorphism, and mylonite formation in this area is unknown, although regional tectonic arguments suggest that high-grade metamorphism is associated with the Proterozoic, 1.78-1.71 Ga Big Sky Orogeny.

Introduction

Recent studies, north of the Ruby range, in the Tobacco Root Mountains (e.g. Burger et al., 2004; Harms et al., 2004) has revealed geologic evidence for a Proterozoic tectonic event termed the Big Sky Orogeny that occurred 1.78 to 1.71 Ga. The Big Sky Orogeny was associated with collisional tectonics and high-grade metamorphism. The goal of this project is to study the kinematic history of mylonitic rocks in an effort to unravel a portion of the tectonic history affecting the southern portion of the Ruby Mountains in southwestern Montana. Asymmetric kinematic indicators allow for the determination of the sense of movement in ductile shear zones and provide information on the nature of tectonism that affected this region. In addition, metamorphic mineral assemblages in the ductile shear zones and adjacent country rocks yield information on the P-T conditions during the development of the ductile shear zone. Our work will provide a better understanding of the nature of tectonic activity in this part of southwest Montana in Proterozoic time. A modern analog similar to the results obtained in this study is found in the Himalayas of Pakistan and Nepal. Continued continental collision between the Indian and Eurasian plates resulted in the formation of numerous thrust faults and subsequent high-standing topography. The South Tibetan detachment, which is a large-scale normal fault, developed in response to the gravitational instability due to the overthickened crust (Burchfiel et al., 1992). Normal motion within the Himalayan orogen continues today even though it is within an overall compressional tectonic environment.

Background

The Ruby Mountains are one of several Archean-aged (2.7 Ga) metamorphic and igneous basement-cored uplifts exposed during Late Cretaceous-Tertiary time (Tysdal, 1981). The range extends approximately 60 km along its northeast trend and 20 km across in an east-west direction. The Ruby Mountains occur along the northwestern margin of the Wyoming province. Rocks in the Ruby and Tobacco mountains are believed to have been subsequently metamorphosed about 1.78-1.71 billion years ago during an event known as the Big Sky Orogeny (Harms et al., 2004a; 2004b). This event was first described as affecting rocks in the Tobacco Root Mountains to the north but most likely extends into the Ruby Mountains to the south (Burger et al, 2004; Harms et al., 2004a).

Several different lithologic units are present throughout the study area. These include; 1) biotite and hornblende gneisses, 2) calcitic-dolomitic marble, 3) amphibolite, 4) sillimanite-pelitic schists and gneisses, 5) quartzites, 6) banded iron formation, and 7) granitic and leucogranitic mylonite gneiss (Garihan, 1979; Karasevich et al., 1981). In addition, several small (10's-100 m) isolated bodies of ultramafic rock intrude the metamorphic sequence and locally result in contact metamorphism and partial melting of adjacent country rock (Alcock et al., 2006). Our study concentrated on granitic mylonites interlayered in sequences of calcitic marble and amphibolite.

Meso-Microscopic Observations

Field work conducted in the Ruby Mountains involved geologic mapping, structural analysis, and sample collection of mylonitic rocks that occur near the crest of the southern portion of the Ruby range. We were able to differentiate several distinctive lithologic units in the study area including; 1) calcitic-dolomitic marble, 2) biotite and hornblende gneiss, 3) amphibolite, 4) sillimanite pelitic schist, 5) quartzite and 6) granitic and leucogranite mylonites. Isolated pods of ultramafic rock occur as 10-100 m wide bodies intruding a variety of the metamorphic units. Understanding the regional-scale structural relationships is part of on-going research performed by Dr. Krol and his colleague from SUNY-Oneonta. Asymmetric kinematic indicators (Passchier and Simpson, 1996) were used to decipher the movement directions of mylonitic rocks in the ductile shear zone.

The first outcrop examined was a sequence of interlayered calcitic marble and leucogranitic mylonite gneiss (Figure 1). The gneiss contains a strongly mylonitic texture, whereas the marble displays highly contorted and folded calc-silicate layers. The leucogranitic mylonite occur as layers about one meter thick within the encompassing marble layers. The mylonitic foliation strikes N67E and dips 50°NW. A mineral stretching lineation in the mylonite trends due north, and plunges 47°N. Kinematic indicators in the mylonite zone show a strong top-to-the-south or reverse sense of movement in the field. Mineral assemblages in the adjacent marble include calcite, diopside, and graphite. The folded calc-silicate layers of the marble found in this area have axial orientations that are sub-parallel to the lineation in the mylonite. However, their orientations are difficult to measure in the field.

To the east are alternating layers of calcitic marble and more granitic mylonite outcrops (EG-56-07; Figure 2). The mylonite has a foliation striking N70E and dips 40°NW. A mineral lineation trends N15E and plunges 38°N. Kinematic indicators in the form of σ-porphyroclasts reveal oblique top-to-the-south sense (reverse) movement. The mylonite possesses a mineral assemblage which includes; quartz, K-feldspar, biotite, garnet, and kyanite. Kyanite is sub-parallel to the mineral lineation in the mylonite. Structurally below this zone shearing appears to intensify with the development of a stronger, more well-defined foliation. The foliation changes slightly with a strike of N60E and dip of 35°NW and a mineral lineation of N10E, plunging 24°N.

Station EG-2-07s consists of calcite-diopside-biotite marble intruded by an undeformed granitic pegmatite. The marble contains calc-silicate layers that appear much less deformed as previously observed and the pegmatite also shows sign of minor deformation and no effects of mylonitization. However, to the east the pegmatite becomes weakly mylonitized. Also found at this location are layers of amphibolite which appears to display a mylonitic fabric. The amphibolite has a foliation striking N78E and is dipping 36°NW.

Approximately 1.5 km to the northwest and structurally above the marble unit is station EG-4-07s. The rocks here are dominated by a thick sequence of amphibolite (~7-8 m) interlayered with 0.5-1 m thick layers of granitic mylonite (Figure 3a). The amphibolite also displays a mylonitic texture as well. Foliations strike N60E and dip 35°NW. These rocks also display a well-developed lineation with a trend of N5E, plunging 35°N, which is similar to the orientation observed in the granitic mylonites. The leucogranitic layers contain large, sheared kyanite crystals. Kyanite porphyroclasts are asymmetric and provide evidence for top-to-the north (normal) sense of shear (Figure 3b).

Structurally above the layered amphibolite is a unit of finer-grained, gray hornblende gneiss. The hornblende gneiss also displays the effects of mylonitization showing an oblique, top-to-the-north movement sense (Figure 4). The foliation strikes N65E and dips 35°NW with mineral lineations trending N20E and plunging 30°N.

Metamorphic Conditions

Petrographic analysis of mylonitic rocks reveal mineral assemblages that include; quartz + microcline + plagioclase + garnet ± muscovite ± sillimantite ± kyanite ± biotite (Figure 7). This assemblage is characteristic and indicative of high-grade metamorphism in the upper amphibolite to lower granulite facies. Sillimanite needles and kyanite define the mineral lineation in some of the granitic mylonite indicating they grew contemporaneous with regional deformation and metamorphism. Mineral assemblages indicate P-T conditions reached 7-11 kb and 750-800°C (Figure 8).

Discussion

Several conclusions can be made based upon the field and petrographic observations. Previous work proposed that the mylonites represented several discrete shear zones within a metamorphic sequence of amphibolite, pelitic schist, and calcite marble (Olsen et al., 2007). However, geologic mapping and kinematic analysis during the summer of 2007 indicate the zone of ductile shearing may actually encompass a much broader zone of deformation rather than concentrated along a series of discrete and distinct zones restricted to the granite and leucogranite mylonites. The highly deformed nature of the marble units and the presence of sheath folds with axes sub-parallel to the mylonitic foliation suggest the two are closely related and developed during the same tectonic event(s). Given the rheological and mechanical contrasts between marble and granitic mylonites and similar nature of deformation experienced by these units, we argue that the zone of movement must be accommodated over a larger, structurally thicker zone and not along thin, isolated zones of highly concentrated shear.

The presence of kyanite and sillimanite, which define the mineral lineation, suggests that the tectonic event responsible for the formation of the ductile shear zones was associated with high-grade metamorphism with pressures of 7-11 kb and temperatures of 750-800°C. The alignment of the sillimanite grains that define the lineation in the granitic mylonite shows that high-grade metamorphism was coeval with ductile shearing and is not an older relict mineral assemblage. The question that still remains is the timing of ductile shearing and the relationship between the two movement episodes as it relates to regional tectonism.

The intriguing observation in the Ruby Mountain shear zones is the preservation of both thrust and normal movement in the same zone. Based upon those observations a two phase tectonic model is developed (Figure 9). The first phase of this model coincides with a time of regional compression creating reverse movement and crustal thickening, some of which was accommodated by the zone of ductile deformation. The second phase of this model represents a period of normal movement within these same zones. This sequence of events is also believed to be the most likely relative age of these two events. One possible explanation for the change from reverse movement to normal movement is in effect, gravity. The compressional phase resulted in an overly thickened crust that ultimately becomes gravitationally and topographically unstable. Therefore, a change in the regional stress field resulted in a change from reverse movement to a normal sense of motion. A modern-day analogue can be seen in the Himalayan Mountains of Pakistan and Nepal (Burchfiel et al., 1992; Krol et al., 1997; Dougherty et al., 1998). There have been several normal faults identified within the mountain range, the most extensive being the South Tibetan Detachment System (Burchfiel et al., 1992). These normal faults have been identified as being contemporaneous with thrusting at depth. Burchfiel et al. (1992) concluded this was due to collapse of high-standing topography driven by gravity. So while shortening was occurring at deeper crustal levels in an overall compressive stress regime, crustal extension was occurring synchronous at higher crustal levels. The result is a mid-crustal wedge that exposes rocks that show both thrust movement at the bottom and extensional movement at the top.

Another possibility for the multiple directions of movement within the same shear zone is the idea that as granitic magma was intruded into the calcitic marble and amphibolite units it thermally weakened the crust resulting in the topographic collapse. Aoya et al. (2005) concluded, based upon U-Pb dating and ^{40}Ar-^{39}Ar dating, that the emplacement of a granitic pluton occurred at the time of the Himalayan Orogeny. He concluded that a transition took place from compressional to extensional movement the same time this pluton intruded, suggesting this was the driving force behind the collapse. This collapse would have caused decompression melting and additional intrusions of granitic magmas, further weakening the overlying crust.

Conclusions

It remains unclear which scenario caused the nearly simultaneous extensional and compressional movement within the ductile shear zone in the southern portion of the Ruby Mountains. This area was initially thought to consist of several small, discrete ductile shear zones restricted to the granitic mylonites, however, recent work suggests the zone of ductile deformation is distributed across a much wider zone. Asymmetric kinematic indicators reveal a predominantly top-to-the-south sense of movement that coincides with regional compression. A transition from reverse (top-to-the-south) to normal movement (top-to-the north) developed in response to gravitational collapse of high topography or collapse driven by thermal weakening of the crust due to granitic intrusions. Additional work is required to distinguish between these possibilities.

Metamorphism of the granitic mylonites and adjacent country rocks indicate pressure and temperatures of 7-11 kb and 750-800°C, respectively. Ductile shearing was coeval with high-grade metamorphism as shown by the alignment of sillimanite needles parallel to the shearing lineation. Based upon regional correlations and similarities with rocks in the Tobacco Root Mountains north of the Ruby range, the shearing event is believed to be linked with the Big Sky Orogeny which took place during the early Proterozoic 1.78 to 1.71 Ga.

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Figure 1. Granitic mylonite outcrop within a sequence of calcitic marble, Elk Gulch quadrangle. View to the east (hammer for scale). Foliation dips to the north (left).

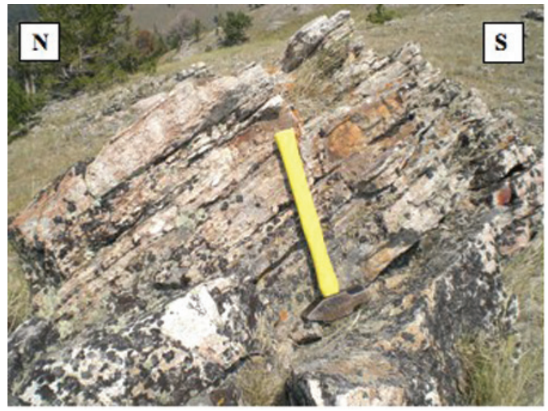


Figure 2. Granitic mylonite interlayered within calcitic marble (pencil for scale).

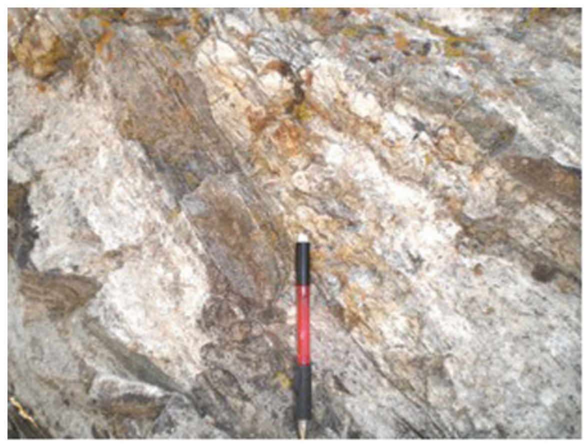


Figure 3. A) Dark layered amphibolite with thin light colored granitic mylonite zones. The overall shear sense is top-to-the-north. Jess Sousa for scale. B) close-up of asymmetric kyanite (ky) porphyoclast and boudinaged and sheared felsic layer showing top-to-the-north sense of shear.

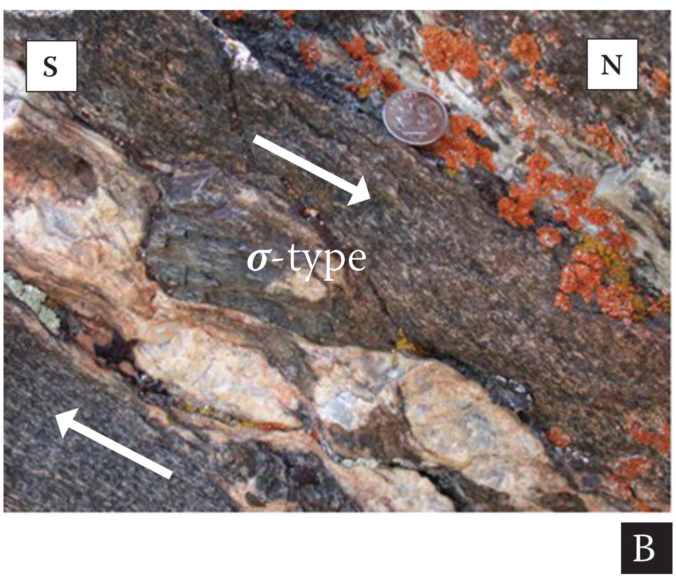


Figure 4. *σ*-type porphyroclast of feldspar showing top-to-the-north sense of shear. Montana quarter for scale.

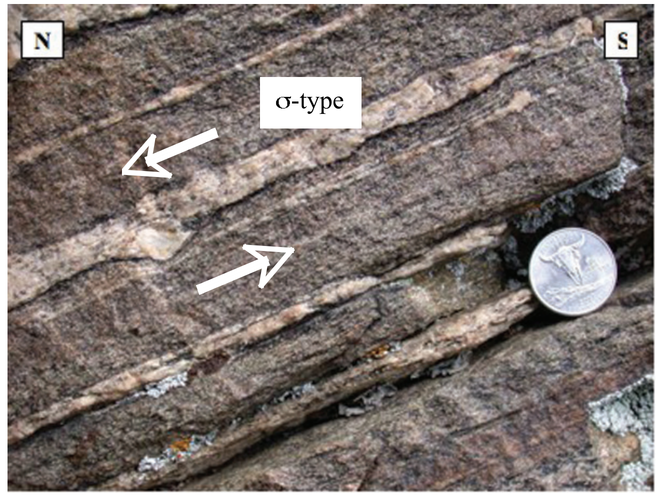


Figure 5. Photomicrograph of a σ-type feldspar (Fsp) porphyroclast showing top-to-the-north shear sense in a granitic mylonite. Field of view 2 mm.

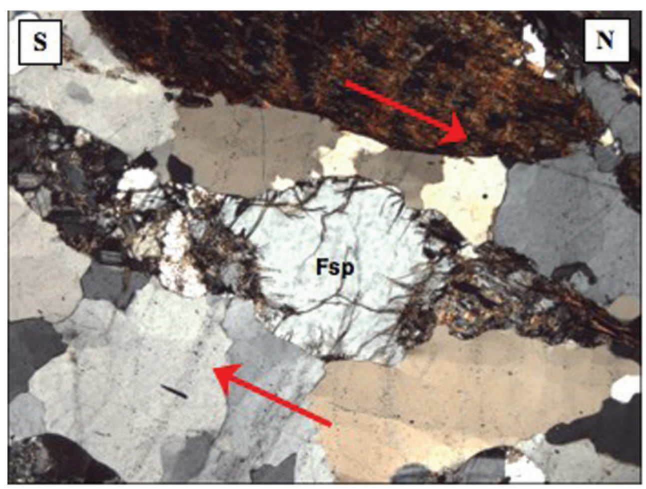


Figure 6. Equal-area stereographic projection of metamorphic and mylonitic fabric elements. Note tight clustering of mineral lineations plunging north.

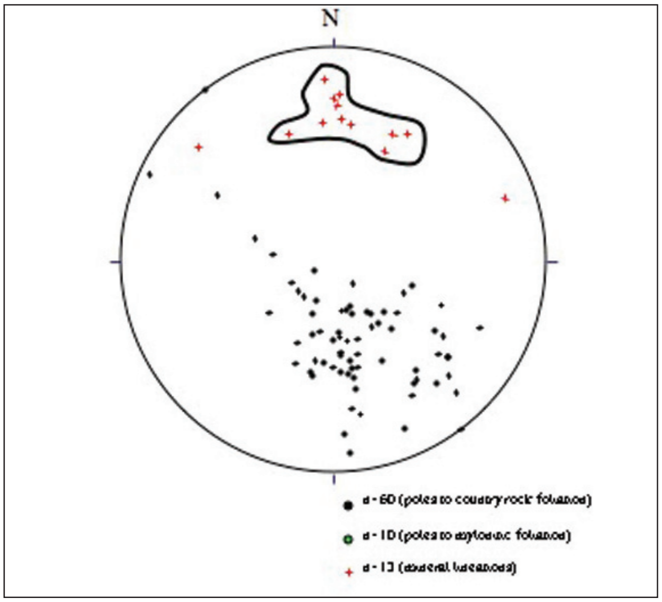


Figure 7. Photomicrograph of sillimanite crystals defining the mineral lineation. Plane polarized light, field of view 4 mm.

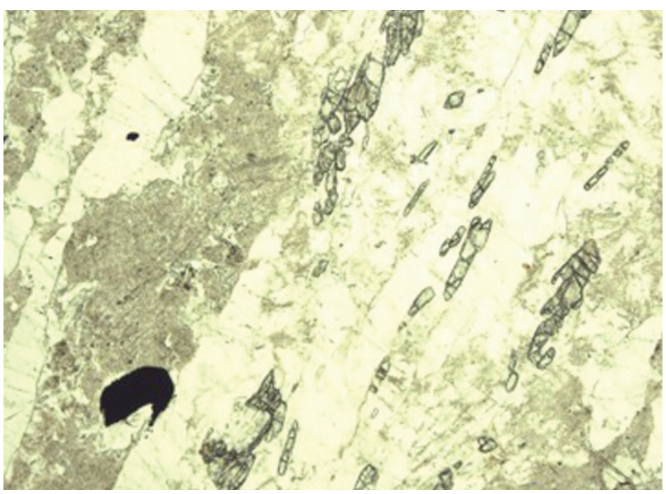


Figure 8. P-T grid showing mineral assemblages and possible P-T conditions during ductile shearing. Gray box shows P-T range of mylonitic rocks.

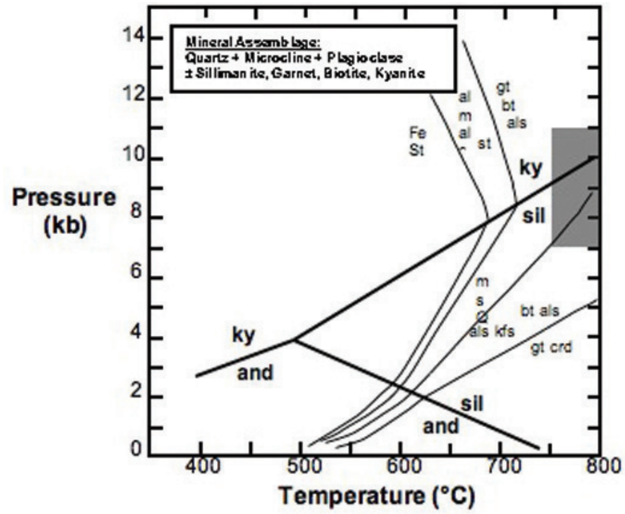
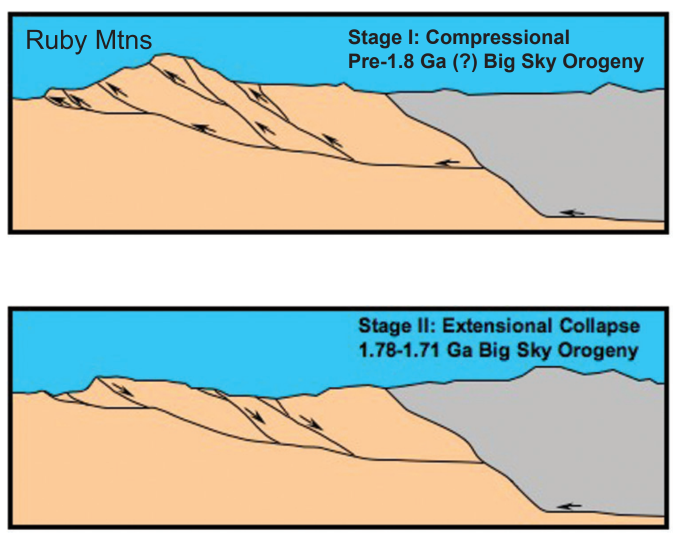


Figure 9. Proposed tectonic model for the development and subsequent collapse of the Ruby Mountains during the 1.78-1.71 Ga Big Sky Orogeny.



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