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Fluid-controlled grain boundary migration and switch in slip systems in a high strain, high temperature contact aureole, California, USA

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ABSTRACT

Within the highly strained aureole surrounding the Eureka Valley–Joshua Flat–Beer Creek (EJB) composite pluton of eastern California, an inversion in microstructures and crystallographic preferred orientations (CPOs) exists with distance from the contact. An inner aureole (<250 m from the contact) consists of quartzites that are interbedded with marbles and calc-silicates. These quartzites are incompletely recrystallized. Most grain boundaries have migrated, although it is clear that grain boundary migration (GBM) is not extensive. Multiple data sets indicate that temperatures of deformation were above 650 °C. CPOs are indicative of <a> slip in quartz. Within the outer aureole (250 m to 1500 m from the contact), quartzites are interbedded with pelitic schist and are completely recrystallized and microstructures are indicative of extensive GBM. CPOs are indicative of prism [c] slip. Oxygen isotope ratios in the inner aureole are only slightly shifted from their original values. Oxygen isotopes from the outer aureole are shifted more, which is consistent with equilibration with locally derived fluids. We suggest that recrystallization in the outer aureole was aided by pore water, water derived from fluid inclusions, and water generated by prograde reactions in the schists. The pore fluids in the inner aureole were also probably initially water-rich. However, during prograde reactions in the intervening calc-silicate rocks, and perhaps more importantly, between calcite cement and quartz in the quartzites, the pore fluid composition in the inner aureole changed to become dominated by CO_2, which acted as a non-wetting phase and decreased the fugacity of water slowing grain boundary mobility. Low water fugacity also suppressed the activity of prism [c] slip. Therefore, we propose that dry conditions or a grain boundary fluid with a significant non-wetting component (CO_2) can result in apparent temperatures of deformation that are more than 100 °C lower than the real temperatures of deformation.

1. Introduction

It is known that the amount and type of fluid have a significant control on the creep strength of the crust which is often based on the characteristics of the deformation of quartz (Fitz Gerald et al., 2006; Menegon et al., 2011). The rheology of the crust is often viewed as strength profiles of dry and wet quartz based on experimental results (Kohlstedt et al., 1995; Mackwell et al., 1998; Jackson, 2002; Burov and Watts, 2006). The addition of a few tenths of weight percent water can drastically decrease the creep stress of deformed quartzites (Mainprice and Paterson, 1984; Kronenberg and Tullis, 1984; Post et al., 1996; Post and Tullis, 1998) and can also drop the transition temperature between dislocation creep regimes by approximately 100 °C (Hirth and Tullis, 1992). Decrease of creep strength with depth is thought to be a result of the increase in water fugacity with increasing confining pressure (Kohlstedt et al., 1995; Post et al., 1996; Selverstone, 2005; Chernak et al., 2009; Holyoke and Kronenberg, 2013). The actual process of how water causes weakening is still unclear, although it is thought to occur when water-associated crystal defects increase in number. TEM studies indicate that vacuum dried Heavitree quartzite shows very little evidence for dislocation climb and dislocation glide appears to be difficult, whereas water-enriched Heavitree quartzite shows ample evidence for climb and glide (Mainprice and Jaoul, 2009).

Most data on recrystallization mechanisms come from experiments because it is difficult to document the fluid environment that existed during natural deformation. The experiments of Tullis and Yund (1982) documented how grain boundary migration and resulting grain growth were enhanced when the grain boundaries were wet. In natural systems it is much harder to document the role fluids played because fluids can move through rocks and ultimately become trapped (or not) at various stages during deformation or exhumation. There are few studies that directly tie the fluid composition that existed during deformation to the type of deformation. Mancktelow and Pennacchioni (2004) observed different recrystallization mechanisms and drastically

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different grain sizes in Alpine quartzites that were deformed in water-deficient conditions versus water-rich conditions. Wawrzyniec et al. (1999) used fluid inclusions to document a correlation between CO_2-rich zones and brittle deformation along the Simplon fault in the Alps. In contrast, they observed that the water-rich zones were deformed by ductile deformation mechanisms.

Increasing the X_{CO_2} of the fluid not only decreases the X_{H_2O}, it may also decrease the ability of the water to penetrate the crystal. First, by decreasing the X_{H_2O}, the f_{H_2O} is decreased, which may inhibit dislocation climb (Selverstone, 2005; Mainprice and Jaoul, 2009). Secondly, CO_2 is a non-wetting fluid that will tend to isolate any intergranular water on grain boundaries and therefore decrease the effective permeability for water. Even very low amounts of CO_2 can promote non-wetting behavior (Watson and Brennan, 1987; Holness and Graham, 1995). Therefore, the creep strength of quartz apparently does not depend solely on the amount of *intragranular* water, but also on the amount of *intergranular* water (Post et al., 1996; Post and Tullis, 1998).

In this study we document differences in the microstructures and in the slip systems between the inner and outer aureole quartzites of the Eureka Valley–Joshua Flat–Beer Creek (EJB) composite pluton and attribute these differences to the fluid composition that existed during deformation. Both parts of the aureole were intensely deformed at temperatures above 600 °C. An initial study of five samples from part of this aureole (Morgan and Law, 2004) indicated that variable amounts of available water were the cause of the differences in slip-systems and amounts of recrystallization but more data was needed to validate the change between the inner and outer aureole and also to support the fluid-controlled hypothesis. Here we present the data from twenty-two samples collected across the aureole (we include the data from the 5 original samples) and use stable isotopes and metamorphic mineral assemblages to make the case that the inner aureole quartzites deformed under dry conditions, probably due to the increase of X_{CO_2} within the fluids due to in-situ prograde calc-silicate reactions. For a more detailed discussion of the metamorphism and partial melting within the aureole see Nabelek and Morgan (2012) and for a discussion on the emplacement of the EJB pluton see Morgan et al. (2013).

2. Geologic setting

The central White-Inyo Range in eastern California (Fig. 1) is dominantly composed of a moderately deformed Neoproterozoic to upper Cambrian sedimentary package that is over 7000 m thick and formed part of the Cordilleran passive margin sequence (Stewart et al., 1966). Fossils are still preserved throughout the range (Nelson et al., 1991) although there are zones of intense deformation adjacent to plutons and thrust faults. A well-developed slaty cleavage is observed in the pelitic units and a spaced fracture cleavage is often found in the carbonates. The sedimentary sequence was subjected to greenschist-facies metamorphism (chlorite zone) prior to pluton emplacement (Ernst, 1996). The structure of the range is dominated by an anticline–syncline pair trending NNE with wavelengths on a scale of 15–20 km (Fig. 1). Many smaller-scale associated folds can be found throughout the range. In a structural window in the topographically lowest part of the center of the range, the Neoproterozoic to upper Cambrian sequence is on top of and in thrust contact with a Devonian and Mississippian sedimentary sequence (Stewart et al., 1966; Dunne et al., 1978; Corbett et al., 1988). Thrusting was to the east and is constrained to have formed between the early Permian and earliest Triassic (Snow, 1992; Stevens et al., 1997). The large-scale folding in the range is probably related to ramps in the underlying thrusts (Corbett et al., 1988). An older, NE-trending set of folds with wavelengths of 4–5 km is also associated with a slaty cleavage and the resulting interference of NE and NW folds has produced a series of structural domes and basins (Nelson et al., 1991; Morgan and Law, 1998). Morgan and Law (1998) and Morgan et al. (2013) document how both periods of deformation predate the emplacement of Jurassic and Cretaceous plutons.

3. Description of undeformed sedimentary formations

Nelson (1962) was the first to map in detail and describe the sedimentary sequence within the central White-Inyo Range. Within the EJB aureole traverse studied here, the oldest sedimentary unit is the lower Cambrian Harkless Formation, which dominates most of the study area. The following description is mostly based on the work of Nelson (1962). The Harkless Formation (~650 m thick) is dominantly composed of green to gray shale with subordinate interbeds of fine-grained sandstone and locally thick sequences of quartzite. The quartzite is not always present but when it is, it is notable for its abundant skolithos trace fossils. The top of the Harkless is defined by thin limestone beds. Above the Harkless Formation is the Saline Valley Formation (~275 m thick), which is divided into a lower and an upper half. The lower half is dominated by sandstone and shale and capped by limestone. The upper half is a mix of sandstone, shale, and limestone. Above the Saline Valley Formation is the Mule Spring Formation (~300 m thick, Nelson, 1962), which is a blue-gray, locally dolomitic, limestone. The Mule Spring Formation caps the lower Cambrian sequence. The Middle Cambrian begins with the Monola Formation (~400 m), which is defined by thinly bedded siltstone and shale. The Monola Formation abuts against and is intruded concordantly by the EJB pluton in the area studied.

This study examines a 1800 m traverse on the east side of the EJB pluton (Fig. 2) where all lithological layering and the foliation are subvertical to steeply dipping. The Harkless Formation takes up more than 1500 m of the traverse. The reason for this is that the traverse does not follow a straight line and the sedimentary units do not maintain their north–south strike away from the pluton. The traverse is initially oriented east–west (Fig. 2) and perpendicular to the concordant formations at the pluton contact. At approximately 300 m from the pluton contact, the sedimentary formations rotate approximately 45° clockwise to strike NE. Exposure is limited at this distance from the contact and in order to continue sampling quartzite, the traverse rotates from its E–W trend to become NE trending to follow an exposed ridge of the Harkless Formation.

Within the traverse (Fig. 3), the main difference between the Saline Valley quartzites, found closer to the pluton, and the Harkless quartzites is that the Saline Valley Formation is interlayered with calc-silicate and marble layers while the Harkless Formation is interlayered with andalusite–sillimanite schists.

4. Strain and kinematic framework

A detailed analysis of the strain and kinematics of the aureole associated with the emplacement of the EJB pluton has been addressed in a separate paper (Morgan et al., 2013). Here we summarize the salient points; 1) the deformation is a result of the forceful emplacement of the EJB pluton and therefore the timespan of the strain and the thermal pulse is limited to the magmatic life of the pluton. 2) The percent shortening in the inner aureole, based on the change in the thickness of the Saline Valley Formation (based on comparison with published regional values to the thickness in the aureole) is between 43 and 47%. We were unable to measure the finite strain in the outer aureole. 3) The strain is dominated by flattening; chocolate-tablet boudinage is common throughout the entire aureole. The greatest separation between boudins is always in a vertical direction and where lineations are observable, they are subvertical (Fig. 16 in Morgan et al., 2013). Therefore, all thin sections have been cut perpendicular to the foliation and are in a vertical plane.

5. Methods

Percent recrystallization was accomplished by taking digital images of four random areas of each sample/thin section. Individual grains were counted and grains with smooth and rounded boundaries covering a