Preservation of an extreme transient geotherm in the Raft River detachment shear zone

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ABSTRACT

Extensional detachment systems separate hot footwalls from cool hanging walls, but the degree to which this thermal gradient is the product of ductile or brittle deformation or a preserved original transient geotherm is unclear. Oxygen isotope thermometry using recrystallized quartz-muscovite pairs indicates a smooth thermal gradient (140 °C/100 m) across the gently dipping, quartzite-dominated detachment zone that bounds the Raft River core complex in northwest Utah (United States). Hydrogen isotope values of muscovite (δD_{Ms} ~ −100‰) and fluid inclusions in quartz (δD_{Fluid} ~ −85‰) indicate the presence of meteoric fluids during detachment dynamics. Recrystallized grain-shape fabrics and quartz c-axis fabric patterns reveal a large component of coaxial strain (pure shear), consistent with thinning of the detachment section. Therefore, the high thermal gradient preserved in the Raft River detachment reflects the transient geotherm that developed owing to shearing, thinning, and the potentially prominent role of convective flow of surface fluids.

INTRODUCTION

Extensional detachment systems are critical interfaces that typically separate the cool, brittle upper crust from high-grade lower and middle crust exhumed in metamorphic core complexes. Detachments are zones of localized deformation, fluid flow, and thermal exchange (Nesbitt and Muehlenbachs, 1989, 1995; Wickham et al., 1993; Morrison, 1994; Morrison and Anderson, 1998; Holk and Taylor, 2000; Mulch et al., 2006; Mulch et al., 2007; Person et al., 2007), but the interplay among these processes is poorly understood. Here, the focus is on the footwall shear zone of the Raft River detachment system in northwest Utah (United States). The shear zone is dominantly in quartzite, such that quartz microfabrics provide a useful record on the kinematics and thermomechanics of this detachment system. Hydrogen isotope ratios of quartz fluid inclusions and of fabric-forming, recrystallized white mica demonstrate that surface fluids permeated the shear zone during deformation. Oxygen isotope thermometry based on recrystallized quartz-mica pairs uncovers an extremely high gradient of metamorphic temperatures preserved in the 100-m-thick shear zone. The influx of cool surface fluids likely produced and preserved the high geotherm that developed during detachment tectonics.

THE RAFT RIVER DETACHMENT SYSTEM

The east-rooted, Miocene Raft River shear zone (Malavieille, 1987; Wells et al., 2000; Wells, 2001) is localized in the Proterozoic Elba Quartzite, which unconformably overlies an Archean basement complex (Compton, 1972, 1975). Cenozoic $^{40}Ar/^{39}Ar$ white mica ages from the quartzite define a west-to-east age gradient from 47 to 15 Ma (Wells et al., 2000). This study focuses on the easternmost exposure of the Miocene shear zone (Clear Creek Canyon; Wells, 2001; Sullivan, 2008), where the shear zone is localized in an ~100-m-thick quartzite-dominated shear zone.

The Elba Quartzite includes, from bottom to top, a basal quartzite-cobble metaconglomerate, an alternating sequence of white quartzite and muscovite-quartzite schist, a distinctive layer of red quartzite, and a pebble-metaconglomerate that includes alternating feldspar-rich quartzite, pure quartzite, and quartz-pebble metaconglomerate (Fig. 1) (Wells et al., 1998; Sullivan, 2008). Paleozoic metasedimentary rocks are preserved as a few scattered klippen above the quartzite and overlying schist unit, and define the hanging wall of the Miocene Raft River detachment (Compton, 1975, Wells, 1997, 2001, 2009; Wells et al., 1998).

QUARTZ MICROFABRICS

The well-developed mylonitic foliation and lineation are constant in orientation throughout the quartzite and are defined by flattened and elongated quartz and white mica grains. The strongly deformed quartzite shows two populations of quartz grains, including coarse (>1000 μm long)

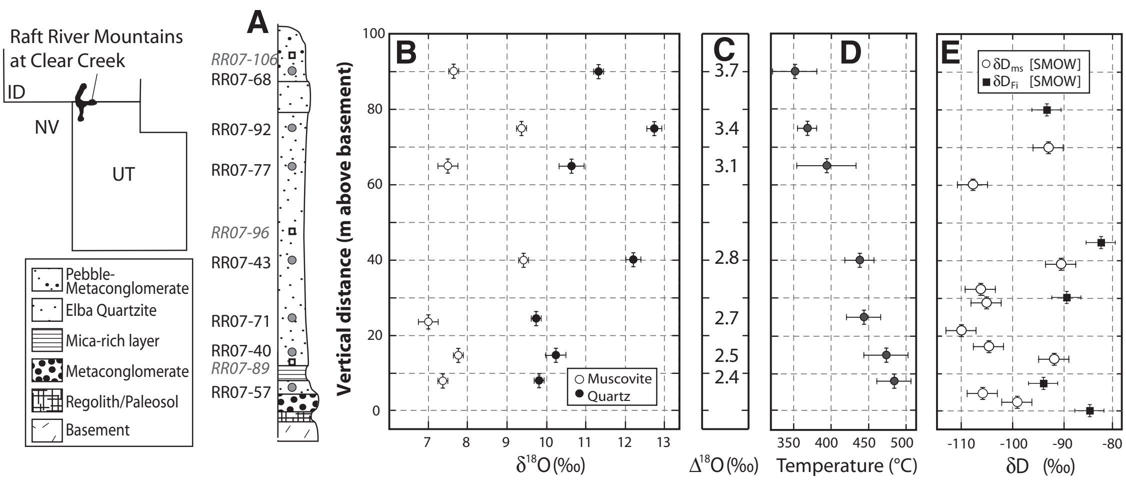

Figure 1. A: Synthetic vertical profile (for scale). B: Oxygen isotope compositions of quartz and muscovite. C: Quartz-muscovite fractionation. D: Temperatures calculated from quartz-muscovite fractionation. E: Hydrogen stable isotope compositions. SMOW—standard mean ocean water.

elongated grains that define the macroscopic fabric, and finer recrystallized grains (50–100 μm) along the boundaries of coarser grains. Large grains commonly display strong undulose extinction, deformation bands, and even deformation lamellae, indicating that quartz deformed under high flow stress conditions (Hirth and Tullis, 1992). The fine recrystallized grains are commonly equant to slightly elongate, and have a direct relation to subgrains present in large grains, suggesting that the dominant process of recrystallization was subgrain rotation (Regime II; Hirth and Tullis, 1992). Recrystallized grains may form an oblique secondary foliation, indicating top-to-the-east sense of shear, but their long axes are locally subparallel to the foliation planes defined by aligned mica, suggesting some component of coaxial flow (Wells, 2001; Sullivan, 2008).

Electron backscattered diffraction analyses of quartz across the detachment zone reveal strong lattice-preferred orientations developed in the dislocation creep regime (Fig. 2). Quartz c-axes define type-I cross-girdles (Lister, 1977), and a-axis maxima are nearly symmetrical, indicating a strong coaxial component of deformation during fabric development, which was also documented by Compton (1980), Wells (2001), and Sullivan (2008). The opening angles measured on 16 c-axis fabric patterns are 50°–60°, indicating deformation temperatures of 400–475 °C ± 50 °C using the Kruhl (1998) geothermometer, with no clear trend across the sampled section.

MUSCOVITE MICROSTRUCTURE

The mylonitic Elba Quartzite typically contains 5%–10% muscovite. Muscovite grains are 50–200 μm long and a few tens of micrometers thick.

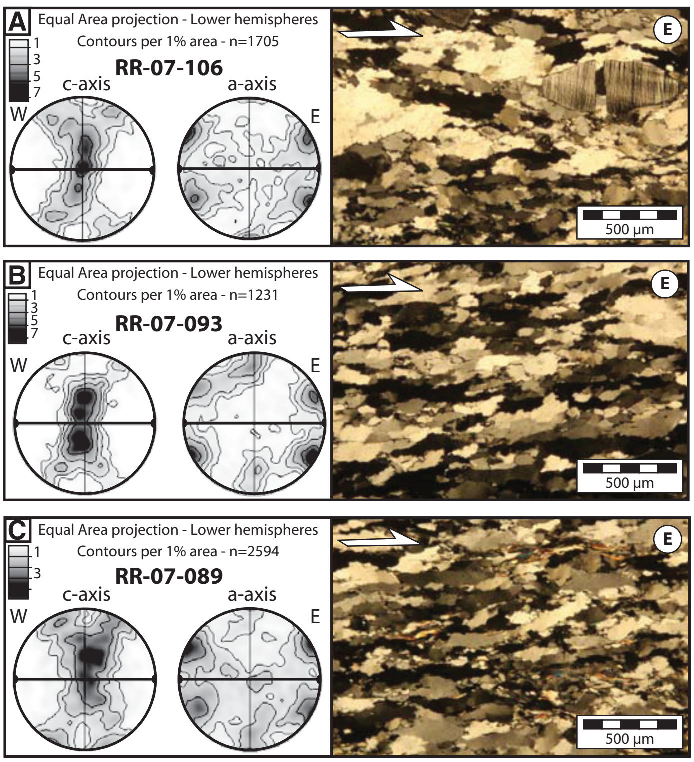

Figure 2. A–C: Characteristic microstructures of the deformed Elba Quartzite, positions of samples indicated by squares boxes and gray label in Figure 1. Thin sections cut perpendicular to foliation and parallel to lineation. Top-to-the-east sense of shear indicated by white arrows. Typical Regime II microstructures of Hirth and Tullis (1992), with formation of subgrains by subgrain rotation recrystallization processes. Electron backscatter diffraction pole figures display symmetrical type-I crossed girdles (Lister, 1977), suggesting strong coaxial strain (Lister and Hobbs, 1980, Schmid and Casey, 1986).

White mica defines the mylonitic foliation in the shear zone, is distributed uniformly on the thin section scale, is ~~in~~ general blocky, and shows little evidence of deformation; mica fish are rare. These observations suggest that mica recrystallized during deformation by dissolution-precipitation creep, which facilitates oxygen and hydrogen isotope exchange between mica and fluid at elevated temperature (e.g., Mulch et al., 2005, 2006).

STABLE ISOTOPE ANALYSES

Oxygen ($\delta^{18}O$) and hydrogen (δD) isotopic compositions were measured at the University of Lausanne, Switzerland, and Stanford University, California (see the Appendix in the GSA Data Repository[1]). Results of oxygen isotope analyses (Table DR1 in the Data Repository) of quartz-muscovite pairs sampled across the shear zone indicate that absolute $\delta^{18}O$ values of quartz and muscovite are variable and range from 9.8‰ to 12.7‰ for quartz and 7.1 ‰ to 9.4 ‰ for muscovite, without any systematic relationship to position in the vertical profile (Fig. 1). However, the temperature-dependent quartz-muscovite oxygen isotope fractionation ($\Delta^{18}O_{Qtz\text{-}Musc}$) increases systematically from 2.4‰ ~10 m from the basement/quartzite contact, to 3.7‰ at the top of the section, irrespective of the absolute $\delta^{18}O$ values of both quartz and muscovite. Using the calibration of Chacko et al. (1996), and assuming isotopic equilibrium between quartz and mica, this increase in the $\Delta^{18}O_{Qtz\text{-}Musc}$ values indicates a decrease in temperature from 485 °C near the base to 345 °C at the top of the ~100-m-thick shear zone section (Fig. 1).

Hydrogen isotope compositions measured from muscovite (δD_{ms}) (Fig. 1; Table DR2) display values from −90‰ to −120‰, with no clear trend in the section. The isotopic value of the fluid present during hydrogen isotope exchange at the temperatures estimated using quartz-muscovite oxygen isotope thermometry is $\delta D_{Fluid} \approx -100‰$ to −70‰ (Suzuoki and Epstein, 1976), which is in the range for meteoric fluids (e.g., Taylor, 1977). Similarly, δD values of quartz fluid inclusions (δD_{FI}) analyzed in five samples over the entire thickness of the shear zone (Fig. 1; Table DR2) have a narrow range, from −94‰ to −82‰, with no systematic variation in the section. These values are in good agreement with those calculated from δD_{ms} values, and are also consistent with meteoric fluids.

DISCUSSION

Analyses of finite strain, kinematic vorticity (Wells, 2001; Sullivan, 2008), deformation mechanisms, and thermometry results from a quartzite-dominated section of the Raft River shear zone are integrated to evaluate the role of deformation and fluids in the thermomechanics of detachment systems. The smooth change in isotopic fractionation between quartz and mica across the section, independent of the absolute $\delta^{18}O$ values of quartz and mica pairs, is likely related to an increase in temperature of equilibration downward through the 100-m-thick shear zone. Even though absolute temperature estimates are biased depending on the choice of the calibration used for fractionation, relative temperature trends across the detachment are robust. Despite an analytical error of 20–30 °C on temperatures determined from each quartz-mica pair, the high apparent linear metamorphic gradient (140 °C/100 m) indicated by our $\delta^{18}O$ measurements is incompatible with a conductive structure and requires a compressed thermal gradient.

The quartzite microstructure is quite constant over the Clear Creek section, in apparent conflict with the temperature gradient revealed by oxygen isotope thermometry. However, in dislocation creep, quartz microstructure is controlled by flow stress, which is dependent on temperature/strain-rate relations (Hirth and Tullis, 1992). At Clear Creek, microstructures reflect relatively high flow stress during detachment tectonics,

[1]GSA Data Repository item 2011228, isotopic analyses, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

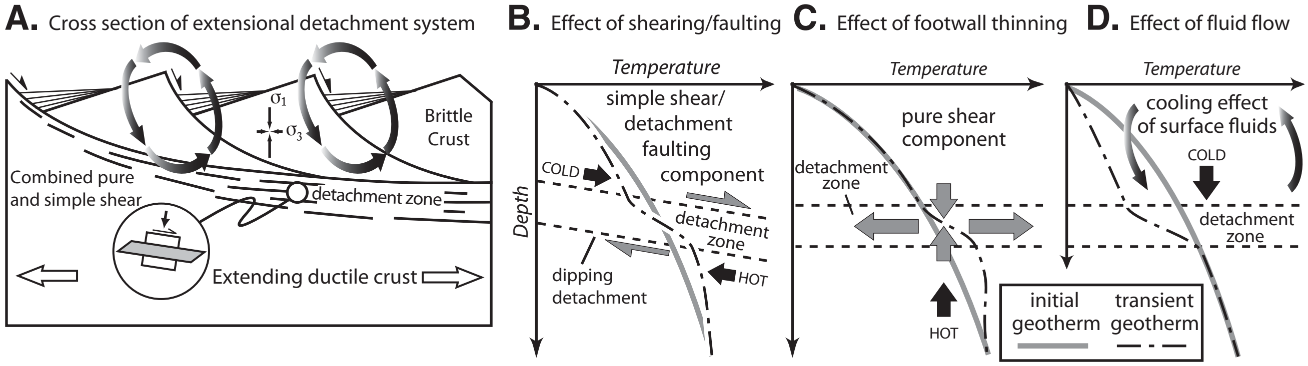

Figure 3. A: Conceptual diagrams of the transient effects of extensional shearing. B–D: Schematic representation of effects of deformation and fluid flow on geotherm.

irrespective of temperature, which suggests that temperature and strain rate self-adjusted to maintain near-constant stress. Given the relatively uniform finite strain documented by Sullivan (2008) on this section, the thermal gradient revealed by mineral pair thermometry may indicate that microstructure at the bottom of the section developed at a higher strain rate for a shorter time compared to the top of the section. This scenario necessitates migration of the deformation front through the shear zone, with a tendency for strain to localize downward (toward higher temperature), which could be tested, for instance, by dating synkinematic micas.

Three factors can perturb syndeformational geotherms in detachment systems such as the Raft River shear zone (Fig. 3). First, the dipping shear zone advects and juxtaposes hot rocks from the footwall and cold rocks from the hanging wall, such that a steep transient geotherm is established (Fig. 3B). For the Raft River shear zone, which probably evolved at shallow dip angles (Wells, 2001), this effect may account for the high metamorphic gradient only if the shear zone accommodated large displacements (Wells et al., 2000). Second, thinning of the footwall shear zone may also lead to heat advection (Fig. 3C). Coaxial flow was an important component of deformation in the Raft River shear zone (Compton, 1980; Wells, 2001; Sullivan, 2008), and our quartz crystallographic data support this conclusion (Fig. 2). Hence, the isotopic ratios and temperatures determined for the Raft River shear zone are likely to have been preserved during synkinematic thinning. However, given the original thickness of the Elba Quartzite, thinning alone cannot account for the preserved thermal gradient. Finally, the influx of cool surface fluids down to the detachment can maintain a steep transient geotherm over the time scale of shearing and/or exhumation (Fig. 3D).

Hydrogen isotope ratios measured in quartz fluid inclusions and white micas indicate that the fluids present during deformation were of meteoric origin. Fluid inclusion δD values are constant throughout the section, and are similar to the mean of the values calculated to be in equilibrium with the white mica in the Elba Quartzite at their temperatures of formation. Therefore, it is reasonable to infer that cool surface fluids reached the detachment shear zone and therefore likely played a role in the thermal evolution of this detachment system. While simple shear and pure shear strain in the detachment shear zone are capable of creating a steep isotherm, we propose that cooling induced by fluid flow is the dominant process by which a transient geotherm develops and remains preserved across detachment shear zones. What is true for the Raft River shear zone is likely the case for other detachment systems in which the presence of meteoric fluids has been recognized (Morrison and Anderson, 1998; Holk and Taylor, 1997, 2000, 2007; Mulch et al., 2004, 2006, 2007).

In extensional detachment systems, fluid circulation in the upper crust is driven by surface topographic gradients and by heat flux from below, which drives fluid flow by buoyancy (Person et al., 2007; Saar, 2011). Crustal extension associated with orogenic collapse is a setting in which high-amplitude topography creates a hydraulic head, for example through domino-style tilting of upper crustal blocks (e.g., Basin and Range). This hydraulic forcing develops at the same time as hot crust is brought in contact with cool crust by detachment tectonics. In the upper crust, subvertical fracture patterns enhance the transfer of fluids, and normal faults are natural fluid conduits that provide pathways for upward and downward fluid flow (Fig. 3A). Studies of mineral isotopic compositions show that surface fluids do not, in general, penetrate the deep footwall of detachment systems (Fricke et al., 1992; Holk and Taylor, 2007) but do penetrate detachment shear zones (Mulch et al., 2004, 2006, 2007). This circulation of surface fluids must participate in cooling the detachment system (Person et al., 2007). Yet, time-integrated water-rock ratios typically diminish downward, which indicates that larger-scale conductive cooling of the detachment footwall is limited to the detachment shear zone (Mulch et al., 2006, 2007).

In conclusion, thermal structure, thermal exchange regime, fluid flow, and strain critically control the dynamics and transient geotherm of extensional detachment systems. The high thermal gradient of ~140 °C/100 m across the Raft River shear zone revealed by isotope thermometry was probably generated by displacement across the detachment system, including coaxial thinning of the footwall shear zone, and more critically by the circulation of surface fluids, which produced a transient geotherm that was likely sustained over the duration of detachment tectonics.

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