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Strain and permeability gradients traced by stable isotope exchange in the Raft River detachment shear zone, Utah

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ABSTRACT

Combined geochronological and stable isotope data of quartzite mylonite from the footwall of the Raft River detachment shear zone (NW Utah, USA) reveal that an important phase of ductile deformation and infiltration of meteoric water in the shear zone occurred in Miocene time. $^{40}Ar/^{39}Ar$ release spectra are complex, and plateau ages decrease systematically from 31.1 ± 0.8 Ma at the top to 20.2 ± 0.6 Ma at the bottom of the quartzite mylonite section, capturing a segment of the ~40–15 Ma geochronologic record that has been documented regionally and is likely related to partial to total overprinting of Eocene white mica $^{40}Ar/^{39}Ar$ ages in the Miocene. Hydrogen stable isotope values of syn-kinematic muscovite range from −123‰ to −88‰ and suggest that meteoric water infiltrated the detachment shear zone during mica (re)crystallization and mylonite development. Bulk stable isotope analyses from fluid inclusions in quartz support a meteoric origin for the fluid (low D/H and $^{18}O/^{16}O$ ratios). Quartz and muscovite oxygen isotope analyses show varying degrees of ^{18}O depletion, suggesting spatially variable time-integrated interaction of meteoric fluids with recrystallizing shear zone minerals. The overall pattern of D/H and $^{18}O/^{16}O$ ratios indicates that fluids were channelized along restricted layers or shear zones within the deforming detachment system. The variability in $^{18}O/^{16}O$ ratios of both quartz and muscovite and the fluid-rock isotopic exchange results can be explained by variations in the shear zone permeability (confined versus diffuse flow) along with strain variations along the transport direction (from flattening to constriction).

1. Introduction

The presence of fluids during active deformation has a profound impact on the thermal state and the rheology of the crust, even at deep levels where rocks deform ductilely (e.g. Kohlstedt et al., 1995; Ranalli, 1997; Bürgmann and Dresen, 2008). Actively migrating fluids influence heat and mass transport, facilitate melting and mechanical deformation, and are an important control on the thermomechanical evolution of crust, particularly in the detachment shear zones that bound metamorphic core complexes (e.g. Mulch et al., 2006; Person et al., 2007; Gottardi and Teyssier, 2013). However, our understanding of the hydrology and permeability structure of ductile shear zones is incomplete. Here we combine strain and stable isotope analyses in an extensional detachment shear zone to shed light on how (meteoric) fluids and rock interact at the grain scale and how shear zones transmit fluids during deformation.

2. Hydrology of detachment shear zones

When thick orogenic crust undergoes extension, the cool brittle upper crust is commonly separated from the hot lower crust by a detachment zone that localizes deformation, fluid flow, and thermal exchange (e.g. Brun et al., 1994; Rey et al., 2001; Teyssier et al., 2005).

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Detachment activity eventually leads to the formation of metamorphic core complexes (MCC) in which heat transfer produces strong thermal/metamorphic gradients (Brun et al., 1994; Rey et al., 2001; Teyssier et al., 2005; Mulch et al., 2006; Tirel et al., 2008, 2009; Gessner et al., 2007; Rey et al., 2009; Huet et al., 2011; Whitney et al., 2013). Extensive brittle faulting in the upper crust results in significant increase in permeability and porosity, with the potential of enhancing the circulation of fluids at the crustal scale. Based on oxygen (δ^{18}O) and hydrogen (δD) stable isotope analyses, the presence of surface-derived (meteoric) fluids during mylonitization has been documented in many different extensional detachments including those that bound the Thor-Odin dome (Holk and Taylor, 1997, 2000; Mulch et al., 2004, 2006), the Kettle dome (Mulch et al., 2007), the Bitterroot MCC (Kerrich and Hyndman al., 1986; Quilichini, 2012), the Raft River Mountains (Gottardi et al., 2011), the Ruby Mountains (Fricke et al., 1992), the Snake Range (Gébelin et al., 2011, in press), the Whipple Mountains (Morrison and Anderson, 1998; Gébelin et al., 2012), the Simplon detachment in the Central European Alps (Campani et al., 2012), the Menderes MCC in Turkey (Hetzel et al., 2013) as well as the South Tibetan Detachment at Mount Everest (Gébelin et al., 2013) even though there exist cases where low δD and δ^{18}O values may be derived from surface alteration prior to burial (e.g. Raimondo et al., 2013).

Modeling studies of crustal-scale fluid, heat, and oxygen isotope transport and exchange in regions of crustal extension show that fluid migration and fluid–rock exchange at mid-to lower-crustal levels is primarily controlled by the permeability contrast between the different crustal rocks (Person et al., 2007; Gottardi et al., 2013). High permeability contrast between adjacent rock units leads to focused fluid flow and can result in significant lowering of the δ^{18}O of the country rock, given that large amounts of fluid with δ^{18}O values much lower than the country rock is present for a period sufficiently long to equilibrate with the rock.

However, complete understanding of the hydrology of detachment zones based on field observations is commonly limited owing to lack of exposure and a restricted number of analyses. Thus, samples are usually collected along transects across or along detachment zones (Kerrich and Hyndman, 1986; Fricke et al., 1992; Holk and Taylor, 1997, 2000; Morrison and Anderson, 1998; Mulch et al., 2004, 2006, 2007; Gottardi et al., 2011; Gébelin et al., 2011, 2012, 2013, 2014; Quilichini, 2012; Campani et al., 2012). Here, we combine oxygen and hydrogen isotope geochemistry and ^{40}Ar/^{39}Ar geochronology from a quartzite mylonite of the Miocene Raft River detachment shear zone (Utah) to evaluate the permeability along and across the shear zone and the extent and duration of fluid flow during extension. The combined data show that an extensive hydrological system draining low D/H and low ^{18}O/^{16}O meteoric fluids was active during the evolution of the shear zone in Miocene time. Quartz and muscovite oxygen isotope analyses show different degrees of ^{18}O depletion that are likely related to: (1) different time-integrated interaction of synkinematically (re)crystallized minerals with meteoric fluid, (2) variation in permeability in the basement units (confined versus diffuse flow), and (3) strain variations from flattening (planes) to constriction (pipes) along the transport direction of the detachment shear zone.

3. Geologic setting

The Raft River Mountains form the eastern limb of the Albion–Raft River–Grouse Creek metamorphic core complex in NW Utah and expose amphibolite-to greenschist-facies Archean to Permian rocks (Fig. 1). These rocks experienced alternating crustal

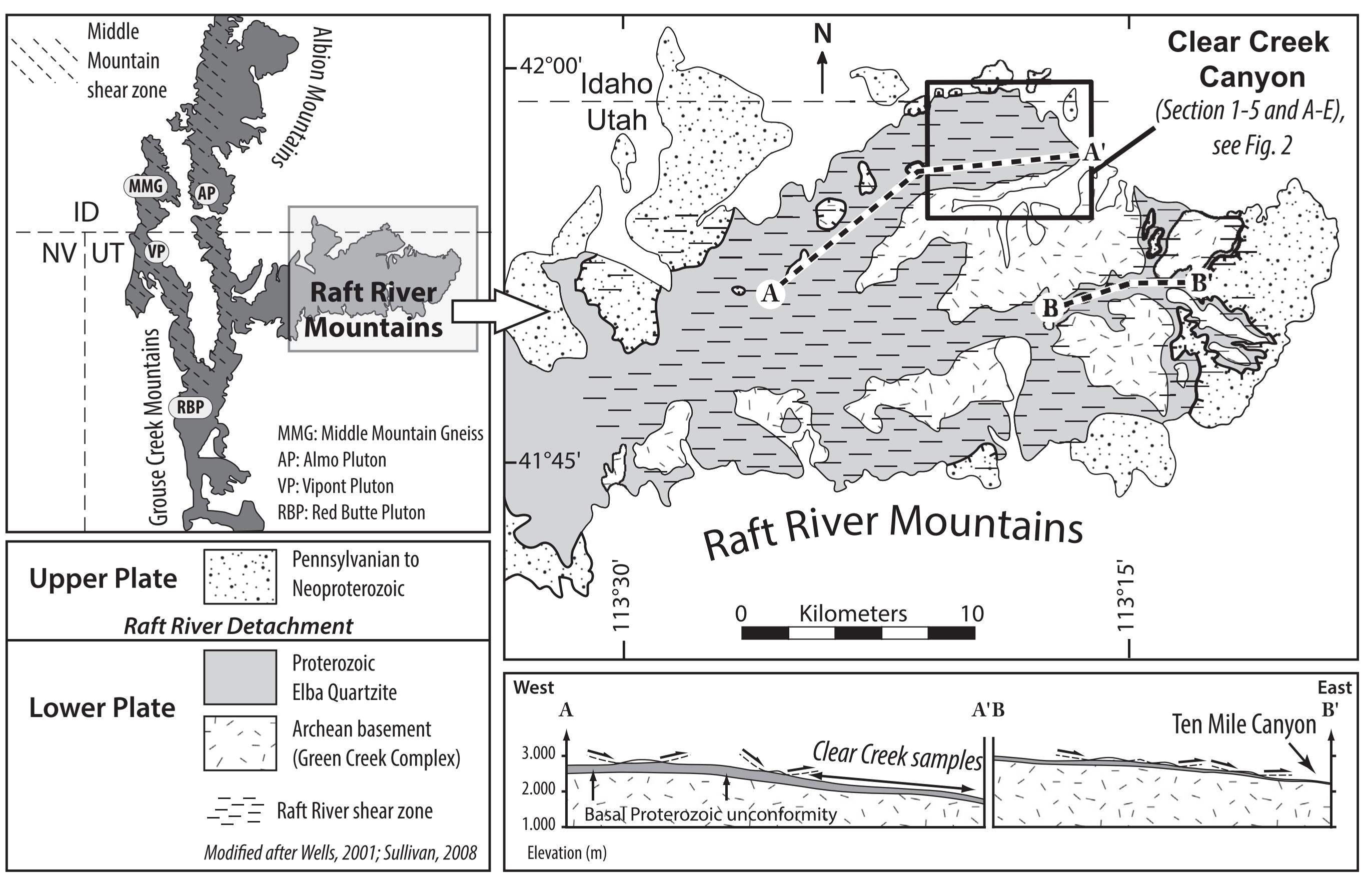

Fig. 1. Simplified geologic map of the Raft River metamorphic core complex showing the location of Fig. 2. Adapted from Wells (1997), Wells et al. (2000), and Sullivan (2008).