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Identification of magmatic and meteoric fluid sources and upward- and downward-moving infiltration fronts in a metamorphic core complex

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ABSTRACT

A combined study of O, H, and C isotope variations in the Ruby–East Humboldt Range metamorphic core complex has identified infiltration of aqueous fluids originating from both the surface of the earth, and from deep crustal or mantle levels. At deep structural levels, metamorphic fluids flowed upward and were rich in water, had mantle-like isotopic compositions, and were probably derived from crystallizing magmas. Conversely, at higher structural levels, a major meteoric-hydrothermal system developed in response to rapid uplift, causing meteoric fluids to penetrate downward into plastically deforming metamorphic rocks at depths of 10 to 15 km below the surface. Infiltration fronts associated with both processes have been recognized, allowing us to determine fluid fluxes and flow geometries at mid-crustal levels.

INTRODUCTION

Fluid flow associated with most active continental rift systems involves fluids derived from two principal sources. Vigorous flow of meteoric water down into anomalously warm rock and back to the surface characterizes the major meteoric-hydrothermal systems that are a ubiquitous feature of continental and oceanic rift zones (e.g., Taylor, 1990). Helium isotope studies of active rifts have identified the presence of mantle-derived He; the $^3He/^4He$ is commonly far above the crustal average (e.g., Mamyrin and Tolstikhin, 1984), implying that mantle He and probably other volatile species of deep-seated origin are flowing upward through the crust in such regions. In active rifts, however, the geometry of fluid flow at depth is very difficult to define, particularly the maximum depth of penetration of surface fluids and the flow pathways and transport media of mantle-derived fluids. In this paper we use stable isotope data from an ~3 km section of mid-crustal rocks in the Basin and Range extensional province to characterize the transport of fluids derived from surface and deep-seated sources within a Tertiary continental rift-zone.

REGIONAL SETTING

A simplified geologic map of the Ruby Mountains–East Humboldt Range (Fig. 1) identifies the principal localities discussed herein. The area preserves a considerably attenuated transition from amphibolite facies gneiss (lower plate) that equilibrated at mid-crustal depths (3–7 kbar) to subgreenschist facies supracrustal rocks (upper plate) (Howard, 1971; Snoke and Howard, 1984; Snoke and Miller, 1988; Snoke et al., 1990). The high-grade rocks comprise Proterozoic and Paleozoic orthogneiss and paragneiss, and many (mostly metre scale) intrusive igneous rocks of Mesozoic and Cenozoic age.

The high-grade rocks are complexly deformed as a result of Mesozoic and Cenozoic tectonism. In the Tertiary, strong extensional deformation emplaced slabs of low-grade supracrustal rocks (upper plate) over the high-grade complex along low-angle normal fault systems, and there was extensive ductile attenuation of the lower plate rocks, generating extensive mylonite zones toward the top of the lower plate. The zones of mylonite, and the detachment fault and associated breccia sheets, are prominently exposed along the western flanks of the range (Fig. 1). The deepest structural levels of the metamorphic complex are exposed in the center and north of the East Humboldt Range along its eastern flank.

Numerous geochronologic measurements have documented both Mesozoic and Cenozoic intrusive events (e.g., Snoke et al., 1979; Kistler et al., 1981; Dallmeyer et al., 1986; Dokka et al., 1986; Wright and Snoke, 1986). Mesozoic thermal effects were extensively overprinted by a major mid-Tertiary heating event (particularly at deep structural levels) caused by the intrusion of numerous different magma types, including 29 Ma monzogranite, 32 and 39 Ma granitic gneiss (Wright and Snoke, 1986), and 39 Ma hornblende diorite sills, in addition to larger plutons such as the Harrison Pass pluton (36 Ma). This event is represented by texturally late sillimanite in metapelites and quartzites,

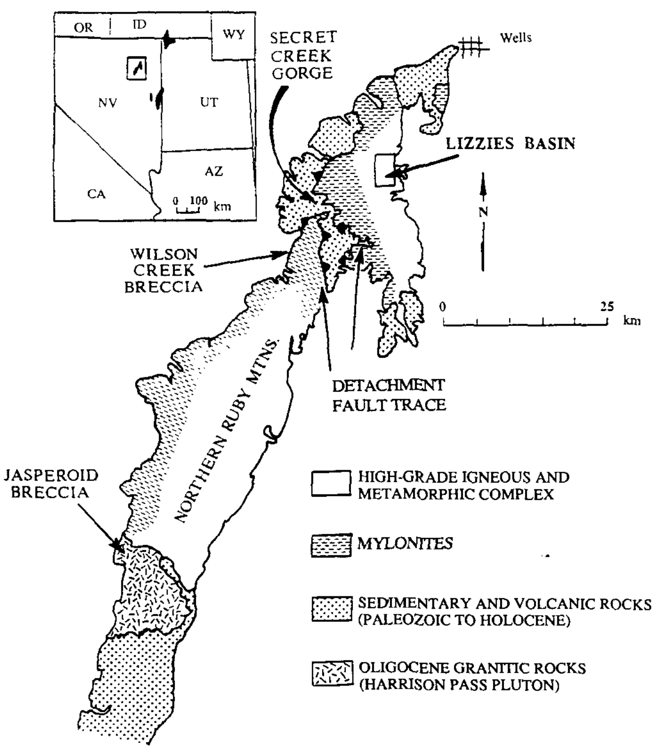

Figure 1. Location of study area in northeastern Nevada (inset) and simplified geology of Ruby–East Humboldt Range core complex. Mylonite overprint is present through much of upper structural levels of high-grade igneous and metamorphic lower plate rocks (dash pattern), becoming more intense close to low-angle detachment fault (toothed line) that separates them from overlying low-grade rocks. Inset map also marks location of other nearby core complexes, including Snake Range in eastern Nevada and Grouse Creek–Albion Mountains in northwestern Utah and southern Idaho.

water-rich retrograde reactions in metacarbonates, biotitization of amphibolites, and reequilibration of garnet rims. Peters (1992) summarized evidence that this most recent high-temperature event in the central and northeastern East Humboldt Range (the deepest structural level exposed in the lower plate) was at 600–700 °C and 5–7 kbar. Isotopic age measurements of mylonites that underlie the detachment fault at much higher structural levels suggest that recrystallization probably continued until more recent times (32–23 Ma; Wright and Snoke, 1986; Dokka et al., 1986). Hurlow et al. (1991) estimated pressures of 3–4 kbar and temperatures of 580–620 °C for the conditions of mylonitization at these structural levels.

DOWNWARD FLOW OF METEORIC FLUID

Some of the best exposures of the mylonites forming the uppermost part of the lower plate are at Secret Creek gorge (Fig. 1). At this locality these rocks are mostly quartzites, marbles, and leucogranites, which are continuously exposed to a structural depth of about 100 m below the detachment fault that separates them from the low-grade, upper plate rocks (see Snoke, 1980; Lister and Snoke, 1984; Fricke et al., 1992, for further details).

In common with the rocks adjacent to detachment fault zones in several other core complexes (e.g., Kerrich, 1988), many of the Secret Creek gorge rocks preserve clear evidence of interaction with meteoric waters by their anomalously low δD and $\delta^{18}O$ values. What is exceptional about this locality, however, is the evidence that meteoric water was not restricted to the brittlely deforming upper plate rocks, but penetrated lower plate rocks that were still undergoing plastic deformation at relatively high pressures and temperatures. The Secret Creek quartzites have much lower $\delta^{18}O$ values (down to +2) than those of quartzite from deeper structural levels. Such low values could only arise by interaction of the quartzite with meteoric water (see Fricke et al., 1992). This conclusion is supported by the low and uniform δD values of biotite from the same rocks (−157 to −147) which would have been in isotopic equilibrium with local meteoric water at the estimated temperature of mylonitization (Hurlow et al., 1991; Fricke et al., 1992). Fricke et al. (1992) suggested that this water was present in hydrostatically pressured fractures in the upper plate rocks and was drawn down across the detachment surface into the lower plate mylonites by seismic pumping.

At Secret Creek gorge, the lowest $\delta^{18}O$ values (<+6) are all observed in samples <50 m below the detachment fault, and below this level the values range up toward typical quartzite values of +10 to +12. No other low $\delta^{18}O$ values consistent with meteoric water infiltration are observed anywhere else in the Ruby–East Humboldt Range, as is clearly illustrated in Figure 2, where whole-rock $\delta^{18}O$ values of silicate metasedimentary rocks from throughout the region (mostly quartzite and pelite) are plotted against structural depth, estimated from field mapping (Howard et al., 1979; McGrew, 1992). All samples in the northern Ruby Mountains (at structural depths of typically a few hundred metres below the detachment surface) have $\delta^{18}O$ values >+9; this is also true of all the samples that we have analyzed from the Angel Lake region (Wickham et al., 1991; Peters, 1992). These data are consistent with penetration of a low-$\delta^{18}O$ oxygen front associated with meteoric water infiltration only about 50–100 m into the lower plate.

All the biotite samples analyzed from Secret Creek have very low δD values in the range −140 to −160, but unlike oxygen, similar low values are seen elsewhere in the region (see Fig. 3). At the deepest exposures at Lizzies basin (~2500 m below the detachment fault) the biotites have normal plutonic values of −50 to −70, but at higher levels at Lizzies basin and at Angel Lake (1000 to 1500 m below the detachment fault), values are moderately low ($\delta D_{biotite}$ ranges from −110 to −80). The values suggest that the upper part of Lizzies basin may be close to the limit of penetration of the low-δD hydrogen front associated with downward flow of meteoric fluid. This pattern is further supported by several low-δD analyses from the northern Ruby Mountains (Fricke et al., 1992); the structural depths are difficult to estimate precisely, but all are <1200 m below the detachment fault (Fig. 3). The structural depth of the deepest low-δD biotite samples below the detachment may be readily estimated from field relations (McGrew, 1992). Inasmuch as pure H_2O will transport a hydrogen isotope front ~20 times faster and farther than an oxygen isotope front through typical crustal rocks containing 2–3 wt% H_2O (Bickle and McKenzie, 1987), an oxygen isotope front that moved ~100 m down from the detachment surface will be associated with a hydrogen isotope front that traveled ~2000 m. This is similar to the estimated depth below the mylonite zone of the structurally lowest low-δD biotites at Lizzies basin and is consistent with the notion of downward penetration of meteoric water from the detachment surface into the lower plate.

For pure H_2O flowing through rock with ~50% oxygen by weight, these distances correspond to a total fluid volume of ~150 m^3/m^2 (Fricke et al., 1992). Inasmuch as meteoric water infiltration accompanied mylonitization, the pressure estimates of Hurlow et al. (1991) indicate that, at the time of mylonitization, the Secret Creek rocks were 10–12 km below the surface. Our hydrogen isotope data suggest that meteoric water penetrated at least 2 km deeper than this level, and the combined evidence is consistent with meteoric water circulating to depths of 10–15 km below the surface of the earth (cf. Kerrich, 1988).

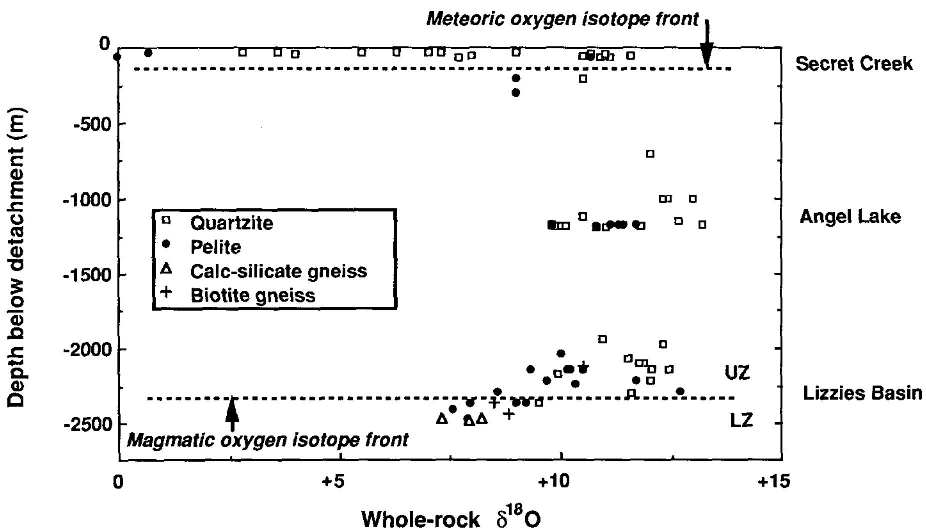

Figure 2. Whole-rock $\delta^{18}O$ values of silicate metasedimentary rocks from throughout Ruby–East Humboldt Range (mostly pelites and quartzites) plotted against structural depth (measured as depth below detachment fault). Zone of very low $\delta^{18}O$ values occurs immediately below detachment fault, and must result from interaction of mylonites with meteoric water. Elsewhere in section, $\delta^{18}O$ is mostly >+10, except in lower part where there is sudden change to values <+9. Data taken from Kistler et al. (1981); Wickham and Peters (1990); Grunder and Wickham (1991); Wickham et al. (1991); Fricke et al. (1992); and Peters (1992). UZ and LZ refer to upper and lower zones at Lizzies basin.

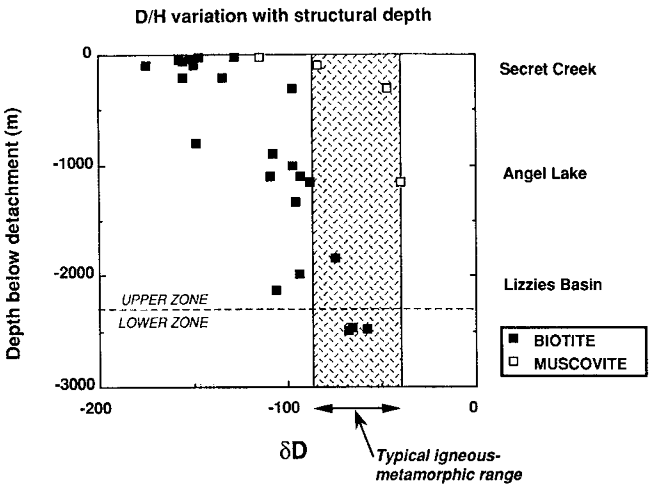

Figure 3. Variation of δD in biotite and muscovite over entire range of structural depths exposed in Ruby–East Humboldt Range. Only at very deepest levels are normal igneous values observed in biotite. Over rest of area, δD is affected by interaction with meteoric water and is low and variable; clear trend is toward values more depleted in D at higher structural levels. Lowest δD values are observed in quartzite mylonites immediately below detachment fault. Data from Wickham et al. (1991) and Fricke et al. (1992); following are additional biotite samples: MPAL-216, depth below detachment 1100 m, δD = −109; MPAL-78, depth 1100 m, δD = −93; MPWL-22, depth 1334 m, δD = −96; LB201, depth 1833 m, δD = −75; MPWL-1, depth 1984 m, δD = −94; and 73-P1-2, depth 2133 m, δD = −106.

UPWARD FLOW OF MAGMATIC VOLATILES

It is clear from Figure 2 that extreme ^{18}O depletion caused by meteoric water is restricted to the upper 100 m of the lower plate. At deeper levels, quartzites and pelites have more typical metamorphic values (+10 to +15), and it is only in the very deepest part of the area that significant ^{18}O depletion is again observed. At Lizzies basin the metasedimentary rocks in the lower part of the section have been strongly ^{18}O depleted, and all the silicate rocks have whole-rock $\delta^{18}O$ values between +6 and +8.5 (Wickham and Peters, 1990; Wickham et al., 1991; Grunder and Wickham, 1991). This lower zone passes upward abruptly into an upper zone of much less strongly ^{18}O-depleted and more isotopically heterogeneous metasedimentary rocks.

The ^{18}O depletion and isotopic homogenization in the lower zone must have been caused by fluid flow because it occurs over a distance of hundreds of metres perpendicular to compositional layering and for an along-strike distance of 2–3 km (Wickham and Peters, 1990; Grunder and Wickham, 1991). Biotites from the deepest levels at Lizzies basin have typical igneous δD values of −50 to −70 (Wickham et al., 1991; see Fig. 3). $\delta^{18}O$ of quartz in the lower zone is uniform and low at +9.0 to +9.5 (Wickham et al., 1991), and the average value of +9.4 would be in equilibrium with olivine of +5.5, diopside of +6.5, and anorthite of +7.2 at 700 °C (Clayton et al., 1989; Chiba et al., 1989). In other words, the oxygen isotope composition of the lower zone rocks could have been generated by exchange and equilibration with a fluid whose oxygen isotope composition was controlled by high-temperature equilibration with mantle-derived material. This suggestion is consistent with the observation that whole-rock $\delta^{18}O$ values in the lower zone approach but are never less than +6. Further limitations are provided by C-O covariation in marbles (Wickham and Peters, 1992) which suggests that calcite marbles at Lizzies basin have all exchanged to varying degrees with a common water-rich C-O-H fluid reservoir having $\delta^{18}O \sim +8$ and $\delta^{13}C \sim -6$, values consistent with a mantle carbon source and a mantle or deep-crustal oxygen source.

The low $\delta^{18}O$ values of rocks from the deepest part of the terrane correlate with a marked increase in the abundance of pegmatitic leucogranite pods and sills (from ~20% to ~50% by volume going from the upper to the lower zone at Lizzies basin; Peters [1992]; McGrew [1992]). Subvertical, north-south–trending quartz-biotite veins emanate from many of these pods and contain a widely observed, retrograde calc-silicate assemblage where they cut metacarbonate layers (Peters, 1992). These observations suggest that the retrograde calc-silicate reactions, as well as the lower zone ^{18}O depletions, were driven by infiltration of water-rich magmatic fluids released from the leucogranites (Peters, 1992). The steep orientation of the veins indicates that they, and the leucogranites with which they are associated, were emplaced toward the end of extensional deformation, and provides further evidence suggesting that many leucogranites have Tertiary ages.

The abrupt transition from the ^{18}O-depleted lower zone values to the more normal upper zone values is best explained as an infiltration front. Upward flow of water-rich magmatic fluids released from the abundant lower zone (and deeper) magmas would have transported oxygen and hydrogen isotope fronts at varying rates in exactly the same way as the downward-moving meteoric fronts described earlier. In this case the magmatic hydrogen isotope front is not distinguishable because it has been overprinted by the downward-moving meteoric hydrogen isotope front. However, the variation in the $\delta^{18}O$ values at Lizzies basin is similar to the predicted geometry of such an infiltration front that has been slightly broadened (~50 m?) by diffusion and dispersion. Model calculations (Wickham and Peters, 1992) demonstrate the plausibility of this process and suggest that an alteration zone of the observed thickness could have been generated by a flux of aqueous fluid derived from a layer of basalt several kilometres thick or a granite layer hundreds of metres thick (or hundreds of metre-scale granite pods, as observed within the Lizzies basin lower zone).

Wickham and Peters (1992) have suggested that a time-integrated flux of ~400 m^3/m^2 could have generated the observed isotope alteration. The leucogranites that transported this aqueous fluid to the base of the Lizzies basin section were clearly crustally derived, despite having low $\delta^{18}O$ values of +7 to +8 (Grunder and Wickham, 1991). These magmas acquired such values either because they were derived from a low-$\delta^{18}O$ source rock (e.g., Precambrian cratonal basement gneisses, which appear to have been the source for relatively low $\delta^{18}O$ granites [+6 to +9] immediately to the east of the study area in Utah and Colorado; Solomon and Taylor [1989]) or because this source had its $\delta^{18}O$ value lowered by exchange with other low-$\delta^{18}O$ crustal lithologies, or fluids, at some stage prior to or even during melting (Wickham, 1990; Grunder and Wickham, 1991). Grunder and Wickham (1991) observed a decrease with time in the $\delta^{18}O$ value of silica-rich crustal material involved in mid-Tertiary volcanism in eastern Nevada, which is consistent with the latter process. However, note that although the leucogranites are mostly crustal in origin, most of the *water* transported in these magmas was probably originally mantle derived, existing as a dissolved magmatic constituent until it was released from the leucogranites at mid-crustal levels. There is abundant evidence for the emplacement of basaltic magmas beneath this area during the Tertiary (Gans, 1987; Valasek et al., 1989; Feeley and Grunder, 1991), and these could have originally transported the water and passed it on to the leucogranite magmas during crustal anatexis. Such processes, possibly involving other volatile species, may be typical of the deeper regions of rifted continental crust.

CONCLUSIONS

The systematic variation of $^{18}O/^{16}O$ over the ~3 km of structural depth observed in the Ruby–East Humboldt core complex defines meteoric and magmatic oxygen isotope infiltration fronts that have moved, respectively, downward (50–100 m) and upward (200–300 m) through the high-grade rocks of the lower plate. Because both zones of isotopic alteration may be wider than observed (due to truncation by the detachment fault and the limitations of exposure), these distances translate into minimum fluid volumes of ~150 m^3/m^2 for the meteoric water and ~400 m^3/m^2 for the magmatic water. Meteoric fluids penetrated plastically deforming mylonites of the lower plate, but in quantities such that only rocks close to the detachment were strongly ^{18}O depleted. However, hydrogen isotope systematics indicate that these fluids in fact penetrated several kilometres into the lower plate to depths of 10–15 km below the surface of the earth. At deep structural levels, ^{18}O depletions are correlated with the abundance of leucogranites, and these magmas appear to have introduced the fluids responsible for the isotopic effects (Peters, 1992). Between the zones of oxygen isotope alteration, ^{18}O depletions are less extreme and may have resulted from internal homogenization of different rock types or exchange with pore fluids during earlier (Mesozoic?) metamorphism.

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