Oceanic detachment faults focus very large volumes of black smoker fluids

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ABSTRACT

It is generally assumed that the seawater-derived fluids that feed black smoker vent fields on the seafloor are discharged vertically from depths of ~1–3 km. We present new oxygen and strontium isotope data that show that fluids at black smoker temperatures of 300–400 °C were focused along a low-angle detachment fault at 15°45′N near the Mid-Atlantic Ridge. Isotopic alteration is the most extreme ever reported from oceanic rocks altered at similar temperatures, indicating intensely focused fluid flow both in recharge and discharge parts of the hydrothermal system. Rare earth element mobility in the fault rocks demonstrates isotopic alteration by evolved hydrothermal fluids, not conductively heated seawater. The fault zone protolith was predominantly ultramafic, but also included mafic rocks, with metasomatic alteration to talc-tremolite-chlorite schists resulting mainly from chemical exchange between these lithologies during fluid flow. Fluids in equilibrium with this assemblage would be similar to ultramafic-hosted black smoker fluids. We present a new model in which hydrothermal circulation around detachment faults evolves from basalt hosted (TAG type), to footwall ultramafic hosted (Rainbow type), to low-temperature ultramafic hosted (Lost City type). Key features of our model are the intrusion of gabbro bodies immediately below the detachment to provide a heat source for circulation, and focusing of fluid flow into the detachment fault to allow venting away from the neovolcanic axis.

Keywords: ocean crust, hydrothermal circulation, oxygen isotopes, strontium isotopes, detachment faults, talc-tremolite schist.

INTRODUCTION

The fluids that feed the black smoker vent fields along mid-ocean ridges are generally believed to rise vertically to the surface through permeable pipes within sheeted dikes and lavas (Humphris and Cann, 2000; Sinha and Evans, 2004). This process is driven by heat from magma bodies directly beneath the ridge axis. In contradiction to this model, some major Atlantic vent fields are several kilometers from the neovolcanic zone and show an association with serpentinite and gabbro exposures and with nearby detachment faults (Gràcia et al., 2000; Tivey et al., 2003; German and Lin, 2004). Recent data show that such faults are much more common in the Atlantic than previously thought (Smith et al., 2006), and that the TAG hydrothermal field is underlain by an ~20° dipping fault zone that passes into a zone of seismicity dipping at an angle of 70° beneath the neovolcanic zone and reaching depths of 7 km (deMartin et al., 2007). Here we demonstrate that a currently inactive low-angle detachment fault at 15°45′N near the Mid-Atlantic Ridge was the locus of intense flow of hydrothermal fluid at black smoker temperatures during deformation. We suggest that active detachment faults commonly act as channels for black smoker fluids at slow-spreading ridges, and present a model explaining the occurrence of the three major end-member vent types occurring away from the neovolcanic zone on the Mid-Atlantic Ridge.

GEOLOGICAL SETTING

Corrugated domal massifs exposing lower crustal and mantle rocks are common along slow spreading ridges, and indicate extension involving tectonic rather than solely magmatic processes (Cann et al., 1997; Tucholke et al., 1998; Ildefonse et al., 2007). A massif 25 km west of the Mid-Atlantic Ridge at 15°45′N was sampled by remote seabed drilling and dredging during cruise JR63 (MacLeod et al., 2002). The surface of this massif is a fault zone composed of talc-tremolite-chlorite schists, metamorphosed at greenschist facies (black smoker temperatures), with a footwall composed of serpentinized peridotites intruded by gabbro bodies (Escartín et al., 2003). The schists are of predominantly ultramafic protolith, as shown by trace element contents and the presence of relict chromite grains. They were intruded by basalts with chilled margins now metamorphosed to greenschist facies; basaltic clasts also occur within the schists. Both deformed and undeformed metabasalts are variably chloritized, often with complete plagioclase replacement. Alteration of both mafic and ultramafic protoliths involved significant chemical mass transfer, and it is clear that deformation, fluid-rock interaction, and igneous activity occurred coevally (MacLeod et al., 2002; Escartín et al., 2003). Similar talc-tremolite schists have been reported from detachment faults elsewhere in the Atlantic (Schroeder and John, 2004; Boschi et al., 2006). Subsequent to our sampling, two Ocean Drilling Program (ODP) drill holes (Site 1275) penetrated gabbroic rocks down to 209 m below seafloor; basaltic intrusions are common in the upper part of the holes (Kelemen et al., 2004).

ISOTOPE DATA

Oxygen and strontium isotopes are sensitive tracers of seawater flow through the ocean crust. Oxygen isotopes show large temperature-dependent fractionations between water and rock-forming minerals (Chacko et al., 2004). At temperatures <200–250 °C, the fractionation is greater than the difference between seawater and unaltered crust (~5.5‰; see Fig. 1), with the result that seawater-rock interaction leads to increase in $\delta^{18}O$ (Shanks, 2004). At higher temperatures, decrease in $\delta^{18}O$ results from fluid-rock reaction. Therefore, oxygen isotopes are indicators both of the extent and the temperature of fluid-rock interaction. In contrast, fractionation of Sr isotopes during fluid-rock interaction is negligible, and interaction of unmodified seawater with oceanic crustal or mantle rocks invariably leads to an increase in rock $^{87}Sr/^{86}Sr$ ratios. However, because seawater contains less Sr (~10 ppm) than basaltic rocks (50–200 ppm), isotopic anomalies generally do not advect far along the flow path, the hydrothermal fluid quickly acquiring an isotopic ratio similar to that of unaltered crust (Teagle et al., 2003). In contrast, rock-forming minerals and water contain comparable concentrations of oxygen, so oxygen isotope anomalies normally advect fur-

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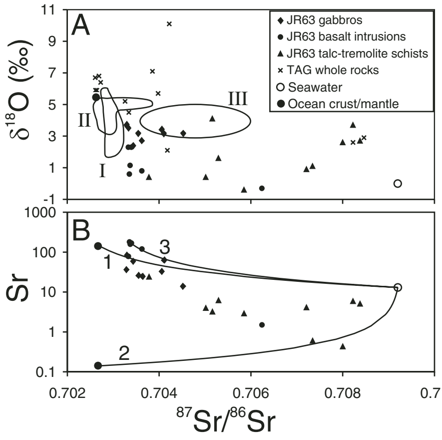

Figure 1. A: Isotopic data from JR63 (solid symbols) compared with other oceanic data sets. Altered basalts and veins from beneath TAG hydrothermal mound are from Teagle et al. (1998). I: Variably ductilely deformed gabbros from Ocean Drilling Program (ODP) Hole 735B (Hart et al., 1999). II: Altered diabase dikes interpreted as reaction zone, ODP Hole 504B (Alt et al., 1996). III: Range of isotopic values in epidosites and diabase from Troodos ophiolite (Schiffman and Smith, 1988; Bickle and Teagle., 1992; note that oxygen and strontium isotopes were measured on different samples). Seawater and ocean crust/mantle values are from Shanks (2004). At 300 °C, silicate minerals in equilibrium with seawater would have $\delta^{18}O$ values 0‰–3‰ higher than seawater, but same $^{87}Sr/^{86}Sr$. B: Variation of Sr isotopes with Sr concentration. Calculated mixing lines: 1—Seawater with ocean crust (Sr content is mean of 11 fresh intrusive basalt samples from JR63 area analyzed by L. Coogan [2006, personal commun.]); isotopic composition is assumed to be normal mid-ocean ridge basalt. 2—Seawater with fresh harzburgite (mean Sr content of four samples from ODP Leg 209; analyzed by M Godard, 2006, personal commun.). 3—Seawater with highest Sr basaltic intrusion from this study.

ther along the flow path than strontium isotope anomalies (Teagle et al., 2003).

Figure 1A shows data from three separate rocks types: fault schists, metabasaltic intrusives into the fault zone, and gabbros dredged from the footwall. Due to fine grain size, all samples are whole rocks cut out of thin-section billets. (For mineralogy, see GSA Data Repository Table DR1[1].) Fault schists show the most extreme alteration for oxygen and strontium isotopes ever reported from similar grade rocks in the ocean floor. Most have $\delta^{18}O$ values <+2‰, combined with unusually high $^{87}Sr/^{86}Sr$ ratios ranging to 0.7084. The $^{87}Sr/^{86}Sr$ ratios >0.705 in the ocean floor are normally only found in minerals precipitated at low temperature, such as carbonates associated with the Lost City vent field (Früh-Green et al., 2003), where they are combined with $\delta^{18}O$ values >+20‰. The only data comparable to ours are from two chloritized basalts from beneath the margins of the TAG hydrothermal mound in the mid Atlantic (Teagle et al., 1998). Even our gabbroic samples from the footwall are far more altered in $^{87}Sr/^{86}Sr$ than is normal in oceanic plutonic rocks (Fig. 1), although comparable degrees of alteration are seen in some ophiolites (Bickle and Teagle, 1992).

COMPOSITION AND ORIGIN OF FLUIDS IN THE FAULT ZONE

The $\delta^{18}O$ values of the most altered fault zone samples and metabasaltic intrusions indicate alteration by a fluid close to seawater in isotopic composition. The best calibrated fractionation available to us is between chlorite and water, and ranges from +1‰ at 260 °C to –0.5‰ at 360 °C (Cole and Ripley, 1999). The most extreme chlorite-rich sample has a $\delta^{18}O$ value of –0.3‰, and must have interacted with a fluid of approximately seawater composition (0‰) at temperatures of 300–400 °C. In contrast, typical black smoker vent fluids have $\delta^{18}O$ between +0.5‰ and +2.5‰ (Shanks, 2004). Our chlorites could only precipitate from such a fluid at temperatures too high to be consistent with the mineralogy of the fault zone. Amphibole at 300–400 °C should be 0.5‰–1‰ more depleted in ^{18}O than chlorite (Chacko et al., 2004), while talc is expected to be ~3‰ more enriched (Savin and Lee, 1998). The variability of whole-rock $\delta^{18}O$ values in the schists therefore mainly reflects variations in mineral proportions, with higher values in talc-rich samples. However, the overall low values (Fig. 1A) require very high fluid fluxes, significantly greater than for most previously studied oceanic systems. Compared to the fault rocks, footwall gabbros show a lower degree of oxygen isotope alteration, consistent with interaction with evolved seawater at temperatures of 350–500 °C (Hart et al., 1999).

The extremely high $^{87}Sr/^{86}Sr$ ratios in the fault rocks also require interaction with a fluid preserving isotopic ratios close to seawater, and the oxygen isotope data show that this occurred at high temperature. One possible explanation for this is that the fluids reacted with unevolved, conductively heated seawater, as suggested for some altered basalts in the margins of the TAG hydrothermal mound (Humphris et al., 1998; Teagle et al., 1998). We can discard this hypothesis on the basis that rare earth elements (REE) have been strongly mobilized in the fault zone (Fig. 2). Chloritized basaltic rocks are depleted in REEs and show a negative Eu anomaly, including one sample that is strongly enriched in ^{87}Sr. REEs are mobilized in low-pH, reducing, high-salinity fluids, but not in seawater (Humphris et al., 1998; Douville et al., 2002, Teagle and Alt, 2004). In the TAG field, chloritized basalts, altered by hydrothermal fluids, show strong depletion in REEs with negative Eu anomalies, while basalts altered by unevolved conductively heated seawater show little or no change in REE content (Humphris et al., 1998). We conclude that in our case the ^{87}Sr-enriched fluids were not pure seawater, but included a significant component of evolved hydrothermal fluid. The $^{87}Sr/^{86}Sr$ ratio of this fluid would have been much higher than that seen in typical black smokers (Shanks, 2004).

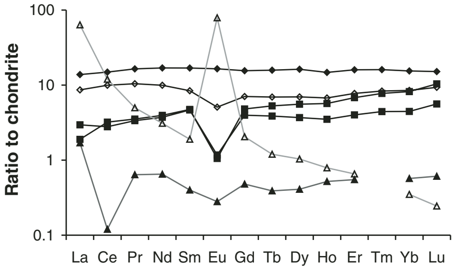

Figure 2. Rare earth element data comparing relatively unaltered basaltic intrusions (solid diamonds) cutting the fault zone and highly chloritized basalt within the fault zone (squares). Open diamonds represent chloritized chilled margin of fresh basalt, chilling against talc-tremolite schist. Solid triangles are seawater × 10^5; open triangles are Rainbow vent fluid × 10^3 (Douville et al., 2002).

Figure 1B shows that the fault-rock Sr compositions cannot be explained by simple mixing between seawater and either typical ocean crust (curve 1) or mantle rocks (curve 2), but that three-component mixing involving seawater and both mafic and ultramafic rocks could explain all the fault-rock data. The unchloritized late metabasaltic intrusions, and some gabbros, are outside these mixing lines, but all the data are beneath a mixing line between seawater and the most Sr-rich metabasalt of this study (curve 3). No data on fresh basaltic rocks are available from the study area, and it is possible that the $^{87}Sr/^{86}Sr$ ratio of the metabasalt is primary, with a plume influence (Douglass and Schilling, 2000). More likely, initial albitization increased $^{87}Sr/^{86}Sr$ without decreasing Sr content (Teagle and Alt, 2004), with subsequent chloritization occurring due to chemical exchange with the fault rocks, which were already strongly enriched in $^{87}Sr/^{86}Sr$ before the basalts were intruded.

DISCUSSION

Link Between Fault Rock Assemblages and Vent Fluids

We suggest that our metasomatic fault rocks formed part of the reactive pathway for a black smoker system similar compositionally to the

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[1] GSA Data Repository item 2007230, Table DR1, lithological summary and isotope data, and Table DR2, major and trace element data, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

ultamafic-hosted Rainbow vent field. Rainbow fluids are characterized by low pH, and high abundances of Fe, Mn, Ca, Y, and REEs compared to mafic-hosted vent systems (Douville et al., 2002). In terms of Ca and Si content, these fluids would be in equilibrium with talc and tremolite in the reaction zone (Seyfried et al., 2004). Textures in our fault rocks clearly indicate replacement of harzburgite by talc + tremolite, and basalt by chlorite ± tremolite and/or actinolite (Escartín et al., 2003). These coupled reactions involving Ca and Si mass transfer will occur wherever fluids pass between mafic and ultramafic rocks under greenschist facies conditions.

A key feature of our model is that the mixture of mafic and ultramafic rock types in the fault zone, coupled with active deformation, enhances metamorphic recrystallization, release of chemical components to the fluid, and isotopic alteration. In particular, previous studies of ocean-floor reaction zones (Bach et al., 1996) have failed to find the source of positive Eu anomalies in vent fluids (Fig. 2). In our case the Eu anomaly is easily explained by plagioclase chloritization driven by fluid moving from ultramafic to mafic rocks, although the mobility of Eu in highly reduced fluids may also play a part (Douville et al., 2002).

Fluid Flow Pathways and Fluxes

The fault zone with its intense metasomatic alteration is most likely to form part of the focused discharge zone of a hydrothermal system. It is normally assumed that recharge pathways for hydrothermal cells are diffuse compared to the discharge zones. According to chromatographic theory (Bickle and Teagle, 1992), the transport distance for an isotopic anomaly is directly proportional to the time-integrated fluid flux and the fluid-solid partition coefficient for a given element. A diffuse recharge has a relatively low time-integrated flux compared to the coexisting focused discharge. Our data can only be explained if, in contrast to other proposed discharge zones in the ocean crust, at least some batches of fluid reaching the reaction site preserved near-seawater Sr and O isotopic compositions, despite having interacted chemically with rocks along the flow path. This requires the recharge pathway to be unusually short, unusually high flux, or unusually focused compared to previously studied oceanic hydrothermal systems. A recharge pathway dominated by low Sr ultramafic rocks would help explain the Sr isotope data, but not the exceptionally low $\delta^{18}O$ values. The altered fault rocks are developed over an area of at least 25 km^2, and are not as localized as the stockwork zone beneath a black smoker field. It is likely that they were at depths >1 km below seafloor at the time of alteration, covered by the largely basaltic hanging wall of the fault and intruded by basalts under greenschist facies conditions (MacLeod et al., 2002; Escartín et al., 2003). This is the minimum recharge distance for the fluid, and the recharge time-integrated flux must have been at least comparable to that of 3×10^7 kg m^{-2} calculated for the Troodos ophiolite (Bickle and Teagle, 1992), and significantly higher than the 2×10^6 kg m^{-2} calculated for ODP Hole 504B (Teagle et al., 2003), which is much less altered for both Sr and O isotopes (Fig. 1).

Evolution of the Hydrothermal System

Figure 3 shows how different types of hydrothermal circulation could be associated with different stages in detachment fault evolution. In the early stages of extension, ultramafic rocks are not exposed on the seafloor and TAG-type vents are hosted in hanging-wall basalts. There may be little penetration of fluid into the footwall of the fault at this stage. Continued extension leads to exhumation of peridotite hosting Rainbow-type vents. Further extension and cooling of the footwall sees a change to Lost City–type peridotite-hosted venting at low temperatures. We suggest that emplacement of gabbroic magma into the footwall of the fault is essential to drive vigorous convection, but that enhanced permeability in the fault zone during deformation focuses reaction and discharge within that zone. Active extension also shortens the recharge path, leading to more intense isotopic alteration. As the gabbro cools, circulation penetrates deeper, leading to isotopic alteration in the gabbro and surrounding ultramafic rocks. Alteration to talc and chlorite-rich assemblages also weakens the fault zone, leading to very efficient strain localization along the fault zone (Escartín et al., 2003).

CONCLUSIONS

The intense metasomatic and isotopic alteration in the fault rocks shows that large volumes of fluid were focused along it at greenschist facies conditions. This requires a fault-zone permeability that is at least as great, and probably greater, than that of the hanging wall. Transient enhancement of permeability by many orders of magnitude during deformation has commonly been inferred in continental thrust faults (McCaig, 1997), but not in low-angle faults from the ocean crust. Hydrothermal vents controlled by low-angle faults would be located several kilometers away from the main volcanic zone or magma chamber, could be unusually long lived (cf. German and Lin, 2004), and if hosted mainly in ultramafic rocks, might discharge fluids with unusually high $^{87}Sr/^{86}Sr$ ratios. There is increasing physical evidence for a link between vent fields on slow and ultraslow spreading ridges and low-angle detachment faults (Tivey et al., 2003; German and Lin, 2004; deMartin et al., 2007). We have provided strong geochemical support for this hypothesis, linking alteration on a detachment fault to the chemistry of vent fluids, and showing that large amounts of hydrothermal fluid flowed along the fault.

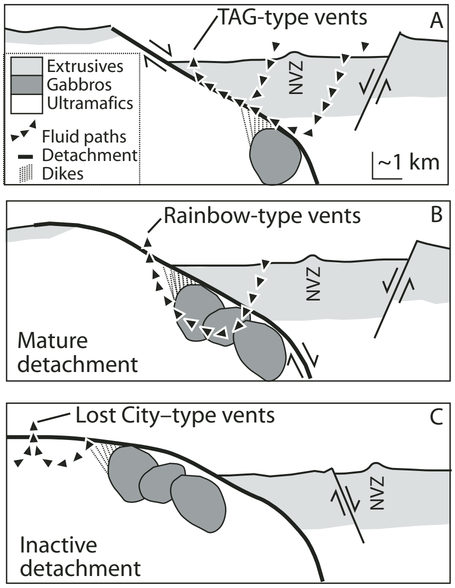

Figure 3. Model for fluid circulation and types of hydrothermal venting in and around detachment faults. A: Early intense circulation at high temperature is driven by gabbroic intrusions into variably serpentinized ultramafic footwall. Flow is focused into detachment due to deformation-enhanced permeability. TAG-type vents arise if final discharge is through highly permeable basaltic lavas at shallow depths in the hanging wall. Geometry of detachment is based on deMartin et al. (2007). B: As early-formed gabbros move away from neovolcanic zone (NVZ), flow moves down into cooling footwall, resulting in observed isotopic alteration in gabbro and intense talc-tremolite alteration in serpentinized peridotite. Discharge through exposed ultramafic-rich footwall would give rise to vent fluids similar in composition to Rainbow, which can be interpreted as occupying a similar tectonic setting (Gracia et al., 2000). C: Well away from the ridge axis and once the footwall peridotite has cooled due to exposure on the seafloor, low-temperature circulation in serpentinite leads to Lost City–type venting (Früh-Green et al., 2003).

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