Crustal magnetization reveals subsurface structure of Juan de Fuca Ridge hydrothermal vent fields

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ABSTRACT

A near-bottom geophysical survey on the Endeavour segment of the northern Juan de Fuca Ridge shows that regions of well-defined low crustal magnetization are strongly correlated with both active and extinct submarine hydrothermal vent sites. In particular, at the Main Endeavour Field, we find discrete magnetization lows associated with each cluster of vents. Magnetization lows are directly centered beneath the vent clusters and have diameters of ∼100 m, which implies a near-vertical, narrow, pipe-like source region located directly beneath the surface expression of the vent edifices. Lows are also separated from each other by only 200 m, which further implies highly focused zones. Magnetization lows are also associated with inactive and extinct vent areas, which indicates that alteration of the magnetic minerals in the crust rather than (necessarily temporary) thermal demagnetization is the primary process responsible for the low magnetization. These narrow pipe-like bodies are highly characteristic of alteration pipes found in ophiolites and are indicative of hydrothermal fluid up-flow zones. Thus, each magnetization low may define an individual upwelling zone, with distinct subsurface plumbing and thermal structure. The crustal-magnetization patterns provide important constraints on the geometry of the subsurface plumbing beneath these hydrothermal vent systems. At the Main Endeavour Field, magnetization lows are distributed along the trend of the rift valley in a semiregular pattern with a spacing of ∼200 m, arguing that upward flow may be partitioned into regularly spaced intervals along the axis of the rift valley.

Keywords: magnetic field, hydrothermal vents, marine geology, ocean crust.

INTRODUCTION

Many of the world's major metalliferous ore deposits are known to have formed in high-temperature seafloor hydrothermal environments (e.g., Hannington et al., 1995). Typically these mineral deposits have been found associated with ophiolitic rocks such as in Cyprus and Oman. Studies of these ancient deposits provide clues to the subsurface structure of such deposits. For example, in Cyprus, pipe-like alteration zones and stockwork zones, to 100 m in diameter, have been mapped beneath ancient copper deposits (Richards et al., 1989). While our understanding of the processes that control ore-body formation is limited by the tectonism, alteration, and metamorphism of these ancient deposits, it is now recognized that present-day seafloor hydrothermal systems are the modern analog to these ancient deposits. Thus, by studying the modern system we can gain insight into the processes that create significant ore deposits.

One of the key questions concerning seafloor hydrothermal systems is the geometry of the fluid circulation system through oceanic crust. Although upwelling paths, reservoir location and size, and the sites of recharge are basic parameters for any fluid-circulation system, they are almost completely undefined for marine hydrothermal systems. From ophiolite and seafloor studies it is known that hot corrosive fluids are transported from the lower crust to the water-rock interface along discrete up-flow zones (Hannington et al., 1995; Richards et al., 1989). The factors that control the geometry and the interaction between adjacent vent systems remain largely unknown. For example, surface vents can be frequently correlated with fault zones, but it is not known whether the upwelling pathways are controlled by these local tectonic features, by local porosity heterogeneities in the crust, or by larger, segment-scale circulation. Any horizontal flow in the upwelling path or connection between adjacent vent systems at depth is also purely speculative, but extremely important. The geometry of the up-flow zone also controls the location of the sulfide and oxide mineralization and how this mineralization is ultimately distributed within the host rock, either as disseminated or as massive bodies. Fluid flow geometry could have an important impact on the distribution of microbial populations within the oceanic crustal environment (e.g., Huber et al., 2002; Summit and Baross, 2001).

Geophysical techniques such as magnetic field mapping have proven useful in determining the lateral extent of alteration pipes in ophiolites (Hall et al., 2001; Johnson et al., 1982) and in some isolated seafloor vent systems (Tivey et al., 1993). The magnetization of young oceanic crust arises primarily from the extrusive basaltic lavas that form the uppermost section of the seafloor. This magnetization is a primary thermal remanent magnetization carried by ferrous-rich titanomagnetite grains, which are highly sensitive to alteration. The acidic and corrosive fluids that form marine hydrothermal vent systems can quickly alter or replace the iron-rich magnetic minerals, reducing the magnetic remanence of the crustal rocks, in some cases to zero (Ade-Hall et al., 1971; Auerbach and Bleil, 1987; Johnson et al., 1982; Rona, 1978). Seafloor hydrothermal vent systems are therefore likely to be underlain by discrete zones of altered crust with substantially less magnetization than immediately adjacent unaltered rocks.

DATA COLLECTION AND PROCESSING

A high-resolution near-bottom geophysical survey was carried out over the axial rift valley of Endeavour Ridge, a medium-spreading-rate oceanic spreading center on the northern Juan de Fuca Ridge (Johnson et al., 2002). The survey collected data over the course of two cruises; the first cruise in 2000 and the second in 2001 using the remotely operated vehicle *Jason* and the dynamic-positioning capability of the R/V *Thomas Thompson.* The survey was navigated by using an acoustic transponder net. *Jason* was fitted with a swath-mapping sonar, a conductivity-temperature-depth sensor and a three-axis magnetometer sensor to collect full-swath bathymetry, seawater temperature and salinity, and magnetic field data, respectively. The survey encompassed both the Main Endeavour Field (Delaney et al., 1992; Robigou et al., 1993; Tivey and Delaney, 1986) and the High Rise hydrothermal vent field, ∼2.5 km north of the Main Endeavour Field (Robigou et al., 1993). Data were collected along track lines spaced ∼40 m apart at ∼20 m altitude over an area 3.5 km along axis and ∼1 km across axis. Swath bathymetry mapping utilized the newly available Simrad-2000 sensor, a 200 kHz swath sonar capable of imaging individual structures with a footprint of <1 m. Magnetic field data were collected by using a three-axis magnetometer mounted to *Jason*'s aluminum frame. The magnetic field data were first calibrated for the permanent magnetic field of *Jason* by spinning the vehicle in the water column and

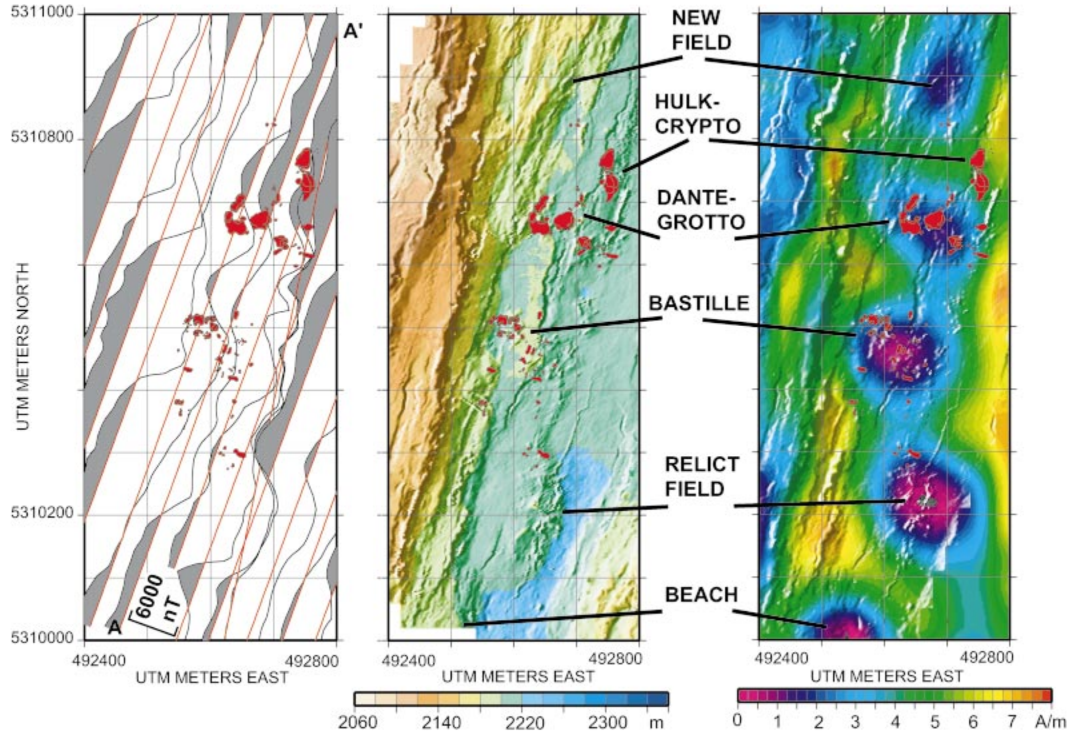

Figure 1. Left panel shows observed magnetic field anomalies along track lines shown in red. Red areas are published locations of Main Endeavour Field sulfide chimney edifices (after Delaney et al., 1992, 1997). A–A′ marks start and end of profile shown in Figure 2. Middle panel shows seafloor bathymetry (Johnson et al., 2002). Vent chimney locations are only approximate; errors in location are ~10 m and have not been adjusted to more detailed bathymetric map. Right panel shows crustal magnetization; note correlation of circular magnetization lows with active and inactive vent areas.

removing the magnetic effect of this motion by using a Nelder-Meade minimization (Press et al., 1986). The three-component magnetic field data were vector summed to give total field. A regional magnetic field based on the 2000 IGRF (International Geomagnetic Reference Field) (IAGA Division V, 2000) and adjusted for the survey years 2000 and 2001 was removed from the observed field. The residual magnetic anomaly data were then interpolated onto a 20-m-spaced grid by using a nearest-neighbor algorithm (Smith and Wessel, 1990). This observed magnetic field grid was then continued upward to a level plane above the bathymetry by using the Guspi (1987) method. The corrected magnetic field was inverted for crustal magnetization by assuming a constant-thickness source layer (500 m), the upper surface of which is defined by the bathymetry and magnetization direction based on the geocentric dipole for lat 48°N (Parker and Huestis, 1974). To reduce the amount of filtering and maximize spatial resolution, we used subsets of the data around several key areas of interest (Fig. 1). For the Main Endeavour Field, the magnetic field was continued upward to −2.09 km level and inverted for crustal magnetization. The data were bandpass filtered (pass band of 320 m to 80 m with cutoffs of 640 and 40 m) to ensure convergence toward a solution during inversion. Magnetization inversion is a nonunique process, and one representation of this property is the annihilator, a magnetization function that when convolved with the bathymetry produces no external magnetic field (Parker and Huestis, 1974). An arbitrary amount of annihilator can be added to the solution without affecting the resultant magnetic field. The annihilator typically produces a simple DC-level offset in the magnetization solution. If we assume that the crust within the axial valley is of normal Brunhes polarity and that no reversely magnetized crust is present, then we can add sufficient annihilator (seven times the annihilator) to make the magnetization nonnegative. The range in crustal magnetization from the inversion of the entire region varies from 0 to 20 A/m, a typical range of values for basalt based on the magnetization of rock samples sampled in the area (Tivey and Johnson, 1993).

RESULTS AND DISCUSSION

Each of the known hydrothermal vent complexes in the Main Endeavour Field area (Fig. 1), with one exception, is associated with clearly defined circular magnetization-anomaly lows. The exception is the Hulk-Crypto edifice, which apparently has no obvious anomaly associated with it. The Hulk-Crypto complex is discussed later. The two main areas of Main Endeavour Field—the Bastille complex to the south and the Dante-Grotto complex to the north (Delaney et al., 1992)—are both associated with well-defined magnetization lows (Fig. 1). Other discrete magnetic lows are found southeast of the Main Endeavour Field and are associated with an almost completely extinct vent field with only very weak diffuse flow observed around large inactive sulfide spires. Magnetic lows are also found associated with a newly discovered smaller vent-field area adjacent to the rift-valley wall, northeast of the Main Endeavour Field, and with the Beach diffuse venting area in the southernmost part of the Main Endeavour Field (Johnson et al., 2002). The anomalies are quite simple in plan view with no short-wavelength components, indicating that the vent chimney structures do not produce any significant anomalies that could be attributed to magnetic sulfide or oxide mineralization. We can make several observations about the spatial distribution of these magnetization-anomaly lows: (1) they are clearly associated with the location of hydrothermal vent areas, (2) the anomalies are typically centered around the vent areas, suggesting near-vertical zones of reduced magnetization beneath the vents, (3) most anomalies have a circular symmetry, indicating that the zone of reduced magnetization has a narrow, pipe-like source region, and (4) magnetization lows are also found associated with extinct vent areas, indicating that alteration rather than (necessarily temporary) thermal demagnetization is the process responsible for the reduced magnetization. These observations apply not only to the Main Endeavour Field, but also on a regional scale. All of the major known active hydrothermal vent fields and inactive or extinct vent fields on the Endeavour Ridge segment between the Main Endeavour Field and High Rise are associated with strong magnetic anomaly lows (Johnson et al., 2002).

An important observation is that these magnetization lows appear to be quite distinct from each other and have clear boundaries. For example, the Bastille vent complex has a magnetization low that is clearly separate

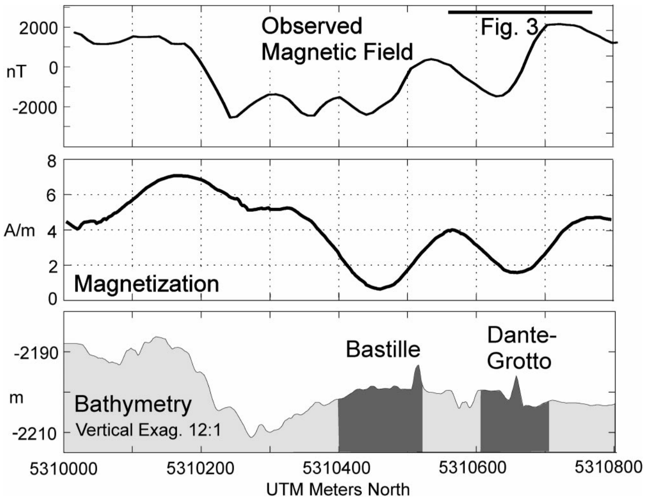

Figure 2. Extracted profile across two main vent complexes (Bastille and Dante-Grotto) of the Main Endeavour Field. Top panel shows observed magnetic field measured at ~25 m altitude and location of Figure 3. Middle panel shows magnetization inversion. Bottom panel shows bathymetry (vertical exaggeration = 12:1). Note that whereas wavelength of magnetization inversion shows zones of low magnetization of 100 m across, these zones are more likely to be ~50 m on basis of magnetic field data.

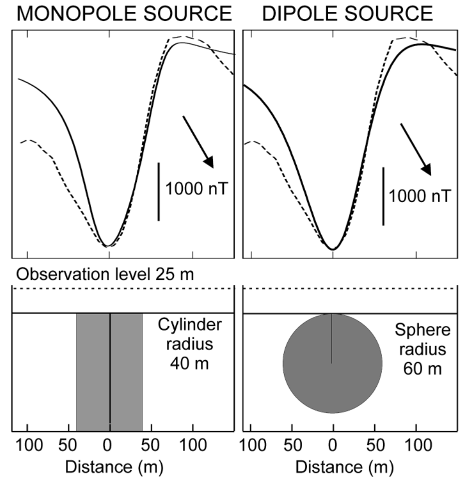

Figure 3. Plot showing fit of monopole (left) and dipole (right) source to part of observed field data (solid line in both plots) over Dante-Grotto area. Dipole source is represented by buried sphere (radius 60 m); monopole source is represented by narrow cylindrical body of 40 m radius with great depth extent. These results show that it is not possible to choose between two models. Arrow indicates field inclination of 68°; source bodies are negatively magnetized relative to surrounding crust.

from a low beneath the Dante-Grotto vent complex, which is located only ~200 m north (Fig. 1B). Although a small fault zone, visible from the bathymetry data, appears to join the two vent systems, there is no corresponding zone of reduced magnetization linking the two systems. This fact implies that the zones of upward fluid flow beneath these two vent systems in the uppermost crust (500 m) are separate and may not intermingle, at least in the upper few hundreds of meters. This view is compatible with the suggestion that the Endeavour types of vents are fed from pipe-like stockwork zones that are armored by silica deposition, preventing significant seawater entrainment (Hannington et al., 1995; Tivey et al., 1999). The Endeavor vent fluids are highly ammonia rich (Butterfield et al., 1994; Lilley et al., 1993) compared with TAG (Trans-Atlantic Geotraverse) and Galapagos vent types, and it is this fluid chemistry that apparently controls the morphology of the vent systems at Endeavour (Tivey et al., 1999).

We can model the observations by using simple magnetic bodies, such as a dipole (represented by a buried sphere or body of limited depth extent) or a monopole (i.e., the top of a narrow magnetized cylinder of infinite depth extent). The magnetic field of a dipole source falls off more rapidly with horizontal distance than that of a monopole source; i.e., $1/r^3$ versus $1/r^2$, respectively, which has implications for the depth and extent of the source region. We matched these two simple models to the raw observed profile (A–A′ in Fig. 1) taken from the survey track across the two main vent areas of the Main Endeavour Field. We fit only the northern side of the anomaly because the southern edge is contaminated with the effect of the nearby anomaly low over the Bastille vent area (Figs. 2 and 3). The observed magnetic field at ~25 m altitude (Fig. 2) shows that it is not possible to choose between the monopole source (a cylinder with infinite depth extent) and the dipole source (a sphere) (Fig. 3). Additional vertical gradient measurements would be needed to resolve the depth to the base of the source body. The amplitude of the anomaly also provides an estimate of the size or volume of the source body. From the magnetization inversion, the maximum gradient of the anomaly marks the presumed edge of the source body, which occurs at ~3 A/m for each of the anomalies (Figs. 1 and 2). The 3 A/m contour produces a roughly circular 100-m-diameter zone, which with an assumed base at 500 m gives a volume of 4×10^6 m^3. The unfiltered observed magnetic-field-anomaly data (Fig. 2) suggest a slightly narrower source region, i.e., ~50 m across, which would imply deeper depth extent by a factor of 4, i.e., 2 km for a perfectly narrow pipe-like zone or, perhaps more likely, a widening of the source zone with increasing depth.

Another observation is the almost regular spatial pattern of magnetization lows that extends in a slightly staggered fashion from south to north in the Main Endeavour Field (Fig. 1). The spacing of the lows is ~200 m, and they are separated from the main west wall of the rift valley by ~100–200 m. Offsets in the trend of the rift-valley boundary fault also appear to correlate with the segmentation of the anomaly lows and the vent regions, suggesting a close tie between local tectonics and faulting and the location of the vent systems (Fig. 4). The close spacing between the up-flow zones along the axis suggests that it is unlikely that hydrothermal circulation is oriented in a ridge-parallel fashion, i.e., slot convection along the axis (Delaney et al., 1997). The observed spatial geometry of the anomalies coupled with the inference of narrow pipe-like source zones having a depth extent of several hundred meters implies an across-axis circulation flow as the primary fluid flow path rather than slot convection.

The Hulk-Crypto vent complex, 100 m north of the Dante-Grotto vent complex, provides the single exception to the tight correlation of vent systems with magnetization-anomaly lows (Fig. 1). No zone of low magnetization is observed centered beneath this complex, even though this field is a large, actively venting system. There are several possible explanations for this lack of correlation: the up-flow geometry beneath this sys-

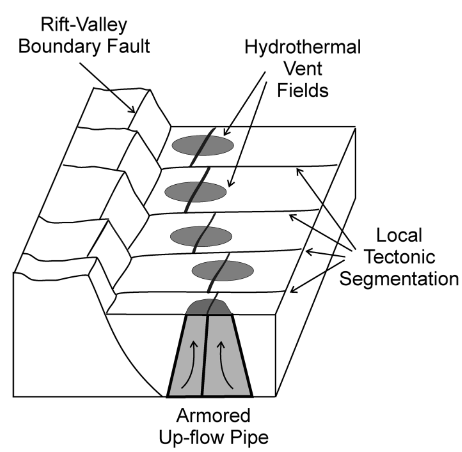

Figure 4. Proposed geometry of hydrothermal circulation in uppermost crust for Main Endeavour Field. Surface hydrothermal vents are located over narrow up-flow zones, which may broaden with depth. These up-flow zones appear to be spaced at regular intervals along axis, suggesting partitioning perhaps by local tectonics and across-axis circulation rather than along-axis slot convection.

tem could be small and the associated alteration may not have developed. The vent structure might be magnetic, which could offset any magnetic low, although its pyrrhotite content is not appreciably greater than any other structure (Tivey et al., 1999). The fluid could be supplied laterally, perhaps from the Dante-Grotto system, thus obviating the need for a root. The Hulk-Crypto complex is venting cooler fluids in the 330–350 °C range with near-seawater salinities compared to the higher temperature and lower chlorinity fluids of the Bastille system in the southern part of the Main Endeavour Field (Butterfield et al., 1994). This suggests that the Hulk fluids have been conductively cooled away from the two-phase curve and may follow a less than direct course to the seafloor interface (Delaney et al., 1997). There is no obvious lateral connection in the magnetization zones between the Dante-Grotto and Hulk-Crypto complexes to suggest significant lateral transport. If the upward flow beneath the Hulk-Crypto complex is very narrow and along a linear fault zone parallel to the ridge axis, we may not have imaged it, given our track-line spacing of 40 m. We note, however, that a survey line directly crosses over the Hulk-Crypto vent and the track spacing was more than adequate to resolve all the other vents in the area (Fig. 1A). We must conclude that any alteration zone, if present, is simply not very well developed at this site. One possibility is that the Hulk-Crypto vent system is relatively young and has not yet developed a significant root system, although morphological evidence suggests that this is a mature vent edifice (M.K. Tivey, 2002, personal commun.).

In conclusion, magnetic-field imaging of the subsurface crustal structure beneath submarine hydrothermal vent systems provides strong evidence for the existence of narrow pipe-like bodies that are the pathways of fluid flow feeding the surficial hydrothermal vent systems. These zones appear to be sharply defined with near-vertical pipe-like geometry and with a depth that reaches at least a few hundreds of meters, possibly to the base of the extrusive crust. These narrow pipe-like zones are compatible with the fluid chemistries and mineral assemblages, suggesting that the Endeavor vent fields are underlain by silica-armored alteration pipes with little or no seawater entrainment at depth (Tivey et al., 1999). The staggered pattern of anomalies with regular 200 m spacing along the rift valley at the Main Endeavour Field suggests an across-axis component to the hydrothermal circulation patterns rather than the along-axis slot-convection model.

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