The magnetic signature of ultramafic-hosted hydrothermal sites

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ABSTRACT

Unlike basalt-hosted hydrothermal sites, characterized by a lack of magnetization, the magnetic signature of ultramafic-hosted hydrothermal sites remains poorly known, despite their wide occurrence at slow-spreading ridges and their strong mineral potential. The first high-resolution magnetic surveys of such ultramafic-hosted sites, achieved by deep-sea submersible on four sites of the Mid-Atlantic Ridge, reveal positive magnetic anomalies, and therefore a strong magnetization at the largest sites. This observation reflects the presence of a wide mineralized zone beneath these sites, the stockwork, where several chemical processes concur to create and preserve strongly magnetized magnetite. Beyond pointing out the importance of subsurface chemical processes in hydrothermal activity, the aging of oceanic lithosphere, and the ocean chemical budget, our results have immediate application for detecting and characterizing economically valuable deep-sea mineral deposits.

INTRODUCTION

Hydrothermalism at mid-oceanic ridges and backarc basins contributes significantly to the dissipation of the Earth internal heat and to the ocean chemical budget. After the first direct observations of hydrothermal systems on the Galapagos Rift (Corliss et al., 1979), the discovery of hydrothermal site TAG (Trans-Atlantic Geotraverse) on the Mid-Atlantic Ridge (MAR) (Rona et al., 1986) revealed that slow-spreading ridges also support high-temperature venting. As a result of a more complex geology (Gente et al., 1995) characterized by a limited magma supply (Cannat, 1993) and a dominant tectonic activity (Tucholke et al., 1998; Escartín et al., 2008), mantle outcrops are frequently observed at slow-spreading ridges, and at least six hydrothermal sites on such a basement have been identified on the MAR (Fouquet et al., 2010, and references therein). While the magnetic response of basalt-hosted hydrothermal systems is well known (Tivey et al., 1993; Tivey and Johnson, 2002; Tivey and Dyment, 2010; Zhu et al., 2010; Caratori-Tontini et al., 2012; Honsho et al., 2013; Szitkar et al., 2014), the magnetic response of high-temperature ultramafic-hosted hydrothermal sites remains poorly documented (Tivey and Dyment, 2010), despite their important mineral potential (Fouquet et al., 2010). In this paper we investigate the magnetic signature of four ultramafic-hosted sites discovered on the MAR.

GEOLOGICAL SETTING OF ULTRAMAFIC-HOSTED SITES

Sites Rainbow, Ashadze 1, Ashadze 2, and Logachev are high-temperature active vents with average fluid temperatures of 296–370 °C (Fouquet et al., 2010; Charlou et al., 2010, and references therein).

Site Rainbow extends over a 300 × 200 m area on the eastern flank of the MAR at 36°13′N, 33°54′W, at a depth of ~2300 m (German et al., 1996; Fouquet et al., 1997). It is located on the western side of a large (10 × 10 km) ultramafic hill, within a non-transform discontinuity. The site consists of three parts, from west to east: a 150-m-wide inactive and tectonized hydrothermal mound bounded by a 50-m-high ridge-facing fault scarp; a 150-m-wide, ~25-m-high fault-controlled active hydrothermal mound covered by black smokers, fallen chimneys, and hydrothermal sediments; and several isolated groups of active black smokers without significant sulfide accumulation, suggesting an immature mound (Fouquet et al., 2010) (Fig. 1).

Site Ashadze 1 is located at 12°58′N, 44°51′W (Cherkashov et al., 2008), 4 km west of the MAR axis. It is one of the deepest known active hydrothermal sites (4100 m). Active and inactive chimneys are found in a 150 × 70 m flat area (Fig. 2), roughly aligned on the crest of an east-west–trending spur (Ondréas et al., 2012; Cannat et al., 2013).

Site Ashadze 2 is located 5 km northwest of Ashadze 1 at 12°59′N, 44°54′W (Cherkashov et al., 2008), at a depth of 3270 m. Fossil chimneys align along the western side of a 200-m-long north-northeast tectonic depression separating a gabbro massif from serpentinite (Fig. 3C). Hydrothermal activity is found in the depression, on a crater-shaped structure, ~5 m high and 25 m in diameter, with numerous venting small chimneys within the crater. This smoking crater suggests explosive episodes of hydrothermal discharge (Fouquet et al., 2010; Ondréas et al., 2012).

Site Logachev is located south of the Fifteen-Twenty Fracture Zone, on the eastern flank of the MAR at 14°45′N, at depths ranging from 3060 to 2910 m (Krasnov et al., 1995). Seven active hydrothermal areas are aligned along a southeast-northwest trend over a distance of 500 m on the flank of a westward slope (Fig. 3D). These sites are <15 m high and <50 m in diameter; five of them are smoking craters (Petersen et al., 2009).

DATA AND METHODS

High-resolution bathymetric and magnetic data were acquired in the four study areas using remotely operated vehicle (ROV) *Victor* of Ifremer (Institut Français de Recherche pour l'Exploitation de la Mer) during cruises MoMARDREAM and Serpentine (Fig. 3). Samples collected at

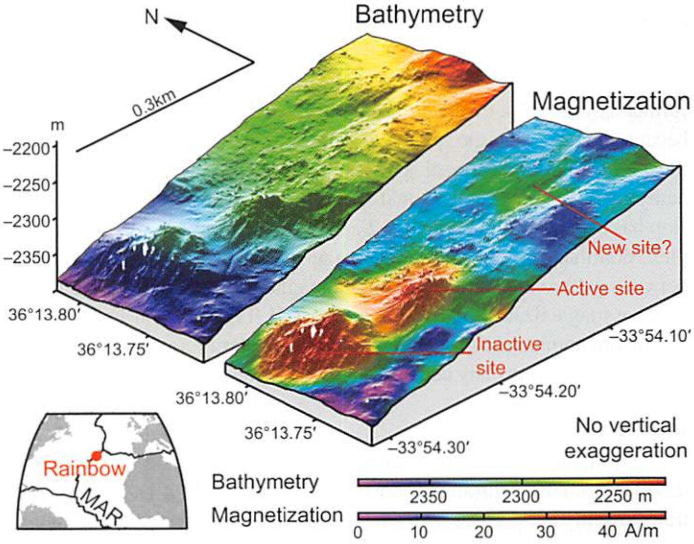

Figure 1. Ultramafic-hosted hydrothermal site Rainbow (Mid-Atlantic Ridge [MAR] at 36°13′N); location shown in inset. Left: Bathymetry in three-dimensional (3-D) view. The westernmost hydrothermal mound is cut by a fault on its western flank, resulting in stockwork mineralization outcrops and hydrothermal debris in the talus. Right: Equivalent magnetization draped on bathymetry in 3-D view. Strong positive magnetization contrasts are associated with the two hydrothermal mounds.

GEOLOGY, August 2014; v. 42; no. 8; p. 715–718; Data Repository item 2014266 | doi:10.1130/G35729.1 | Published online 30 June 2014

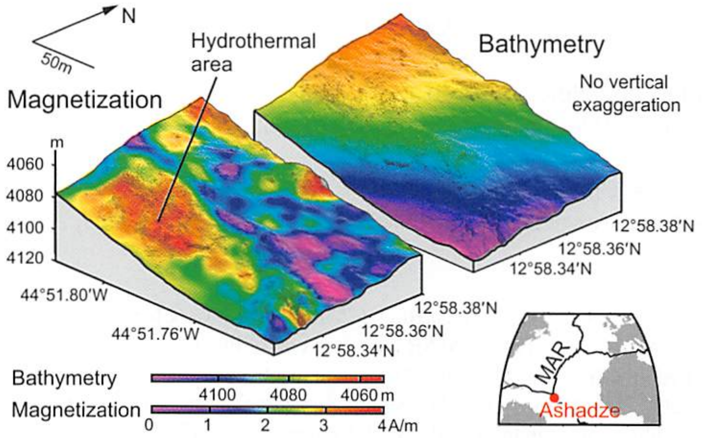

Figure 2. Ultramafic-hosted hydrothermal site Ashadze 1 (Mid-Atlantic Ridge [MAR] at 12°58′N; location shown in inset). Right: Bathymetry in three-dimensional (3-D) view. Left: Equivalent magnetization draped on bathymetry in 3-D view. A strong positive magnetization contrast is associated with the active hydrothermal site.

Rainbow during the 2001 cruise Iris were also measured for their magnetic properties (Fig. 4; see the GSA Data Repository[1]).

The magnetic data were collected at a sampling interval of 50 cm using a 3-component fluxgate magnetometer rigidly fixed to the ROV. The survey altitude was constant at 10 m above the seafloor (with a track line spacing of ~10 m) for both Rainbow and Ashadze 1, and at 20 m above the seafloor (with a track line spacing of 50 m) for Ashadze 2 and Logachev. The ROV magnetic influence was quantified using calibration loops performed during the descent, far from both the ship and the seafloor, and removed from the data to obtain vector and scalar magnetic anomalies (Isezaki, 1986; Honsho et al., 2009). We present the original magnetic anomaly for all sites in Figure 3.

Equivalent magnetizations were computed for Rainbow and Ashadze 1 using a new inversion method (Honsho et al., 2012) that takes full advantage of the varying altitudes and depths of the ROV and alleviates the need for upward continuation of the measurements to a datum plane required by other inversion methods (Parker and Huestis, 1974). We assumed a 100-m-thick magnetized layer, no magnetization variation with depth, and a magnetization vector direction parallel to the local geomagnetic field vector. We further assumed that the magnetization is positive in the investigated areas, because they are near the spreading axis, on oceanic crust younger than the most recent polarity reversal. The resulting magnetization is draped on the bathymetry in three-dimensional (3-D) views (Figs. 1 and 2). No inversion has been applied to Ashadze 2 and Logachev. On Ashadze 2, the complex, dominantly north-northeast, magnetic anomaly reflects the contact between gabbro and peridotite, and no magnetic dipole corresponding to a positive magnetization contrast was detected (Fig. 3C). On Logachev, no significant anomaly is observed on the two western mounds, and the poor data quality prevents any conclusion on the eastern ones (Fig. 3D).

RESULTS

Strong positive magnetization contrasts are found on the two hydrothermal mounds of ultramafic-hosted site Rainbow (Fig. 1). Both the central, currently most active hydrothermal area and the western, now inactive area show a strong positive equivalent magnetization (~30 A/m). The cessation of hydrothermal activity in the western mound has not been dated, but the mound is dissected by a fault on its west flank (Fig. 1), resulting in a 50 m steep scarp and exposing a stockwork zone (Marques et al., 2007). The easternmost part of Rainbow, in the area of small active black smokers, reveals a weaker positive magnetization contrast (~6 A/m), consistent with the hypothesis of an immature site. Hydrothermalism seems to have moved progressively eastward over time. Both active and inactive areas of this ultramafic-hosted hydrothermal site are characterized by a positive magnetization contrast.

Natural remanent magnetization (NRM) and susceptibility measured on a representative collection of rock samples, including massive sulfides, stockwork mineralization, and mantle basement rocks from Rainbow (Fig. 4; see the Data Repository) reveal that neither sulfide nor serpentinized peridotite alone bears a significant magnetization. Conversely, sulfide-impregnated serpentinites exhibit both strong NRM and susceptibility that amount for the amplitude of the observed anomalies. The measured Curie temperature of ~580 °C shows that magnetite is the main magnetic bearer of these samples, and the variability of their Koenigsberger ratio (NRM versus induced magnetization) suggests a diversity of magnetic grain sizes. These rock magnetic measurements confirm that the stockwork zone is the main contributor to the observed positive magnetization. Neither the hydrothermal chimneys (standing or fallen) nor the surrounding serpentinized peridotites contribute significantly to the specific magnetic signature of the site.

On Ashadze 1, the magnetic inversion displays a positive magnetization contrast (~4 A/m) on an area where active black smokers have been observed (Ondréas et al., 2012) (Fig. 2). Although much weaker than on Rainbow, this magnetic signature suggests that high-temperature ultramafic-hosted sites of dimensions larger than ~50 m are characterized by a positive magnetization contrast. Conversely, smaller ultramafic-hosted sites such as Ashadze 2 and Logachev, made of several dispersed mounds, smoking craters, or chimneys, do not show this magnetic signature (Fig. 3), possibly because they correspond to unstable systems with a less focused discharge (Fouquet et al., 2010). Furthermore, our data from these areas are not adequate to detect the anomalies that would be associated with these small features.

DISCUSSION

While the lack of magnetization observed at basalt-hosted hydrothermal sites is mainly due to the alteration of titanomagnetite to less magnetic titanomaghemite, the extra magnetization at ultramafic-hosted sites may also be the consequence of chemical processes active at slow-spreading centers. In contact with seawater and/or hot hydrothermal fluids, peridotite is altered to serpentinite, a transformation that generates magnetite (Toft et al., 1990).

Serpentinized peridotite exhibits various intensities of both induced and remanent magnetizations: its magnetite content and grain size depends on the physical and chemical conditions prevailing at the time of its formation (Oufi et al., 2002). Experiments (Allen and Seyfried, 2003; Malvoisin et al., 2012) and models (McCollom and Bach, 2009) show that iron is preferentially partitioned into brucite below ~150 °C and magnetite between ~150 °C and 300 °C. Our rock magnetic measurements show that magnetite produced in the serpentinized peridotite host rock of the stockwork zone reflects the high temperature and greater fluid flow at the site compared with the surrounding rocks of the Rainbow massif, which presumably encounter diffuse percolation of seawater and low-temperature alteration (Fig. 4). In addition, the high hydrogen content of hydrothermal fluids resulting from the serpentinization process creates a more reducing environment than on a basaltic substratum (Charlou et al., 2010), protecting magnetite from oxidation; the magnetite in contact with hot hydrothermal fluids retains its magnetization, whereas that in contact with cold seawater is altered to maghemite and ultimately to nonmagnetic minerals. A minor additional effect is high-temperature oxidation of the copper sulfide–rich stockwork that may result in the formation of bornite

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[1] GSA Data Repository item 2014266, description and magnetic properties of samples from Rainbow, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

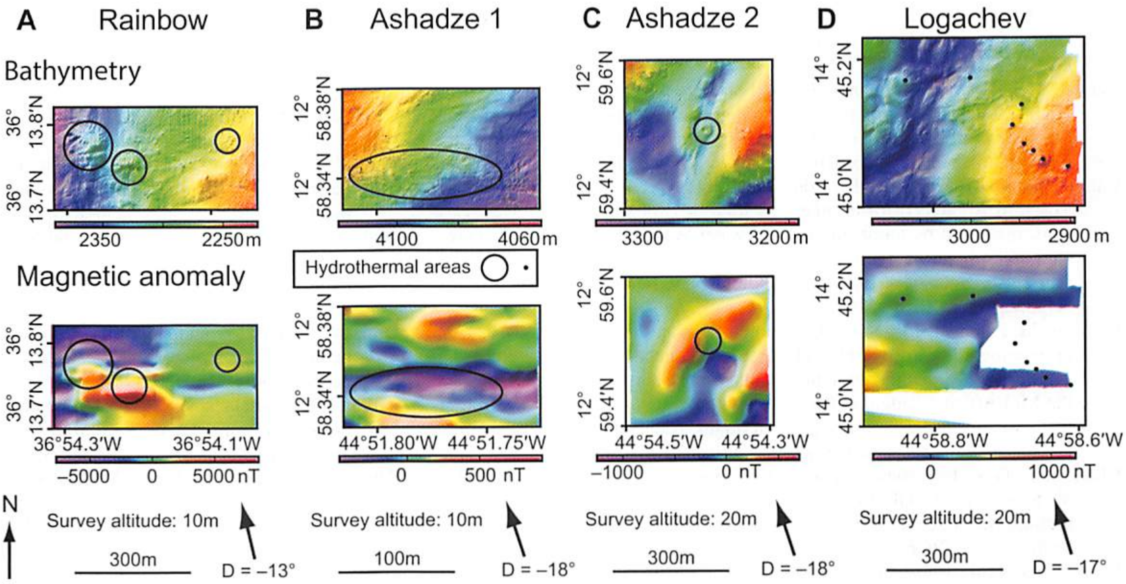

Figure 3. Bathymetry (top) and magnetic anomaly (bottom) for the ultramafic-hosted hydrothermal sites investigated in this study. A: Rainbow. B: Ashadze 1. C: Ashadze 2. D: Logachev. Maps are shown at the same scale, except for Ashadze 1, which is enlarged 3×. Arrow shows direction of the geomagnetic field (D is declination in degrees) and helps recognition of dipolar anomalies associated with geological features: a positive contrast of magnetization creates a dipole with a positive lobe toward the equator and a negative one toward the magnetic pole, as observed on the hydrothermal mounds at Rainbow. Survey altitudes, scales, and locations of the main hydrothermal areas are also indicated. Rainbow and Ashadze 1 display dipolar anomalies corresponding to a positive magnetization contrast, whereas Ashadze 2 and Logachev do not.

and hydrothermal magnetite, as documented on black smoker chimney conduits (Marques et al., 2007). These processes together explain the presence of strongly magnetized magnetite in the stockwork zone underlying the large ultramafic-hosted hydrothermal sites, and therefore the magnetic signature of these sites. Their relative importance, however, remains a matter of further investigation.

The magnetic anomaly amplitude and resultant equivalent magnetization contrast are directly related to the amount of magnetized material; i.e., in first approximation, the volume of the stockwork zone. This is illustrated by Rainbow, where the two main hydrothermal mounds display a thick stockwork zone (~2 × 10^6 m^3, compared to ~0.5 × 10^6 m^3 at TAG) and a strong magnetic anomaly, whereas the nascent eastern hydrothermal site only presents a weak magnetic anomaly. Based on this inference, the amount of magnetic material beneath Ashadze 1 would be one-eighth of that beneath any of the Rainbow mounds.

CONCLUSION

The larger, high-temperature, ultramafic-hosted hydrothermal sites Rainbow and Ashadze 1 are associated with positive magnetization contrasts reflecting high-temperature serpentinization. Conversely, the smaller sites Logachev and Ashadze 2 do not exhibit such a magnetic signature, likely as a result of unstable and less focused hydrothermal activity distributed over faults a few hundred meters long. The strong positive magnetization at large ultramafic-hosted sites is the result of a magnetite-rich stockwork zone, which only reaches a significant size at the more focused and stable sites. The stockwork should be seen as a chemical reactor in which iron plays a major role at ultramafic sites. This is also illustrated by the abundance and variety of iron-sulfide minerals (Fouquet et al., 2010), the iron-rich fluid chemistry (Charlou et al., 2010), and biological symbioses based on the oxidation of Fe^{2+} to Fe^{3+} (Zbinden et al., 2004).

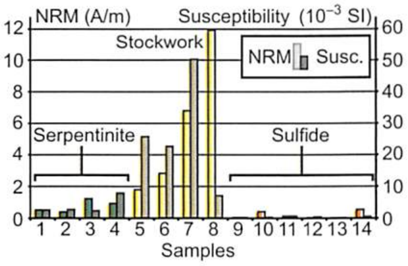

Figure 4. Magnetic properties of samples collected on hydrothermal site Rainbow. Left: Natural remanent magnetization (NRM). Right: Magnetic susceptibility (Susc.). Dredges across the fault marking the western flank of the inactive site gave access to the variety of rocks (marked by bars with different colors) within and around the hydrothermal site. Samples from the deep hydrothermal site (stockwork, made of sulfide-impregnated serpentinized peridotites, yellow) are characterized by both a strong NRM and induced magnetization, whereas samples from the shallow hydrothermal site (chimneys, made of pure sulfide, orange) or from the surrounding seafloor (serpentinized peridotites, dark green) display weaker magnetic properties.

This observation differs from the lack of magnetization associated with basalt-hosted hydrothermal sites, resulting from nonmagnetic hydrothermal deposits and the permanent alteration of titanomagnetite by the hydrothermal fluids (Tivey and Johnson, 2002; Szitkar et al., 2014). These different magnetic signatures appear to be a consequence of the same processes, i.e., high-temperature alteration and hydrothermal mineralization, applied to different geological contexts. Such an observation points out the importance of the subsurface chemical processes in the hydrothermal activity, the aging of the oceanic lithosphere, and the geochemical budget of the oceans. Practically, the magnetic signature of seafloor hydrothermal systems can be used as a tool to detect and characterize active and fossil hydrothermal sites and the type of associated mineral deposits. Furthermore, it offers a means to evaluate the volume of the stockwork for ultramafic-hosted sites, which rank among the richest potential mining targets on the seafloor due to their Cu, Zn, Co, Ag, and Au enrichment (Fouquet et al., 2010).

ACKNOWLEDGMENTS

We thank the captain, crew, and scientific teams of cruises Iris (R/V *L'Atalante*, 2001), Serpentine (R/V *Pourquoi pas?*, 2007) and MoMARDREAM (R/V *L'Atalante*, 2008). IPGP (Institut de Physique du Globe de Paris), CNRS-INSU, Ifremer, and Genavir are gratefully acknowledged for their financial and technical support. Szitkar was supported by a fellowship funded by IFREMER and CNRS, and collaborated with Honsho during a visit funded by an InterRidge Fellowship. We are grateful to D. Levaillant for processing the bathymetric data displayed in Figure 1. We thank the anonymous reviewers for useful suggestions. This is IPGP contribution 3541.

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Manuscript received 30 March 2014
Revised manuscript received 2 June 2014
Manuscript accepted 3 June 2014

Printed in USA