Magnetic exploration of a low-temperature ultramafic-hosted hydrothermal site (Lost City, 30°N, MAR)

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Highlights:

- First magnetic exploration of a low-temperature ultramafic-hosted hydrothermal site
- New inversion method resolves high-resolution magnetic anomaly in a steep environment
- Lost City bears a positive magnetization resulting from specific chemical processes

Abstract

A 2003 high-resolution magnetic survey conducted by the Autonomous Underwater Vehicle *ABE* over the low-temperature, ultramafic-hosted hydrothermal field Lost City reveals a weak positive magnetic anomaly. This observation is in direct contrast to recent observations of strong positive magnetic anomalies documented over the high-temperature ultramafic-hosted hydrothermal vents fields Rainbow and Ashadze, which indicates that temperature may control the production of magnetization at these sites. The Lost City survey provides a unique opportunity to study a field that is, to date, one of a kind, and is an end member of ultramafic-hosted hydrothermal systems. Our results highlight the key contribution of temperature on magnetite production resulting from serpentinization reactions. Whereas high temperature promotes significant production and partitioning of iron into magnetite, low temperature favors iron partitioning into various alteration phases, resulting in a magnetite-poor rock. Moreover, the distribution of magnetic anomalies confirms results of a previous geological survey indicating the progressive migration of hydrothermal activity upslope. These discoveries contribute to the results of 25 years of magnetic exploration of a wide range of hydrothermal sites, from low- to high-temperature and from basalt- to ultramafic-hosted, and thereby validate using high-resolution magnetics as a crucial parameter for locating and characterizing hydrothermal sites hosting unique chemosynthetic-based ecosystems and potentially mineral-rich deposits.

1) Introduction

The discovery of hydrothermal activity along the Galapagos Rift (Corliss et al., 1979) paved the way for large-scale, deep-sea exploration of oceanic ridges, revealing a myriad of hydrothermal vent fields primarily hosted on basaltic crust, with lesser gabbroic and ultramafic material (Kelley and Shank, 2010). In contrast to intermediate- and fast-spreading systems where basaltic rocks dominate, along slow- to ultraslow-spreading centers, the tectonically-dominated geology (Karson and Elthon, 1987; Tucholke et al., 1998; Escartin et al., 2008) gives rise to a higher abundance of hydrothermal systems hosted by variable amounts of ultramafic and gabbroic material, such as the well-known Rainbow and Ashadze hydrothermal fields (Charlou et al., 2002; Charlou et al., 2010; Fouquet et al., 2008). These high-temperature venting systems (>350°C) are characterized by sulfide chimneys emitting low pH fluids rich in carbon dioxide, methane and hydrogen; chemical signatures that are hallmarks of fluid interaction with mafic and ultramafic material in the subsurface (Charlou et al., 2002; Fouquet et al., 2010; Kelley and Shank, 2010; Ohara et al., 2012).

Although the magnetic signature of basalt-hosted hydrothermal sites is well constrained (Tivey et al., 1993; Tivey and Johnson, 2002; Tivey and Dyment, 2010; Szitkar et al., 2014a; Szitkar et al., 2015), that of ultramafic-hosted hydrothermal sites (UMHS) remains comparatively poorly studied and hence understood. Indeed, only the study by Szitkar et al. (2014b) of the Rainbow and Ashadze UMHS reveals that these high-temperature systems composed of variable mixtures of ultramafic, gabbroic and basaltic material are associated with a strong magnetization, implying that a specific set of subseafloor thermal-chemical processes are in play. Within these previously studied, high-temperature systems, mineral-fluid reactions and the formation and alteration of magnetic minerals are influenced by both temperature and the diverse rock compositions (Toft et al., 1990). To better understand magnetization processes in an ultramafic-dominated system characterized by low- to moderate- fluid temperatures, a detailed magnetic survey of the off-axis Lost City Hydrothermal Field (LCHF) was undertaken in 2003 by the Autonomous Underwater Vehicle *ABE* (MAR, 30°N). This unique field, which issues high-pH fluids at temperatures up to 116°C (Seyfried et al., 2015), is in stark contrast to the high-temperature Rainbow-like UMHS, thus it provides an ideal end-member hydrothermal system to constrain the source of magnetization in ultramafic environments.

2) Geological context

The LCHF is located near the summit of the southern wall of the Atlantis Massif, an oceanic core complex marking the inside corner of the intersection between the Mid-Atlantic Ridge and the Atlantis Transform Fault (30°N) (Kelley et al., 2001; Kelley et al., 2005; Kelley and Shank, 2010; Blackman et al., 2002; Karson et al., 2006; Denny et al., 2015). The site sits at ~750 m depth, 15 km away from the spreading axis (Fig. 1A), on a south-facing spur west of a sub-vertical fault (Figs. 1A and B) (Kelley et al., 2001).

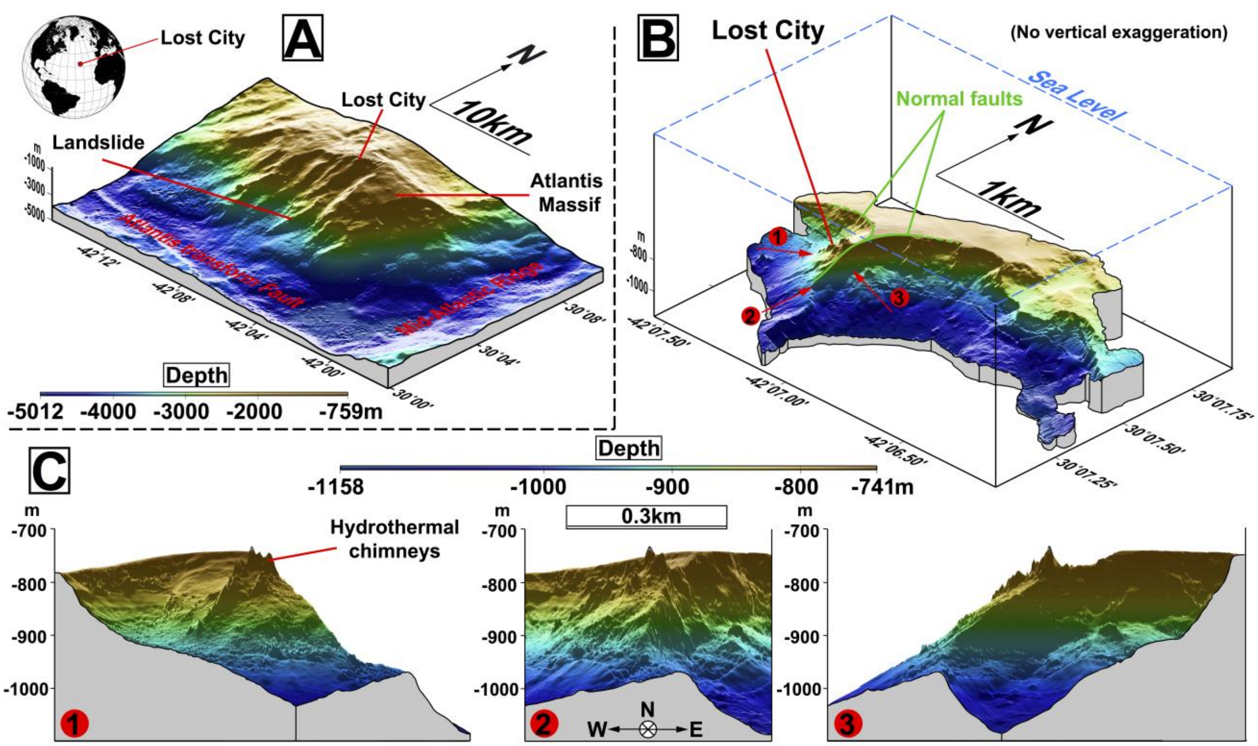

Fig. 1: Bathymetry of the LCHF. (A) Regional, ship-based bathymetry of the Atlantis Massif, at the inside corner of the intersection between the Mid-Atlantic Ridge and the Atlantis Transform Fault. (B) Detailed bathymetry of Lost

City and its surroundings. (C) Lost City seen from various angles, respectively corresponding to the red arrows on B. The Poseidon complex and the near vertical cliff marking the fault immediately east of the site are clearly apparent.

The LCHF is unique to date because it is one of only two low- to moderate- temperature UMHS known (Ohara et al., 2012). It is the only field with massive carbonate hydrothermal structures actively venting high-pH fluids (Fouquet et al., 2010) at temperatures up to 116°C (Seyfried et al., 2015). Fluid temperatures at depth range from 110°C to 250°C (Kelley et al., 2001; Kelley et al., 2005; Früh-Green et al., 2003; Proskurowski et al., 2006; Foustoukos et al., 2008). Moreover, hydrothermal activity is likely a consequence of both exothermic chemical reactions occurring beneath the field between seawater and peridotite rocks, and lithospheric cooling (Kelley et al., 2005). The low- to moderate temperature serpentinization produces the observed high-pH fluids enriched in low molecular weight hydrocarbons and high hydrogen concentrations (Kelley et al., 2005; Proskurowski et al., 2006; Proskurowski et al., 2008).

The core of the field is dominated by the 60 m tall Poseidon complex that forms linear, ~300 m long, east-west trending structure consisting of carbonate minerals and variable amounts of brucite (Fig. 1C) (Kelley et al., 2005). Two extinct fields occur ~300 m downslope and ~450 m west of Poseidon proper (Denny et al., 2015). The intensity of hydrothermal activity rapidly decreases away from the core of the field. Hydrothermal venting on the east side of the field occurs along cockscomb-like structures on the edge of a high-angle normal fault, and as diffuse flow issuing from highly faulted rocks on a near-vertical cliff marking the fault. The southernmost summit of the massif is marked by carbonate-filled fissures cutting the pelagic caprock that are thought to be sites of nascent venting (Kelley et al., 2005; Denny et al., 2015). Compared to other known hydrothermal sites, the LCHF is surrounded by extremely steep terrain resulting from a complex fault network and associated mass wasting (Karson et al., 2006; Denny et al., 2015).

3) Methods and Results

High-resolution magnetic and bathymetric data were collected by the Autonomous Underwater Vehicle (AUV) *ABE* during cruise AT7-34 of R/V *Atlantis* in 2003. The three components of the magnetic field were acquired at 1 Hz sample rate using a fluxgate magnetometer mounted on the AUV frame. To survey the site and its surroundings, *ABE* carried out seventeen dives with tracklines roughly following the isobaths.

The AUV magnetic influence is removed from the data using a calibration method proposed by Isezaki (1986) and Honsho et al. (2009) to resolve the crustal magnetic anomaly. Additionally, because of the geomagnetic field inclination and declination, magnetic anomalies are phase-shifted, i.e., not centered above their causative sources. To eliminate this phase-shift, we use Reduction to the Pole (RTP). This transformation is problematic, however, in this strongly 3D environment. Indeed, the direct RTP is achieved in the Fourier domain and requires the data to be collected on a level datum plane, which is not feasible for this dataset. Consequently, the anomalies either have to be upward-continued to a plane located above the shallowest point of the survey (Guspi, 1987), which would act as a low-pass filter and overly smooth the magnetic response, or we must invert the anomalies into an equivalent magnetization and estimate the RTP in the geometry of the experiment using a vertical geomagnetic field. Because traditional inversion methods are also performed in the spectral domain (Parker and Huestis, 1974), the over-filtering problem remains and details are lost. The new Bayesian inversion method developed by Honsho et al., (2012) and specifically designed for near-seafloor datasets acquired along uneven routes represents the most effective method to obtain a rigorous RTP anomaly while preserving the short wavelengths. The magnetization is estimated along the tracks of the submersible, preserving the high-resolution signals. The result of this inversion is displayed in Fig. 2A and the corresponding RTP anomaly in Fig. 2B.

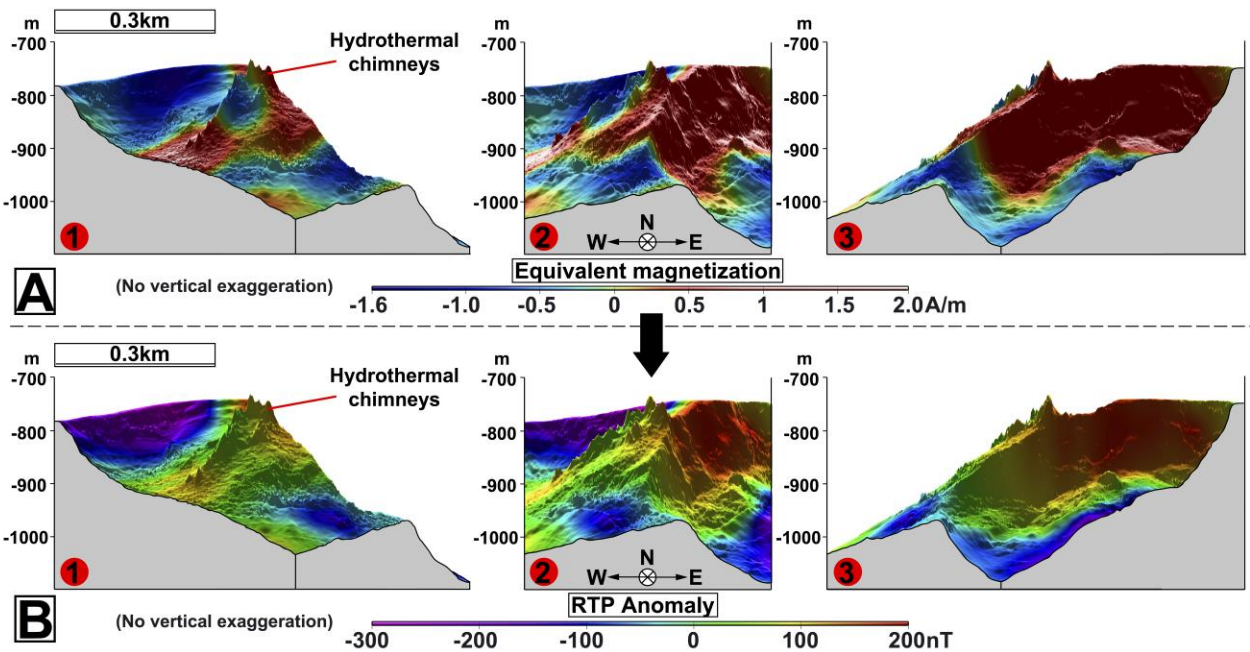

Fig. 2: Equivalent magnetization and magnetic anomaly of the LCHF (Same projections as in Fig. 1C). (A) Equivalent magnetization resulting from the Bayesian inversion and draped on the site high-resolution bathymetry. (B) RTP anomaly recomputed in the geometry of the experiment using this magnetization and a vertical geomagnetic field. The Poseidon complex and the northeastern fault are associated with the highest anomaly amplitude, whereas the rest of the site is characterized by weak positive magnetic signature.

The magnetic inversion reveals a relatively weak magnetization contrast and the recomputed Reduced-to-the-Pole (RTP) magnetic anomaly is characterized by low amplitude. The study by Szitkar et al. (2014b) reveals that high-temperature systems with variable amounts of ultramafic to basaltic material are associated with variably strong positive magnetization, depending on the site dimensions and the amount of magnetized material. The LCHF is comparable in size to the high-temperature UMHS Rainbow (2014b), however its bedrock equivalent magnetization is considerably weaker, yet marginally stronger than the surrounding rocks. These results, therefore, suggest a different intrinsic magnetization of basement rocks proximal to the plumbing system beneath the field proper. The strongest positive anomaly extends over the Poseidon area and upslope along the major north-south oriented fault that bounds the field to the east. Farther west, the anomaly rapidly decreases, but still remains stronger than in the vicinity of the site. At the bottom of the western slope, the anomaly again increases slightly (Fig. 2B).

4) Discussion

The positive magnetization contrast at high-temperature UMHS is interpreted to be a combination of: 1) strongly magnetized magnetite produced by high-temperature subseafloor serpentinization reactions (Szitkar et al., 2014b); 2) the volume and concentration of magnetized material; and 3) the reducing properties of hydrothermal fluids preserving magnetite within the plumbing system from oxidation (Fouquet et al., 2010). In contrast, the magnetite located in the surrounding terrain is subject to low-temperature seawater oxidation and converted into less magnetic minerals (Szitkar et al., 2014b).

By studying the RTP anomaly over the LCHF, the shape of the underlying plumbing system with reference to its magnetite distribution and physical characteristics can be constrained. The intensity of magnetite magnetization is subject to the strength of the magnetizing field (i.e. paleointensity), grain size, and domain state (Dunlop and Prévot, 1982; Cullity and Graham, 2009). Evidence for magnetic grain-size dependence with the degree of serpentinization is lacking (Oufi et al., 2002; Malvoisin et al., 2012), therefore we assume that magnetite formed beneath the LCHF and Rainbow share comparable fine-scale physical properties. The amplitude of the magnetic anomaly is therefore believed to mainly depend on the magnetite concentration within the rocks, which, in turn, can be influenced by temperature, oxidation processes, water/rock ratios, and/or Fe partitioning into brucite or other alteration phases (Früh-Green et al., 1996; Früh-Green et al., 2004; Andreani et al., 2013; Klein et al., 2014).

In this study, a nested forward modeling approach was used to examine various hypotheses on factors controlling the strength of the magnetic anomaly, until results were achieved that reproduced the data (Fig. 2B). To investigate the role of topography in generating magnetic anomalies we compute the magnetic field response of a uniformly, 1A/m magnetized seafloor using the geometry of the experiment. The result of this modeling confirms that the seafloor topography alone is not sufficient to account for the observed anomalies (Fig. S1), and additional sources of magnetization are therefore required.

Magnetic forward models are impacted by a combination of at least three parameters: the seafloor magnetization, the thickness of the magnetized layer and the existence of a non-magnetic deposit covering or within the magnetized basement. To estimate the seafloor magnetization and to constrain the shape of magnetite distribution, we use geometrical considerations. The ridge on which the LCHF is located corresponds to the intersection of two normal faults (Denny et al., 2015), focusing fluid ascent (Kelley et al., 2005; Karson et al., 2006; Ludwig et al., 2006) (Fig. 1B). We assume a uniformly magnetized seafloor and iterate towards a synthetic anomaly comparable to the observed one by adjusting the shape of the magnetite distribution. The result is non-realistic, as an infinitely thick, 1 A/m plumbing system does not generate the correct anomaly amplitude (Fig. S2).

The high-angle normal fault east of the Poseidon area is approximately 200 m high. Moreover, the depth of the sources visible on magnetic anomalies directly correlates with the altitude of the measurements. As our data were collected roughly 70 m above the seafloor, dominating anomalies are generated at maximal depths of 200 to 300 m. We therefore suggest that the upflow zone producing the positive anomaly has a similar height, with seawater seeping where the high-angle fault intersects the seafloor (Fig. 3A and 4A). To the west, the fault plane is less steep and observations suggest that hydrothermal discharge is weak, which could infer that a lesser amount of magnetite has formed in this area. Considering these hypotheses, we contour the fabric geometry (Fig. 3A) to produce an anomaly with a satisfying shape but still far from the correct amplitude.

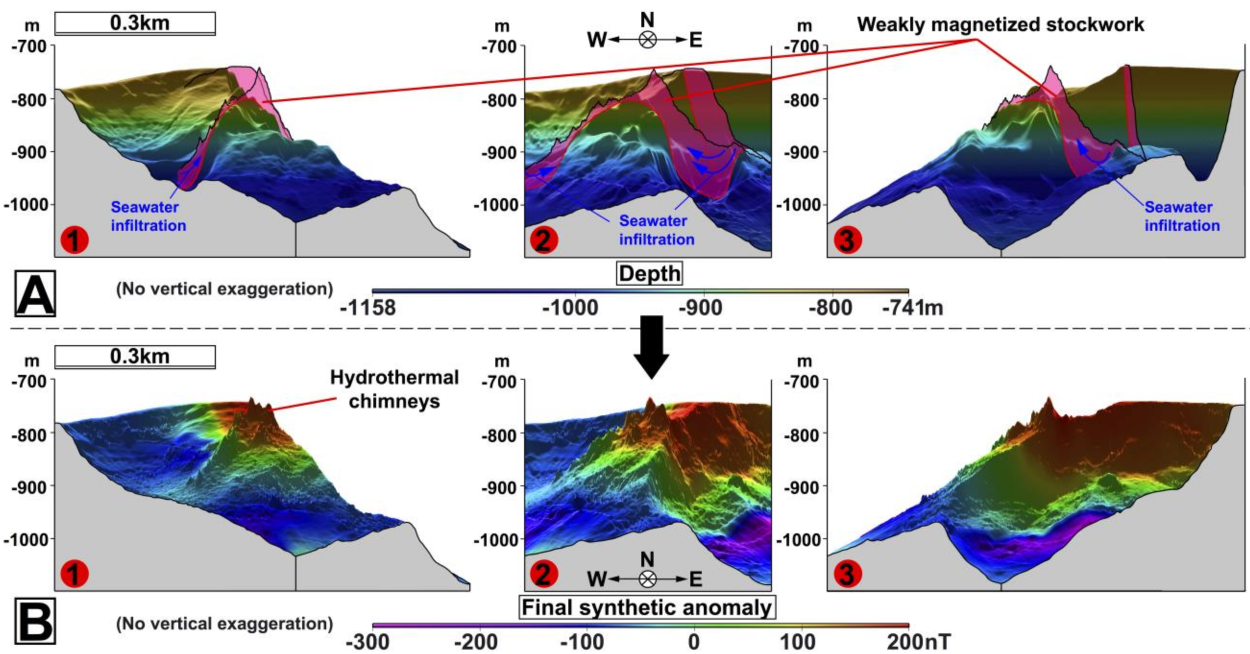

Fig. 3: Geometry of the magnetite distribution at LCHF (Same projections as in Fig. 1C). (A) Contour of the plumbing system lower interface with reference to its magnetite distribution along two across-site profiles (red lines), producing an anomaly with a satisfying shape. The high-resolution bathymetry outline (black lines) is also added. Seawater infiltration occurs at the faults intersection with the seafloor and a weakly magnetized plumbing system is sufficient to account for the observed anomaly amplitude. (B) Synthetic anomaly produced in the geometry of the experiment assuming a vertical geomagnetic field and a 2 A/m magnetized plumbing system. This model fits with the observed RTP anomaly and reveals low magnetite concentration resulting from low-temperature serpentinization reactions.

The last possible option consists of investigating the magnetite concentration within the rock, and recovered basement samples already reveal that magnetite is common, but not pervasive. Although its concentration cannot be unambiguously directly inferred through modeling, a comparison with high-temperature UMHS can be achieved by a variable magnetization with the final models being displayed in Fig. 3B and 4A along two across-site profiles. To account for both the shape and amplitude of the observed RTP anomaly, a magnetite-rich domain of serpentinization must be located under the Poseidon area and extend uphill, along the eastern fault. Moreover, the model reveals that serpentinite produced by the low-temperature serpentinization reaction would have to be weakly magnetized; 2 A/m is enough to generate the observed anomaly amplitude. Nevertheless, as the magnetite magnetization does not depend on the serpentinization degree, the origin of the weak magnetic signature can only result from its concentration within the host rock. Studies of Allen and Seyfried (2003), Klein et al. (2009, 2014), McCollom and Bach (2009), and Malvoisin et al. (2012) reveal that low-temperature serpentinization favors brucite formation rather than magnetite below 150°C, resulting in a magnetite-poor (i.e., less magnetic) rock, while high-temperature serpentinization is associated with magnetite formation and thus a more magnetic rock. However, no brucite has been found within the serpentinized basement rocks of the Atlantis Massif. Instead, the serpentinites are commonly oxidized and contain gabbroic lenses and impregnations. In addition, Si-metasomatism is prevalent, occurring as talc-amphibole-chlorite zones within the serpentinites (Boschi et al., 2006).

In comparison with the Rainbow samples that have a maximum magnetization of ~30 – 35 A/m (Szitkar et al., 2014b), magnetite within Lost City plumbing system appears to be at least fifteen times less intense based on the inversion results. The difference in magnetic characteristics between Rainbow and Lost City may therefore largely reflect the role of temperature and fluid composition in the production/consumption of magnetite during serpentinization reactions, metasomatism and oxidation, and explains the origin of the weak magnetic anomaly amplitude associated with the LCHF.

The highest magnetization contrast at the LCHF is located under the Poseidon area, but also encompasses the fault to the northeast and the easternmost part of Chaff Beach (Denny et al, 2015), marking the top of the spur (Fig. 4B). Such observations reveal that the current active zone of serpentinization and magnetite formation extends upslope, beyond the limits of the main hydrothermal complex, consistent with the diffuse venting observed in this area (Kelley et al., 2001; Denny et al, 2015). To the west, there is a weakly positive magnetic anomaly, in accordance with weak hydrothermal activity, i.e., the magnetite located in this part of the plumbing system is likely to be less abundant than that of the Poseidon and fault areas. The progressive decrease in reduced, focused fluids could allow for more diffuse and oxidized fluids to circulate in the basement and thus promote the alteration of magnetite or the precipitation of less or non-magnetic minerals. However, magnetite produced under the current main active site still benefits from the reducing conditions associated with active serpentinization, and therefore retains a stronger magnetization. Along the fault, the high magnetization suggests that a higher temperature phase has created a magnetite body, which, combined with the nascent venting, supports the hypothesis of a progressive shift of hydrothermal activity uphill proposed by Denny et al. (2015).

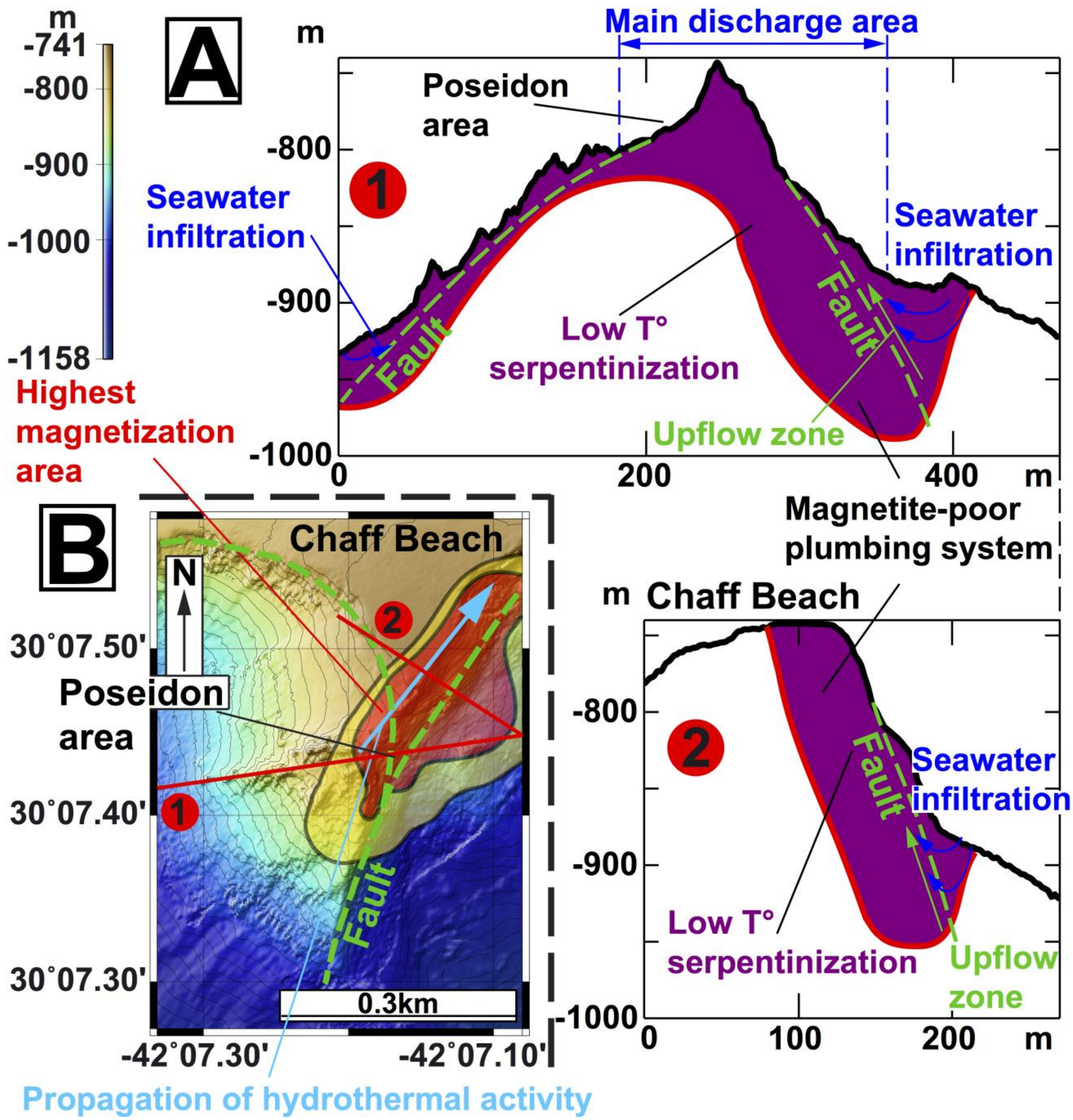

Fig. 4: Sections of the LCHF showing the potential propagation of hydrothermal activity. (A) Proposed geometry of the plumbing system along the two across-site profiles. Seawater infiltration initiates low-temperature serpentinization reaction, i.e., the production of a small amount of magnetite. (B) map view of the site. The highest magnetization area encompasses the Poseidon complex and the fault to the northeast, suggesting a progressive shift of hydrothermal activity upslope.

5) Conclusions

High-resolution, near-seafloor magnetic data reveal that the LCHF is associated with a weak positive anomaly. This observation is consistent with the typical magnetic signature of other UMHS discovered to date, and therefore confirms that UMHS exhibit a magnetic signature opposite to that of basalt-hosted sites. However, the relative weakness of the magnetic response of bedrock at the LCHF likely reflects a lower concentration of magnetite produced during low-temperature serpentinization reactions and the fact that Si-metasomatism is prevalent in the basement rocks underlying the field. Temperature and fluid chemistry are therefore crucial parameters controlling the characteristics of the plumbing systems at UMHS: high-temperature favors the creation of high magnetite concentrations. At low temperature and/or in the presence of hydrothermal fluids, iron can be partitioned into non-magnetic brucite, serpentine, chlorite, talc and amphibole and lead to the production of considerably lower concentrations of magnetite, and thus, a weakly magnetized plumbing system. Moreover, magnetic anomalies are consistent with the suggestion that hydrothermal activity at Lost City is progressively moving upslope, confirming that the location of discharge sites evolve during the lifetime of hydrothermal systems. Our study finally underlines the usefulness of magnetic surveys in identifying and characterizing ultramafic-hosted hydrothermal systems that host distinctive chemosynthetic-based ecosystems (Shock and Schulte, 1998) and potentially rich mineral deposits (Fouquet et al., 2010).

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Figures captions

Fig. 1: Bathymetry of the LCHF. (A) Regional, ship-based bathymetry of the Atlantis Massif, at the inside corner of the intersection between the Mid-Atlantic Ridge and the Atlantis Transform Fault. (B) Detailed bathymetry of Lost City and its surroundings. (C) Lost City seen from various angles, respectively corresponding to the red arrows on B. The Poseidon complex and the near vertical cliff marking the fault immediately east of the site are clearly apparent.

Fig. 2: Equivalent magnetization and magnetic anomaly of the LCHF (Same projections as in Fig. 1C). (A) Equivalent magnetization resulting from the Bayesian inversion and draped on the site high-resolution bathymetry. (B) RTP anomaly recomputed in the geometry of the experiment using this magnetization and a vertical geomagnetic field. The Poseidon complex and the northeastern fault are associated with the highest anomaly amplitude, whereas the rest of the site is characterized by weak positive magnetic signature.

Fig. 3: Geometry of the magnetite distribution at LCHF (Same projections as in Fig. 1C). (A) Contour of the plumbing system lower interface with reference to its magnetite distribution along two across-site profiles (red lines), producing an anomaly with a satisfying shape. The high-resolution bathymetry outline (black lines) is also added. Seawater infiltration occurs at the faults intersection with the seafloor and a weakly magnetized plumbing system is sufficient to account for the observed anomaly amplitude. (B) Synthetic anomaly produced in the geometry of the experiment assuming a vertical geomagnetic field and a 2 A/m magnetized plumbing system. This model fits with the observed RTP anomaly and reveals low magnetite concentration resulting from low-temperature serpentinization reactions.

Fig. 4: Sections of the LCHF showing the potential propagation of hydrothermal activity. (A) Proposed geometry of the plumbing system along the two across-site profiles. Seawater infiltration initiates low-temperature serpentinization reaction, i.e., the production of a small amount of magnetite. (B) map view of the site. The highest magnetization area encompasses the Poseidon complex and the fault to the northeast, suggesting a progressive shift of hydrothermal activity upslope.

Magnetic exploration of a low-temperature ultramafic-hosted hydrothermal site (Lost City, 30°N, MAR)

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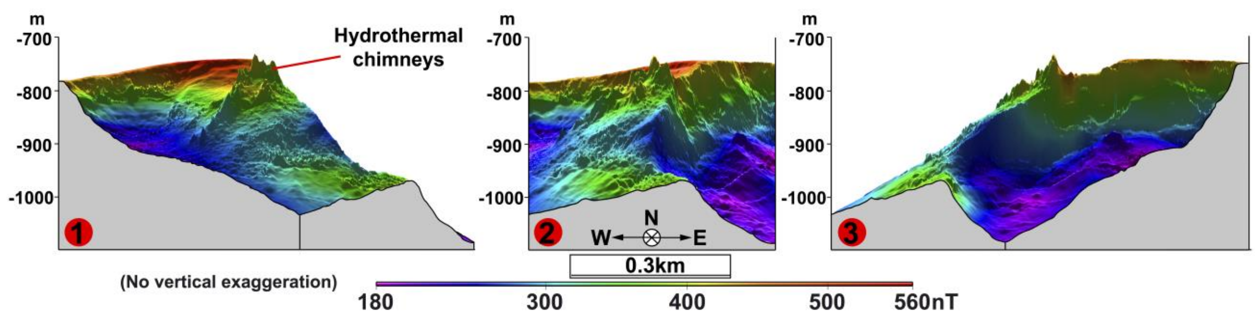
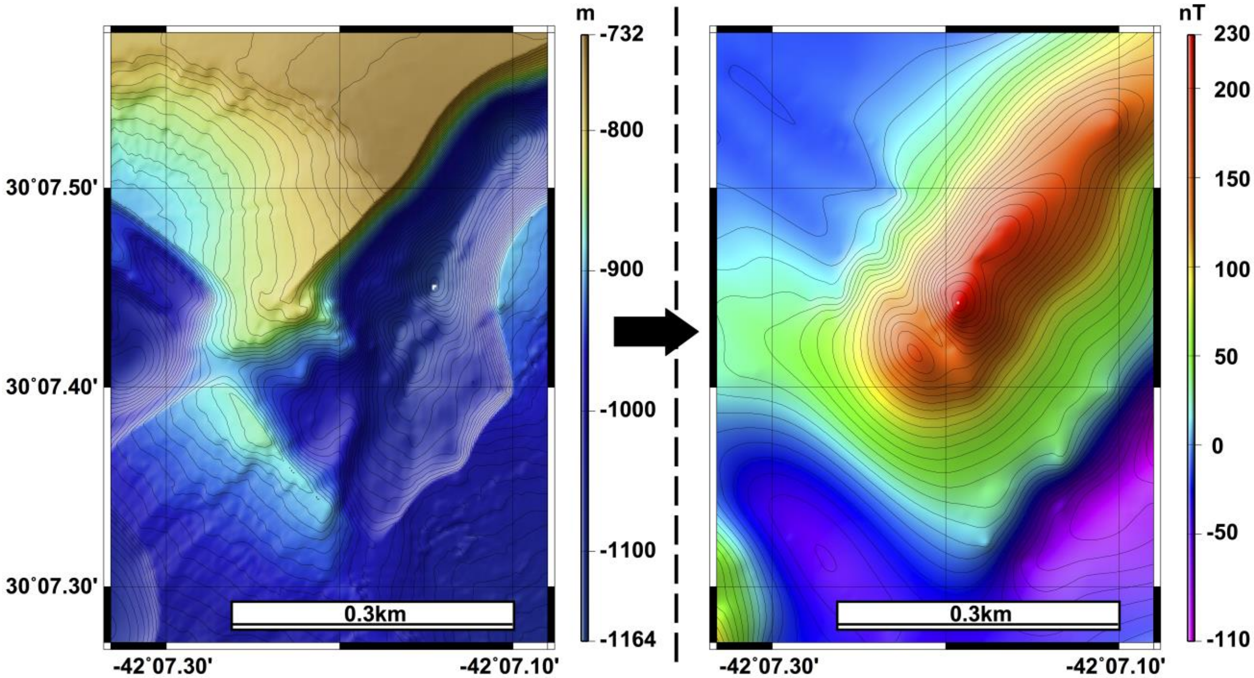
Supplementary material

This supplementary file includes two figures, numbered S1 and S2, and the accompanying captions.



<u>Figure S1:</u> Synthetic anomaly produced by a uniformly, 1A/m-magnetized seafloor in the geometry of the experiment. The result does not match the observed anomaly, confirming that the site is not magnetically neutral.



<u>Figure S2:</u> Left: Lower plumbing system interface producing an anomaly with the right shape, assuming a constant seafloor magnetization. Right: Synthetic anomaly produced by a 1A/m magnetized seafloor in the geometry of the experiment, assuming the above-mentioned plumbing system. The lower interface is located at unrealistic depths, as an infinitely thick plumbing system does not generate sufficient anomaly amplitude. Magnetization variations are required.