

# Near-seafloor magnetic signatures unveil serpentinization dynamics at ultramafic-hosted hydrothermal sites<sup>1</sup>

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## ABSTRACT

A near-seafloor magnetic and bathymetric survey conducted by the autonomous underwater vehicle *AutoSub 6000* over intermediate-temperature, ultramafic-hosted Von Damm Vent Field (Mid-Cayman spreading center, Caribbean Sea) revealed a moderate positive magnetic anomaly, in accordance with the magnetic response of other known ultramafic-hosted hydrothermal vent fields. However, compared with low-temperature ultramafic-hosted hydrothermal activity, the magnetic signature of this intermediate-temperature site indicates a slightly stronger magnetization contrast between the hydrothermal system and its host, but it remains considerably weaker than at high-temperature ultramafic-hosted hydrothermal vent fields. This observation highlights the nonlinear increase of magnetization production with temperature, as iron partitions into weakly magnetic brucite under 200 °C, but magnetite dominates above this temperature, leading to a sudden increase in the magnetic signature of a site. Our study is consistent with recent laboratory experiments and unveils the dynamics of the serpentinization reaction, enabling fine tuning of the magnetic technique for remotely locating hydrothermal systems. In addition to refining our understanding of the magnetic behavior of hydrothermal vent fields, these new results also reveal the orientation of the fluid pathway feeding the hydrothermal site and indicate the nonvertical structure of the complex network of fissures within the host rock and its associated tectonic feature—an oceanic core complex.

## INTRODUCTION

Hydrothermal vents are the hot springs of the deep ocean floor, and active systems play a key role in the dissipation of Earth's internal heat and in the ocean chemical budget. Almost four decades after their first discovery (Corliss et al., 1979), large-scale seafloor exploration, including the use of underwater vehicles, has located over 350 active and inactive hydrothermal sites that are mostly hosted on a basaltic substratum. Along slow-spreading ridges, however, the combination of limited magma supply (Cannat, 1993), volcanic accretion, and tectonic dismemberment of the oceanic crust (Tucholke et al., 1998; Escartín et al., 2008) favors the development of long-lived detachment faults exposing mantle outcrops and oceanic core complexes (OCCs). These settings lead to a greater diversity of hydrothermal vent fields than at fast spreading ridges (Rona et al., 2010). Although the magnetic footprint of basalt-hosted hydrothermal systems is well constrained (e.g., Tivey et al., 1993; Honsho et al., 2013; Sztikar et al., 2014a), that of ultramafic-hosted hydrothermal sites (UMHSs) remains poorly understood. Two recent studies over high and low-temperature UMHSs, the Rainbow and Lost City vent fields (MidAtlantic Ridge), respectively (Sztikar et al., 2014b, 2017), have emphasized the relation between fluid temperature and amount of magnetite generated by serpentinization

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reactions within the sites' stockwork zones or plumbing systems. Nevertheless, the precise evolution of magnetite production with temperature remains unknown. To address the knowledge gap between these two end-member UMHSs, we used high-resolution magnetic and bathymetric data collected over an intermediate-temperature UMHS, the Von Damm Vent Field (VDVF), at the Mid-Cayman spreading center, Caribbean Sea. The VDVF is hosted on an OCC exposing a mixture of ultramafic and gabbroic rocks (Connelly et al., 2012a). Our study revealed that the VDVF is consistently associated with a positive magnetic anomaly. It also suggests that magnetite production, i.e., the serpentinization dynamics, follows a nonlinear evolution when temperature increases, with a slow progression under 200 °C, followed by a dramatic increase in the production rate above this critical temperature. This makes the remote detection of high-temperature UMHSs using magnetic signatures easier. Moreover, the characteristics of the magnetic response at the VDVF suggest the presence of an inclined fluid pathway feeding the vent field, revealing the existence of a complex fault network within the host OCC structure.

## GEOLOGICAL CONTEXT

The Mid-Cayman spreading center is a tectonically isolated, north-south-oriented, 110-km-long, ultraslow-spreading ridge in the Caribbean Sea. Its full spreading rate is 2 cm/yr (Ballard et al., 1979), and the axial valley depth ranges from 4500 to 6500 m, making it the deepest spreading center in the world (ten Brink et al., 2002). At 18°30'N, a prominent bathymetric anomaly rising up to a depth of 2100 m forms the western flank of the axial valley. This 3000-m-high massif, known as Mount Dent, has been identified as an OCC (Fig. 1A; Hayman et al., 2011). It is characterized by the typical dome-like structure of OCCs and exhibits spreading-parallel, east-west-oriented corrugations. The OCC itself is composed of exposed upper-mantle ultramafic and lower-crust gabbroic rocks (Hayman et al., 2011). Not far from its summit, the active UMHS VDVF has recently been discovered at a depth of 2300 m (Connelly et al., 2012a), i.e., comparable to the depth of UMHS Rainbow (Fig. 1B). This UMHS sits 13 km west from the current spreading axis and consists of a single ~50-m-high mound, extending over an area of 200 × 300 m, and dominating the surrounding smooth slope of the OCC (Fig. 1B). Unlike the low-temperature Lost City vent field, which is characterized by massive carbonate structures venting high-pH fluids and a probable shallow heat source (Kelley et al., 2001), the VDVF is associated with a talc-dominated mineralogy and a deep heat source, as a result of the OCC fault network (Hodgkinson et al., 2015). The VDVF is actively venting fluids with a measured temperature of up to 215 °C, and fluid sampling on the site has revealed that iron concentrations within the fluids are lower than at Rainbow (Connelly et al., 2012a; Hodgkinson et al., 2015).

## METHODS

During Cruise 44 of RRS *James Cook* in 2010, (Connelly et al., 2012b) high-resolution magnetic and bathymetric data were acquired by a three-component fluxgate magnetometer mounted on the autonomous underwater vehicle (AUV) *Autosub 6000* along 70-m-apart, regularly spaced, parallel profiles. The AUV's altitude above the seafloor ranged from 20 to 160 m, optimizing the magnetic detection of small-scale targets such as hydrothermal sites. As the magnetometer sensor was directly mounted to the AUV, the magnetic influence of the vehicle had to be derived and removed from the data (Isezaki, 1986; Honsho et al., 2009) to resolve the crustal magnetic anomalies (see the GSA Data Repository1).

Because of the inclination and declination of Earth's geomagnetic field, crustal magnetic anomalies are phase-shifted and need to be corrected for their location to relocate them above their sources within the crust. The data were first used to estimate the seafloor equivalent magnetization using the Bayesian inversion of Honsho et al. (2012). This magnetization

distribution was then used to compute the reduced-to-the-pole (RTP) anomaly (Fig. 2; see the Data Repository).

## RESULTS AND DISCUSSION

The positive magnetic anomaly observed over UMHSs results from several factors, including (1) an accumulation of strongly magnetized magnetite produced by serpentinization reactions within the hydrothermal plumbing and stockwork zones; (2) the dimensions of the hydrothermal system at depth, i.e., the volume of its deep parts; and (3) the presence of reducing hydrothermal fluids that prevent later oxidation of serpentinite-hosted magnetite by contact with seawater (Szitkar et al., 2014b). In addition, it has also been shown that the amount of magnetite produced by serpentinization reactions is influenced by hydrothermal fluid temperature (Szitkar et al., 2017), in accordance with laboratory experiments (Klein et al., 2014). Indeed, high temperatures (>200 °C) favor iron partitioning into magnetite, whereas low temperatures preferentially partition it into less-magnetic brucite (Früh-Green et al., 1996, 2004; Klein et al., 2014). This latter case is likely to result in the formation of a limited amount of magnetite within the stockwork zones beneath UMHSs, and hence a weak positive magnetic anomaly (Szitkar et al., 2017).

UMHSs with different temperature regimes offer the opportunity to explore the amplitude of hydrothermal magnetite-produced magnetic anomalies. The Rainbow and Lost City UMHSs represent the two currently known ultramafic-hosted hydrothermal end members (venting fluid temperatures of 350 °C and 92 °C, respectively); however, the exact evolution of magnetite production with temperature remains unclear, as the two examples are insufficient for precise constraints. At the VDF, we considered two options: either the venting temperature has always been relatively stable, or it was initially higher and progressively decreased over time. In this latter case, precipitated sulfide should be abundant, but none has been observed, and deposits are largely dominated by talc and silica, which can only form under 280 °C. Moreover, low H<sub>2</sub>S concentrations within the fluids suggest a limited magmatic contribution to the heat source, i.e., a moderate venting temperature (Hodgkinson et al., 2015). These observations rule out the possibility of an initially high-temperature UMHS having cooled down. Therefore, it is possible to use the VDF as a comparison with Rainbow and Lost City to fully explore the impact of temperature on serpentinization dynamics and on the magnetic signature of UMHSs.

By studying the RTP anomaly over the site and its surroundings, the relative concentration of magnetite within the stockwork zone can be inferred by comparison with that from Rainbow and Lost City. At first order, the magnetite magnetization is subject to the intensity of the magnetizing field, grain size, and domain state (Dunlop and Prévot, 1982; Cullity and Graham, 2009); however, serpentinization does not have any significant impact on the magnetic grain size (Oufi et al., 2002; Malvoisin et al., 2012). Moreover, on a first order, these three hydrothermal vent fields have comparable dimensions (e.g., Szitkar et al., 2014b, 2017); i.e., the main observed differences are likely to be dominated by variations in the magnetite concentrations within the host rocks (see the Data Repository).

In a first step, we estimated the average seafloor equivalent magnetization out of the hydrothermal area (Fig. DR1 in the Data Repository). This inversion was performed using the same parameters as for Rainbow and Lost City to ensure a proper comparison (Szitkar et al., 2014b, 2017; see also the Data Repository). Away from the vent field, equivalent magnetization reaches an average of 1.2 A/m. In the vicinity of the hydrothermal site, however, the equivalent magnetization peaks at 3 A/m (Fig. DR2). This magnetization is higher than that observed at the

Lost City site (2 A/m; Sztikar et al., 2017) but remains considerably weaker than that at Rainbow (30 A/m).

In order to precisely constrain the role of temperature, we compared the respective amounts of magnetite at these three sites (Fig. 3). The fluid temperature at the VDVF is up to 215 °C (Hodgkinson et al., 2015), i.e., comparable to the critical temperature determined by Klein et al. (2014). Assuming this temperature remained constant over time, and given the similar dimensions of Lost City, VDVF, and Rainbow, it appears that the magnetite concentration does not follow a linear evolution with temperature, because such an evolution would lead to an observed magnetization of 4.5 A/m at Rainbow, whereas the observed RTP anomaly at this last hydrothermal site suggests a magnetization of ~30 A/m (Fig. 3). Instead, the observed magnetization contrasts suggest that the magnetite concentration within the VDVF is 1.5 higher than that at Lost City but at least 10 times weaker than that at Rainbow. This observation is in accordance with the results from Klein et al. (2014), revealing that iron partitions preferentially into weakly magnetic brucite at temperatures under 200 °C, whereas the partition into magnetite dominates above 200 °C. As the magnetization within the VDVF stockwork zone is slightly higher than within the Lost City plumbing system, we propose that the magnetite concentration increases slowly under 200 °C. When breaking the critical ~200°C mark, this rise suddenly intensifies and results in a dramatic increase in magnetite production. Our results therefore underline the temperature dependence of serpentinization reaction products within the deep parts of UMHSs: Under 200 °C, Fe-rich brucite dominates while magnetite production increases slowly with temperature. Beyond 200 °C, the dynamics of the chemical reaction change and mainly produce magnetite, considerably increasing the site's magnetic signature (Fig. 3).

Magnetic data acquired from near-seafloor vehicles like the *Autosub 6000*, used at the VDVF, also allow the sub-seafloor geometry of the magnetizing source to be constrained. At the VDVF, the observed positive magnetic signature is slightly shifted by ~100 m to the north compared to the location of the main, active hydrothermal mound (Fig. 2C). In this area, the data were collected at an altitude of ~100 m; i.e., the sources producing the dominating anomalies are mostly located within 100–200 m under the seafloor. Magnetic modeling using a 3 A/m magnetized stockwork zone surrounded by a 1.2 A/m magnetized seafloor allows precise contouring of the magnetic source geometry, which is seen to be inclined by 40° to the north (Fig. 2; see the Data Repository). If the magnetization is caused by magnetite precipitation in the stockwork system, this suggests that the fluid-flow pathways responsible for the higher-temperature precipitation of magnetite are not vertical but also follow a 40° dip to the north. The cause of the inclined fluid path may reflect the orientation of faults in the vicinity of the VDVF (mostly striking north-south). The inclination may also reflect the domed structure of the OCC, with the VDVF located on the east-sloping, central axis of the domed structure. Buoyant fluids are known to be deflected by the geometry of the seafloor and migrate toward the center of bathymetric highs (e.g., Sztikar and Dymant, 2015). Alternatively, the decrease in temperature of the hydrothermal discharge and increase in age of the deposits toward the north, over a distance of 250 m, at the VDVF (Hodgkinson et al., 2015) suggest that the inclination in fluid flow has evolved from a near-vertical ascent to its now-inclined state, possibly as a result of closure of the permeability of the plumbing system by precipitation of hydrothermal precipitates over time. The presence of the inclined fluid pathway beneath the VDVF also suggests the existence of a heat source deep within the structure of the OCC that is located to the north of the VDVF, consistent with the presence of a neovolcanic ridge that intersects the north side of the Mount Dent OCC, downslope from the VDVF. We suggest that intrusions, propagating southward from this neovolcanic ridge into the OCC, are the heat source for the VDVF, and fluids then ascend up north-south–striking fault planes toward the highest point of the OCC and emerge at the VDVF.

## **CONCLUSION**

High-resolution magnetic data reveal that the VDVF is associated with a stronger positive magnetization contrast than that observed at the lowtemperature UMHS Lost City; i.e., its stockwork zone hosts a slightly higher concentration of magnetite. Nevertheless, this limited additional amount of magnetite supports the need for a faster production rate above the critical 200 °C temperature to reach a magnetic signature comparable to that of high-temperature UMHS Rainbow. This study therefore confirms the fundamental role of temperature in the magnetite production within UMHS stockwork zones or plumbing systems: below 200 °C, UMHSs are associated with a weakly positive magnetic signature slowly intensifying when temperature rises. For venting sites associated with a temperature above 200 °C, the concentration of magnetite drastically increases and makes them easy to identify on deep-sea magnetic data sets. These results consequently refine the knowledge base concerning the magnetic footprint of hydrothermal systems and will facilitate discovery of hydrothermal sites, regardless of their geological and geophysical contexts, during future scientific cruises.

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FIGURES

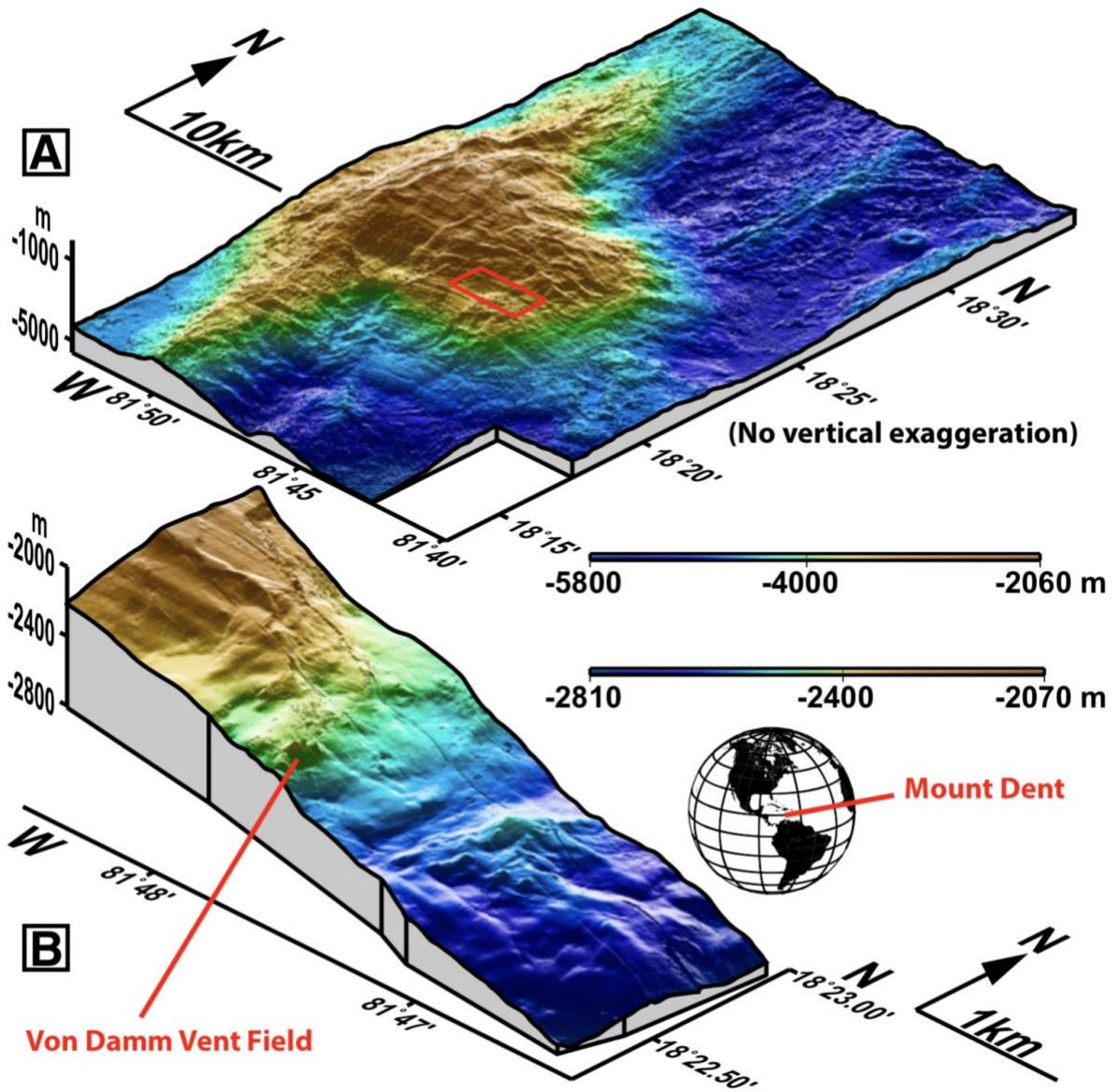


Figure 1. A: Regional bathymetry of Mount Dent oceanic core complex, Mid-Cayman spreading center, Caribbean Sea. Typical dome-like structure and east-west corrugations are clearly visible. B: High-resolution bathymetry of Von Damm Vent Field area, Mid-Atlantic Ridge. Hydrothermal site and associated prominent mound overlook smooth seafloor slope in surrounding area.

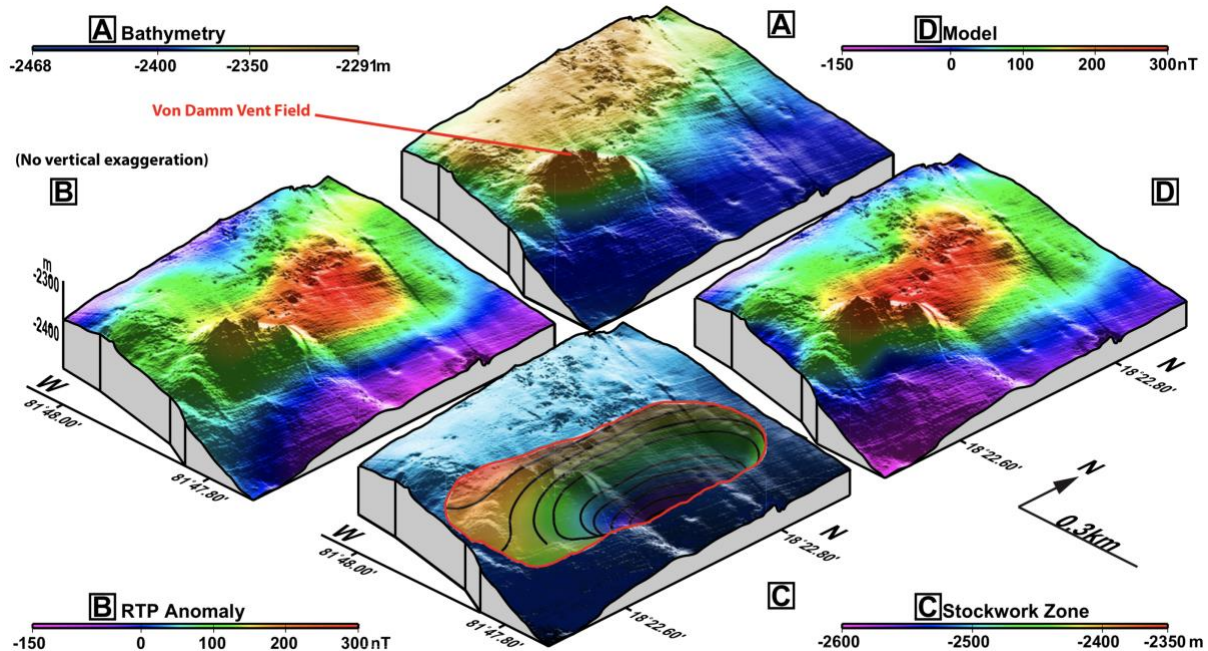


Figure 2. A: High-resolution bathymetry focusing on hydrothermal site. Mound is on average  $200 \times 300$  m in area and 50 m high. B: Reduced- to-pole (RTP) magnetic anomaly computed from equivalent magnetization deduced from Honsho et al. (2012) inversion. Positive anomaly is located  $\sim 100$  m north of mound (Fig. DR2 [see text footnote 1]), revealing existence of an inclined fluid pathway at depth. C: Proposed contours of stockwork geometry. Average magnetization within this stockwork zone is 3 A/m, surrounded by a 1.2 A/m magnetized seafloor. D: Magnetic model estimated using stockwork geometry from C and a 3 A/m magnetized stockwork zone.

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