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Origin of magnetic highs at ultramafic hosted hydrothermal systems: Insights from the Yokoniwa site of Central Indian Ridge

Masakazu Fujii [a,b,*], Kyoko Okino [b], Taichi Sato [c], Hiroshi Sato [d], Kentaro Nakamura [e]

[a] Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[b] Atmosphere and Ocean Research Institute, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, Japan
[c] The National Institute of Advanced Industrial Science and Technology, 1-1-1 Higashi, Tsukuba, Ibaraki, Japan
[d] Senshu University, 2-1-1 Higashimita, Tama-ku, Kawasaki, Kanagawa, Japan
[e] University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

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ABSTRACT

High-resolution vector magnetic measurements were performed on an inactive ultramafic-hosted hydrothermal vent field, called Yokoniwa Hydrothermal Field (YHF), using a deep-sea manned submersible *Shinkai6500* and an autonomous underwater vehicle *r2D4*. The YHF has developed at a non-transform offset massif of the Central Indian Ridge. Dead chimneys were widely observed around the YHF along with a very weak venting of low-temperature fluids so that hydrothermal activity of the YHF was almost finished. The distribution of crustal magnetization from the magnetic anomaly revealed that the YHF is associated with enhanced magnetization, as seen at the ultramafic-hosted Rainbow and Ashadze-1 hydrothermal sites of the Mid-Atlantic Ridge. The results of rock magnetic analysis on seafloor rock samples (including basalt, dolerite, gabbro, serpentinized peridotite, and hydrothermal sulfide) showed that only highly serpentinized peridotite carries high magnetic susceptibility and that the natural remanent magnetization intensity can explain the high magnetization of Yokoniwa. These observations reflect abundant and strongly magnetized magnetite grains within the highly serpentinized peridotite. Comparisons with the Rainbow and Ashadze-1 suggest that in ultramafic-hosted hydrothermal systems, strongly magnetized magnetite and pyrrhotite form during the progression of hydrothermal alteration of peridotite. After the completion of serpentinization and production of hydrogen, pyrrhotites convert into pyrite or nonmagnetic iron sulfides, which considerably reduces their levels of magnetization. Our results revealed origins of the magnetic high and the development of subsurface chemical processes in ultramafic-hosted hydrothermal systems. Furthermore, the results highlight the use of near-seafloor magnetic field measurements as a powerful tool for detecting and characterizing seafloor hydrothermal systems.

1. Introduction

Hydrothermal activity within oceanic lithosphere is a fundamental process in mid-ocean ridges and arc-backarc systems, and it contributes considerably to the cooling of the oceanic lithosphere and to the geochemical cycles in the oceans (e.g., Elderfield and Schultz, 1996; Hannington et al., 2011). The location and spatial extent of hydrothermal activity are difficult to constrain; however, studies of near-seafloor magnetic field can highlight these features because crustal magnetic minerals can be destroyed or created by hydrothermal processes. Reduced magnetization associated with hydrothermal deposits was widely observed in both the active and inactive lava-hosted hydrothermal fields in varied tectonic settings, including: the hydrothermal site TAG (Trans-Atlantic Geotraverse) and the 4°48′S fields of the Mid-Atlantic Ridge (MAR; Tivey and Dyment, 2010; Tivey et al., 1993, 1996, 2003), the Main Endeavour Field and Raven Field of the Juan de Fuca Ridge (JFR; Tivey and Johnson, 2002; Tivey et al., 2014), a site on the Southwest Indian Ridge (Zhu et al., 2010), back-arc-type sites of the Southern Mariana Trough (Fujii et al., 2015; Nakamura et al., 2013), the Hakurei Field within a caldera of the Izu-Ogasawara arc-back-arc volcano (Honsho et al., 2013), and the Brothers Field within a caldera of the Kermadec intraoceanic arc volcano (Caratori Tontini et al., 2012).

Weakened magnetic anomalies are interpreted as locally altered up-flow zones formed by hydrothermal activity, because hydrothermal alteration processes destroy iron–titanium oxide

* Corresponding author at: Atmosphere and Ocean Research Institute, University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba, Japan.
E-mail address: fujii@aori.u-tokyo.ac.jp (M. Fujii).

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minerals (titanomagnetite), which carry magnetic remanence in oceanic extrusive (Ade-Hall et al., 1971; Pariso and Johnson, 1991; Rona, 1978; Wooldridge et al., 1990). Similar magnetic lows were confirmed in the ancient analogs of seafloor hydrothermal systems found in ophiolites, where zones of demagnetized crust are associated with the mineralized stockwork of ore bodies (Hall, 1992; Richards et al., 1989; Walls and Hall, 1998). Furthermore, studies on volcanic geothermal areas in New Zealand showed that hydrothermal alteration of magnetic minerals is the most important mechanism for creating zones of weak magnetization rather than by thermal demagnetization processes (Hochstein and Soengkono, 1997). In the seafloor realm, weak magnetization zones were observed in both active and extinct vent areas, also suggesting that differences in the thermal environment do not significantly affect magnetic anomalies (Fujii et al., 2015; Tivey and Johnson, 2002). Another explanation for zones of weak magnetic response is the accumulation of thick hydrothermal deposits, which may result in an apparent magnetic low due to the increased distance between the measurement point and the underlying magnetized basalt (Szitkar et al., 2014a).

In addition to magnetic lows in lava-hosted systems, it was shown that hydrothermal activity has also lead to enhanced crustal magnetization in the Bent Hill massive sulfide (BHMS) deposits, which are located on a sediment-covered axial valley of the JFR (Gee et al., 2001; Tivey, 1994), and in ultramafic-hosted active hydrothermal fields of the MAR (Tivey and Dyment, 2010; Szitkar et al., 2014b). Enhanced magnetic anomalies are interpreted as magnetized bodies with large quantities of magnetic minerals (mostly magnetite and pyrrhotite) created by high-temperature hydrothermal precipitation (Gee et al., 2001; Szitkar et al., 2014b; Tivey, 1994; Tivey and Dyment, 2010). However, despite high-resolution studies on the magnetization of hydrothermal fields as mentioned above, magnetic mapping studies combined with studies of the magnetic properties of host rocks are limited; therefore, the mineralogical, geochemical and rock magnetic characteristics of magnetic anomalies remain unclear.

Previous studies of near-seafloor magnetics reported high magnetization zones located at active ultramafic-hosted hydrothermal fields where high-temperature venting occurs (Szitkar et al., 2014b; Tivey and Dyment, 2010). These magnetic highs are considered to reflect the presence of mineralized stockwork, in which several chemical processes (e.g., serpentinization and sulfide mineral deposition) create and preserve strongly magnetized magnetite (Szitkar et al., 2014b). At the Rainbow hydrothermal site of the MAR, the magnetization from magnetic anomaly mapping estimates up to ∼30 A/m; however the magnetization of sulfide-impregnated serpentinized peridotite samples collected in the same region are too weak to explain the intensity of the magnetic anomaly (Szitkar et al., 2014b).

Exposures of ultramafic rocks are extensively distributed within slow spreading environments, where alteration processes significantly influence submarine ecosystems and result in high concentrations of metals (e.g. Fouquet et al., 2010; Kelley et al., 2005; Nakamura and Takai, 2014). Therefore, investigating magnetic signatures in these ultramafic-hosted hydrothermal systems is important for detecting active and inactive hydrothermal sites and their mineralization states.

In this study, we explored the ultramafic-hosted Yokoniwa Hydrothermal Field (YHF), located on the Central Indian Ridge (CIR). The YHF is primarily an extinct hydrothermal system and represents a unique target for investigating the differences in magnetic signatures between active and inactive hydrothermal systems hosted within ultramafic rocks. We investigated the magnetization distribution from magnetic anomalies obtained by an autonomous underwater vehicle (AUV) and a human occupied vehicle (HOV) observations, and analyzed magnetic properties of rock samples collected around the YHF. On the basis of these multiple analyses, this study provides insight into: (i) the magnetic signature of ultramafic-hosted inactive hydrothermal systems; (ii) the role of serpentinization in contributing to magnetic anomalies, and (iii) the formation history of magnetic minerals during hydrothermal activity in ultramafic rocks.

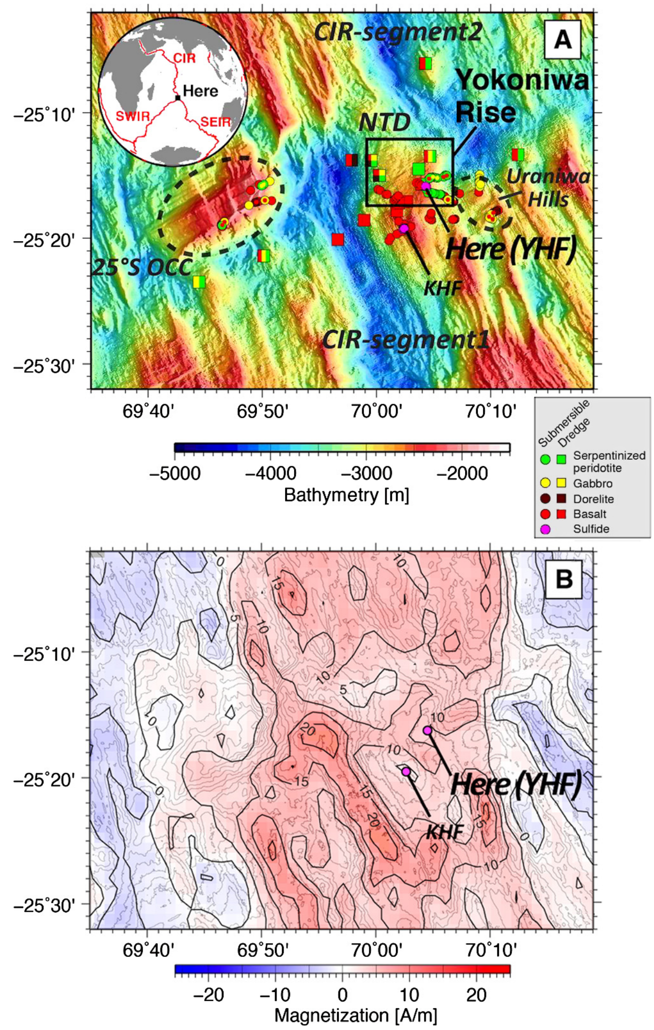

Fig. 1. Bathymetry and magnetization in the Yokoniwa Rise region. Bathymetry (m; A) and magnetization (A/m; B) around the Yokoniwa Rise including the Yokoniwa Hydrothermal Field (YHF; Okino et al., 2015). Rock samples collected by submersible (circles) and dredge (squares) are shown as basalt (red), dolerite (brown), gabbro (yellow), serpentinized peridotite (green), and sulfide (purple). CIR = Central Indian Ridge, NTD = non-transform discontinuity, OCC = oceanic core complex, KHF = Kairei hydrothermal field.

2. Yokoniwa Hydrothermal Field

The YHF (Fig. 1) is located in the southernmost part of the CIR near the Rodriguez triple junction. The tectonic development of the area has been reported by past studies (Briais, 1995; Honsho et al., 1996; Mendel et al., 2000; Okino et al., 2015; Sato et al., 2009). The CIR is a slow–intermediate-rate spreading ridge system with a well-developed axial valley, which is segmented by many fracture zones and non-transform discontinuities (NTDs). The full spreading rate in the southernmost segment, CIR-segment1 (CIR-S1), is approximately 47 mm/yr (MORVEL: DeMets et al., 2010). The CIR-S1 is a 20-km segment with a deep axial valley, where undeformed volcanic cones and flat-topped volcanic knolls are distributed within a neo-volcanic zone. Segment length shortens with age in off-axis area, implying that the CIR-S1 was