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Geomorphological variations at hydrothermal sites in the southern Mariana Trough: Relationship between hydrothermal activity and topographic characteristics

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ABSTRACT

This study presents the first detailed geomorphological characterization of field-scale geological features associated with hydrothermal systems in the southern Mariana Trough, using near-bottom swath mapping data collected by the autonomous underwater vehicle (AUV) *Urashima* during cruise YK09-08 and dive observation data acquired by the submersible *Shinkai6500* during cruise YK10-11. The motivation of this study is to examine the relationship between geomorphological characteristics and hydrothermal activity, and to examine the nature of tectonic and volcanic controls on the hydrothermal system in this area. Two of the hydrothermal sites in the study area (near 12°57′N, 143°37′E) are located on the active backarc spreading axis (the Snail and Yamanaka sites), one is located at the eastern foot of the axial high (the Archean site), and two are located on an off-axis knoll about 5 km from the spreading axis (the Pika and Urashima sites). The on-axis area is divided into tectonically dominant and volcanically dominant zones; volcanically dominant zones are characterized by mounds (height, 5–30 m; diameter, 250–320 m) cut by fissures. The Snail and Yamanaka sites are located adjacent to these fissures, and are possibly represented local activity associated with a 4th order segment-scale diking event (on the basis of comparisons with previously studied cases on the East Pacific Rise with similar on-axis geological characteristics). In contrast to the on-axis sites, the off-axis sites show no evidence of faulting. The Archean site at the foot of the axial high is characterized by a single mound (height, 50–100; diameter, 250–300 m), pronounced off-axis lava flows, and the presence of high-amplitude rugged seafloor features; the site is located at the top of the mound. Numerous ridge lines (height, mainly 2–6 m) extend radially from the top of the mound, and several chimney-like structures (up to approximately 6 m high) occur on the top and slopes of the mound. The Pika site is located on the western peak of an off-axis knoll, and the newly discovered Urashima site is located at the northern foot of the western peak of the same knoll. The western peak is characterized by bumpy seabed textures formed by numerous smaller-scale mounds and ridge lines; however, the eastern peak has a very smooth top and slope, and shows no signs of hydrothermal activity. Numerous mounds (heights, 5–75 m; diameters, 50–350 m) are developed on the comparatively gentle slope of the knoll, in contrast to the numerous ridge lines (height, mainly 1–6 m) developed on the relatively steep slopes of the knoll. On the basis of the associated geomorphological features, the three off-axis sites (Archean, Pika, and Urashima) were identified as localities created by relatively long-term large-scale hydrothermal activity, as compared with sites in the on-axis area. The sustained activity at off-axis sites appears closely related to an off-axis upwelling magma system. The three off-axis hydrothermal sites are composed mainly of breccia assemblages that probably originated from hydrothermal activity with black smoker venting. These areas are characterized by numerous ridge lines, conical mounds, and bumpy seabed texture, whereas the on-axis sites are characterized by the absence of ridge lines, and the presence of white smoker and shimmering observed on dome-shaped pillow mounds. Hence, the distribution of ridge lines, mound morphology, and bumpy seabed texture is likely to correlate with hydrothermal activity.

1. Introduction

High-resolution bathymetric data provide essential information for broad overviews of oceanic hydrothermal systems. Near-bottom high-resolution bathymetric mapping using towed side-scan sonar and photographic imagery has been used for the past 20 years to investigate the complex seabed morphology created by hydrothermal venting in deep-water spreading-ridge environments, and to assess the relationship of such environments to volcanic and tectonic processes (Haymon et al., 1991; Humphris and Klenirock, 1996). More recent technological and scientific advances, such as near-bottom swath bathymetric surveys (grid spacing, 0.2–3 m), have revealed

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the details and distributions of features such as mounds, vents, fissures, faults, and lava flows, (e.g., Kurras et al., 1998; Scheirer et al., 2000; Carbotte et al., 2003; Deschamps et al., 2007; Ferrini et al., 2007; Tanaka et al., 2007; Ferrini et al., 2008; Soule et al., 2008). Many studies have investigated the detailed bathymetry of the East Pacific and Atlantic oceans, such as on the East Pacific Rise (EPR), the Mid-Atlantic Ridge (MAR), the Juan de Fuca Ridge, etc.; however, relatively few surveys have been conducted of hydrothermal sites in the West Pacific Ocean. Here we present the first detailed morphological characterization of field-scale geology and associated hydrothermal systems in the Mariana Trough.

In general, localized hydrothermal systems are organized mainly by the interactions between tectonic and volcanic processes. The occurrences of faults, fissures, and fractures play an important role in the formation of hydrothermal conduits (e.g., Kleinrock and Humphris, 1996; Humphris et al., 2002). Heat sources for hydrothermal systems include axial magma chambers (AMCs) and systems of sheeted dikes beneath the spreading centers, high-temperature rocks located at depth along faults, and combination of these (e.g., Cannat et al., 2004; German and Lin, 2004; Crawford et al., 2010). Because of regional variations in the occurrence and distribution of processes controlling hydrothermal systems, unique and complex geomorphology is produced at any given hydrothermal site. In addition, active and dead chimneys often occur at the summit and on the slopes of mounds, consisting mainly of breccias originating in sulfide deposits and/or lavas (e.g., Tivey, 2007). Hydrothermal activity in a given region is characterized by the particular scale and distribution of hydrothermal structures, and the compositional characteristics of hydrothermal deposits.

As noted above, the collection of near-bottom high-resolution bathymetric data is expected to clarify the relationship between geomorphological features and the characteristics of hydrothermal activity, as well as provide an enhanced understanding of hydrothermal systems. Such data also help us to understand the control of tectonic and volcanic activity on hydrothermal systems in the study area. Of note, the details of seabed geomorphological features are not detectable by hull-mounted multi-beam surveys that produce map data at grid spacings of tens of meters.

In this context, the present study investigates the detailed bathymetric characteristics at four hydrothermal sites in the southern Mariana Trough, using near-bottom swath-mapping data collected by SEABAT7125AUV (Reson Inc.) on the autonomous underwater vehicle (AUV) *Urashima* during the cruise YK09-08 (R/V *YOKOSUKA*). To support the morphological interpretations of the bathymetric data, we also used dive observations acquired by the submersible *Shinkai6500* during the cruise YK10-11. It is also interesting that the tectonic settings (locations) and perhaps the processes driving the hydrothermal systems in the southern Mariana Trough are variable (e.g., Urabe et al., 2004; Kakegawa et al., 2008), despite the fact that hydrothermal sites are located within approximately 5 km of one another (details described in Section 2). Our results indicate that topographic characteristics of hydrothermal sites are quite variable, particularly the seafloor morphological characteristics of sites with large active black smoker chimneys, as compared with sites with small active white smoker chimneys and shimmering.

2. Study area

The research area is located in the southern Mariana Trough, near 12°57′N, 143°37′E (Fig. 1A, B). The Mariana Trough is an active backarc basin that has opened in the past 6 Ma (Fryer, 1996). The spreading axis, located in the eastern part of the basin and close to the volcanic arc, shows highly asymmetric spreading (e.g., Deschamps and Fujiwara, 2003; Asada et al., 2007). In the southern part of the basin, the Mariana arc–trench system curves westerly, and the distance between the backarc spreading axis and the active volcanic arc diminishes to approximately 20 km (Martinez et al., 2000). The morphology of the ridge axis in the southern part of the basin is characteristic of fast-spreading ridges, in spite of its intermediate to slow spreading rate (half-spreading rate, 35 mm/yr) (Seama et al., 2002). Gravity data indicate that the crust in the southern end of Mariana Trough (south of 14°22′N) is relatively thick as compared with that in the north (north of 14°22′N) (Kitada et al., 2006). These observations suggest a high magma supply rate in the region.

Several hydrothermal systems were discovered in the study area in 2003 and 2004 (Fig. 1C): the Snail and Yamanaka sites are located on the active backarc spreading axis; the Archean site is located on the eastern foot of the axial high; and the Pika site is located on an off-axis knoll, about 5 km from the axis (e.g., YK03-09 and YK05-09 cruise reports, Ishibashi et al., 2004; Urabe et al., 2004; Kakegawa et al., 2008). The sites are aligned roughly perpendicular to the spreading axis.

The Snail site consists of a hydrothermal mound of about 20 m in diameter, developed on pillow lavas (Urabe et al., 2004) and surrounded by unaltered pillow and sheet lavas (Kakegawa et al., 2008). The site is an active hydrothermal system with white smoker venting and some dead chimneys; no large chimneys (height: >2 m) as observed at other sites were reported (YK03-09 cruise report). Active venting (approximately 250 °C) was observed when the site was first discovered in May 2003 (Wheat et al., 2003); however, lower vent-fluid temperatures were reported during subsequent cruises in October 2003 (about 110 °C) (Ishibashi et al., 2004) and July 2005 (about 110 °C) (YK05-09 cruise report). Features observed at the Snail site include: shimmering water venting directly from basaltic seafloor (Ishibashi et al., 2004), sulfide crusts covering the altered pillow lavas, clay mounds consisting mostly of nontronite (a clay mineral) and covered by Mn-oxides, and white-colored microbial mats typically associated with low-temperature venting (20–40 °C) (Kakegawa et al., 2008). Two drill core samples (lengths, 7.5 and 4.1 m), obtained using a Benthic Multi-coring System (BMS) on the R/V *Hakurei-Maru #2*, indicate the presence of porous basaltic lavas with numerous fractures (Urabe et al., 2004).

The Yamanaka site, discovered in 2003, is situated on a volcanic edifice (height: >10 m, length of major axis: >200 m) located approximately 1.2 km southwest of the Snail site (Utsumi et al., 2004; Kakegawa et al., 2008; YK03-09 cruise report). The edifice consists of pillow lavas with no sedimentary cover (Kakegawa et al., 2008). A white smoker and several inactive sulfide chimneys (3–8 m high) adjacent to altered pillow lavas were found at the site (Kakegawa et al., 2008; YK03-09 cruise report). The occurrence of large dead chimneys suggests vigorous black smoker venting activity in the past; however, at present, the site is characterized by mainly shimmering and cloudy waters surrounding the edifice (Kakegawa et al., 2008). Mineral deposits (mainly chalcopyrite, pyrite, and sphalerite) occur around the large chimneys (YK03-09 cruise report).

The Archean site was discovered in 2004 at the top of a giant (50-m high) sulfide mound, located at the foot of the axial high (Ishibashi et al., 2004; Urabe et al., 2004). The mound is composed of pyrite, chalcopyrite, and sphalerite (Urabe et al., 2004). The site is an active hydrothermal system, with black smoker chimneys 1–2 m high. The highest observed temperatures were 213 °C (Ishibashi et al., 2004) and 345 °C (YK05-09 cruise report). Several dead chimneys (maximum height, 5 m) and shimmering from seafloor were found on the mound (YK05-09 cruise report).

The Pika site was discovered in 2003 on the summit area of an off-axis knoll (Utsumi et al., 2004; YK03-09 cruise report). The knoll (height: approximately 400 m, length of major axis: approximately 3500 m) is composed of pillow lavas with minor sediment cover (Kakegawa et al., 2008). The Pika site is an active hydrothermal system with active black smoker chimneys, a white smoker chimney, dead chimneys (maximum height, >10 m), shimmering from seafloor, and sulfide mounds (Urabe et al., 2004; Kakegawa et al., 2008; YK03-09 and YK05-09 cruise reports). The highest observed temperature of the black smoker was 330 °C (Urabe et al., 2004). The black