

A deep-towed magnetic survey in the southern Okinawa Trough: Implications for hydrothermal system detection

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Article history:

Received 28 September 2018

Revised 13 February 2019

Accepted 15 February 2019

Keywords:

Deep-tow, Magnetic anomaly,
Hydrothermal system, Southern
Okinawa Trough

Citation:

Doo, W.-B., S.-K. Hsu, H.-F. Wang,
Y.-S. Huang, C.-H. Tsai, C.-L. Lo,
S.-S. Lin, C.-W. Liang, and Y.-J. Lin,
2019: A deep-towed magnetic survey
in the southern Okinawa Trough:
Implications for hydrothermal system
detection. *Terr. Atmos. Ocean.
Sci.*, 30, 675–683, doi: 10.3319/
TAO.2019.02.15.01

ABSTRACT

The Okinawa Trough (OT) is widely recognized as an area with extensive volcanism and hydrothermal activity. However, finding new hydrothermal vent sites in this region remains a technical challenge due to their small sizes. A deep-towed magnetic survey can acquire short-wavelength signals, which can provide useful information on the shallow subsurface structures of hydrothermal systems. In 2017, a deep-towed magnetic survey was conducted in selected area of the southern OT. After data processing and removing the regional magnetic field, crustal magnetization map was obtained by assuming a magnetized layer with a constant thickness of 500 m whose top surface is the seafloor. In addition, onboard echo sounder signals (EK-60) suggest the presence of gas plumes emanating from the seafloor within the water column. Some of these emanating gas plumes are concentrated in several small areas that correlate well with magnetization lows in the study region. The deep-towed magnetic survey results and other geochemical/geophysical observation results suggest that the Geolin Mounds (GLM) site and site Penglai Fault Zone (PFZ) are the highly potential hydrothermal areas in the southern OT.

1. INTRODUCTION

Submarine hydrothermal vents are hot springs on the seafloor where metals are deposited co-existing special biological communities. Cold seawater penetrates percolates into a deep reaction zone and is heated to temperature 350 - 450°C. This hydrothermal fluid becomes buoyant and corrosive before re-entering in the ocean. The resulting solution contains metals and large amounts of compounds such as sulfides and H₂S. When this fluid is ejected out of the seafloor, it mixes with near-freezing seawater (2 - 4°C) forming very fine-grained sulfide minerals that are deposited to form venting black (or white) smokers. These solid minerals form chimney-like structures that can reach a height of 60 m. Recently, hydrothermal sites have attracted much attention, because hydrothermal sulfide deposits are

significantly enriched in valuable metals (Reeburgh 1982; Lowell and Rona 1985; Hannington et al. 1995).

Several previous studies (Tivey et al. 1993, 2014; Tivey and Johnson 2002; Okino et al. 2013; Fujii et al. 2015; Sztikar et al. 2015a; Honsho et al. 2016; Tao et al. 2017) have collected high-resolution magnetic data from hydrothermal fields; highlighting the correlation between low crustal magnetization with both active and extinct submarine hydrothermal vents due to hydrothermal alteration (Rona 1978; Caratori Tontini et al. 2016). In addition, Okino (2018) analyzed high resolution magnetic data which collected in two sites of different host rocks (rhyolitic and basaltic) in the southern OT. The results reveal very low magnetization in the Tarama Knoll (hosted by rhyolitic); positive magnetization caused by newly erupted lava flow and reduced magnetization caused by hydrothermal alteration in the Irabu Knoll (hosted by basaltic). Statistical analysis of sediment samples

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(ODP Leg 169) reveals that strong hydrothermal alteration can result in a complete loss of detrital/diagenetic magnetic signals, which are replaced by weaker hydrothermal signals composed of monoclinic pyrrhotite and pyrite (Urbat et al. 2000). The same conclusion of these studies is that hydrothermal alteration can reduce magnetization.

In addition, previous observations (Tivey and Johnson 2002; Okino et al. 2013; Caratori Tontini et al. 2016) pointed that the horizontal scale of a submarine hydrothermal vent or alteration zone is small (typically a few hundreds of meters in diameter or less). Thus, the detection of hydrothermal vents is a technical challenge. In this study, the survey area is located in the southern OT, and the topography of the study area is between 1200 and 1600 m in depth (Fig. 1). Consequently, using deep-submergence vehicles are required to map the vent sites with the required resolution. According to the results of the abovementioned previous studies (Okino et al. 2013; Caratori Tontini et al. 2014; Sztikar et al. 2015b; Okino 2018), we expect that deep-towed magnetic data can provide vital information for detecting new hydrothermal systems in the southern OT.

2. TECTONIC BACKGROUND

A number of hydrothermal sites have been found in mid-ocean ridges and back-arc systems, including the OT, across the world. The OT is an active back-arc basin that

formed behind the Ryukyu arc-trench system (Lee et al. 1980; Letouzey and Kimura 1986; Sibuet et al. 1987, 1998), where the Philippine Sea Plate is subducting beneath the Eurasian Plate. The OT extends for more than 1200 km from the Japanese mainland to northern Taiwan, and it is traditionally divided into three segments (northern, middle, and southern) by the Tokara Channel and Kerama Depression (Shiono et al. 1980; Kuramoto and Konishi 1989) (Fig. 1). The tectonic setting in the OT is characterized by active rifting structures and the frequent intrusion of magma, which can be expected to provide the heat received for the development of hydrothermal systems, with faults and fracture zones providing channels for hydrothermal circulation. Due to hydrothermal alteration and mineralization, back-arc hydrothermal sulfide deposits generally contain valuable metals such as Zn, Pb, Ag, and Au (Iizasa et al. 2004). In total, 8 hydrothermal vent fields have been discovered in the OT (Watanabe and Kolima 2015) (Fig. 1).

The southern OT has the deepest topography throughout the entire OT, and it gradually narrows and ends formally at the island of Taiwan. Sibuet et al. (1998) reported on the last two extensional phases that occurred in the southwestern OT trending along N150° during the Pleistocene (2 - 0.1 Ma) and trending along N170° during the late Pleistocene-Holocene (0.1 - 0 Ma). The trough is filled with thick clastic sediments derived from the surrounding continents and islands together with volcanoclastic sediments associated

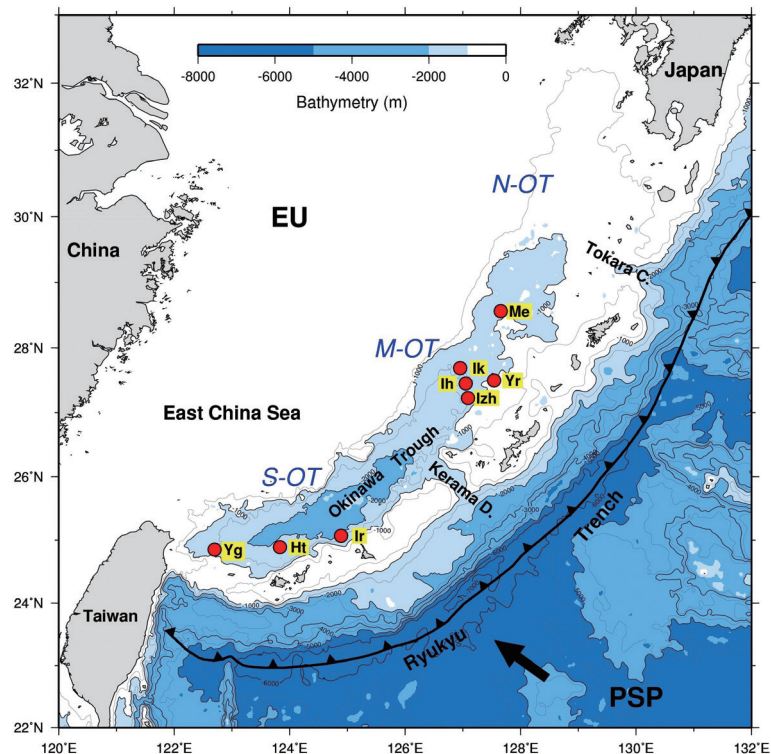


Fig. 1. Distribution of hydrothermal vent fields in the Okinawa Trough. Me: Minami-Ensei Knoll; Yr: Yoron Hole; Ik: Iheya North Knoll; Ih: Iheya Ridge; Izh: Izena Hole; Ir: Irabu Knoll; Ht: Hatoma Knoll; Yg: Daiyon-Yonaguni Knoll.

with arc and back-arc volcanism in this area (Tsugaru et al. 1991). A volcanic lineament called the cross-back-arc volcanic trail (CBVT) (Sibuet et al. 1998; Lin et al. 2007) across the central graben and the Yonaguni Knoll (Yg) hydrothermal field which are both situated in the southern OT (Fig. 2). This represents the coexisting occurrence of zinc- and lead-enriched sulfides and sulfate minerals (Suzuki et al. 2008; Ishibashi et al. 2015). To the west of the CBVT is the most pronounced back-arc basin formation area (Ishibashi et al. 2015), which contains magmatic activity-related hydrothermal venting (Tsai 1999; Lee 2005) that could constitute a highly potential for the formation of hydrothermal systems.

3. DATA COLLECTION AND PROCESSING

The magnetic amplitude will decrease while increasing altitude above the seafloor (Caratori Tontini et al. 2016). To examine the possibility that such small-scale hydrothermal field with a low susceptibility can be detected by magnetic surveys, the magnetic susceptibility contrast between high and low susceptibility zones was assumed to be 10×10^{-4} S.I. Two uniform prisms with a low susceptibility are designed to be 200 m wide and 500 m thick and 100 m wide and 500 m thick. The inclination and declination of these two prisms are set to 35° and -5° , respectively. The magnetic anomalies

at different observation levels are shown in Fig. 3. We can see that if the distance between the instrument and source is larger than 500 m, the variations in the magnetic anomalies are too small to be detected by a magnetometer.

A high-resolution deep-towed geophysical survey was carried out in the southern OT in April 2017; the survey included a sub-bottom profiler, side-scan sonar and a proton-precession magnetometer. Magnetic data were collected along 12 NNE-SSW profiles with a total track length of ~ 268 km that were spaced ~ 500 m apart. The survey track lines are shown in Fig. 2. The magnetometer recorded total field geomagnetic data with a sampling interval of 1 s, and the velocity of the vessel was approximately 2.0 - 2.5 knots. The position of the instrument was calculated retrospectively using the ship position, instrument height above the seafloor and cable length. Geomagnetic data were reduced to magnetic anomalies by subtracting the Earth's regional magnetic field given by the International Geomagnetic Reference Field (IGRF-12 model). The data spectral resolution depends on the distance between the instrument and the magnetized body. Therefore, the deep-towed magnetometer generally cruised at an altitude of several tens of meters (Fig. 4a), allowing the detection of anomalies with a shorter wavelength (blue line shown in Fig. 4b). Meanwhile, we obtained the surface-towed magnetic anomalies along the

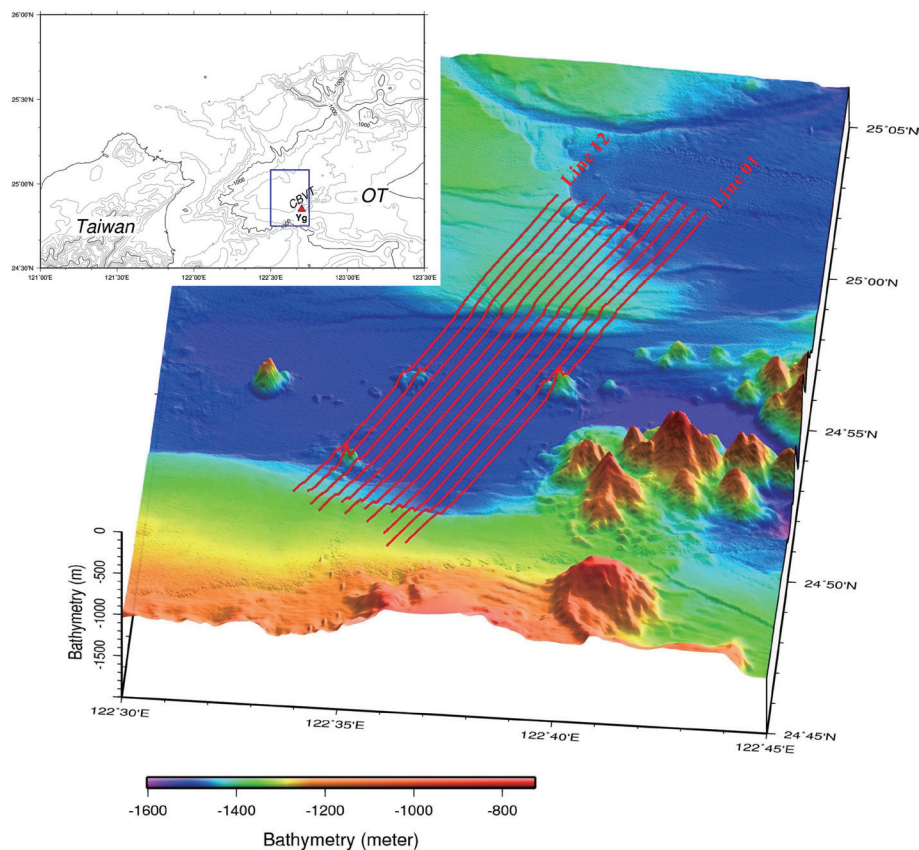


Fig. 2. Map showing the location of this study (blue frame). Red lines indicate track lines of the deep-towed magnetic survey.

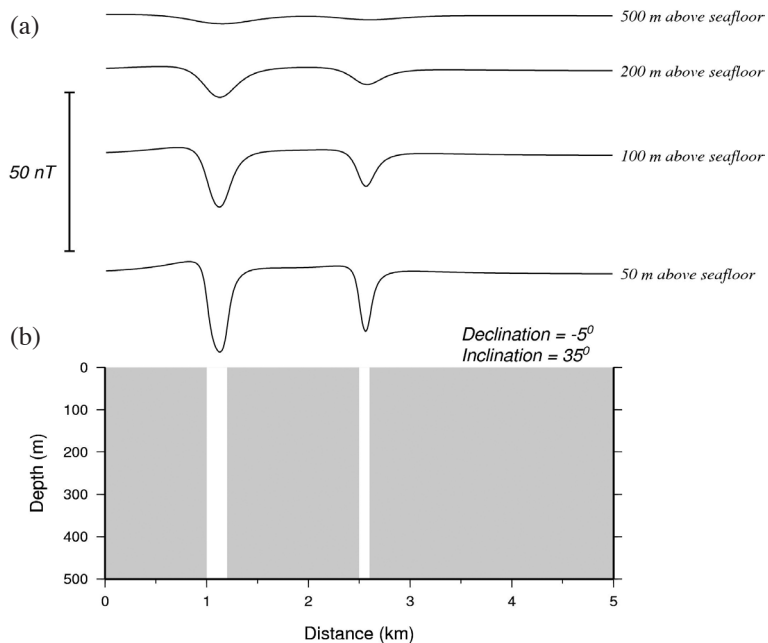


Fig. 3. Modeling magnetic anomalies caused by low magnetic susceptibility objects. (a) Curves show the observed magnetic anomalies at different observation altitude. (b) Two uniform prisms of low susceptibility are 200 m wide 500 m thick (left) and 100 m wide 500 m thick (right).

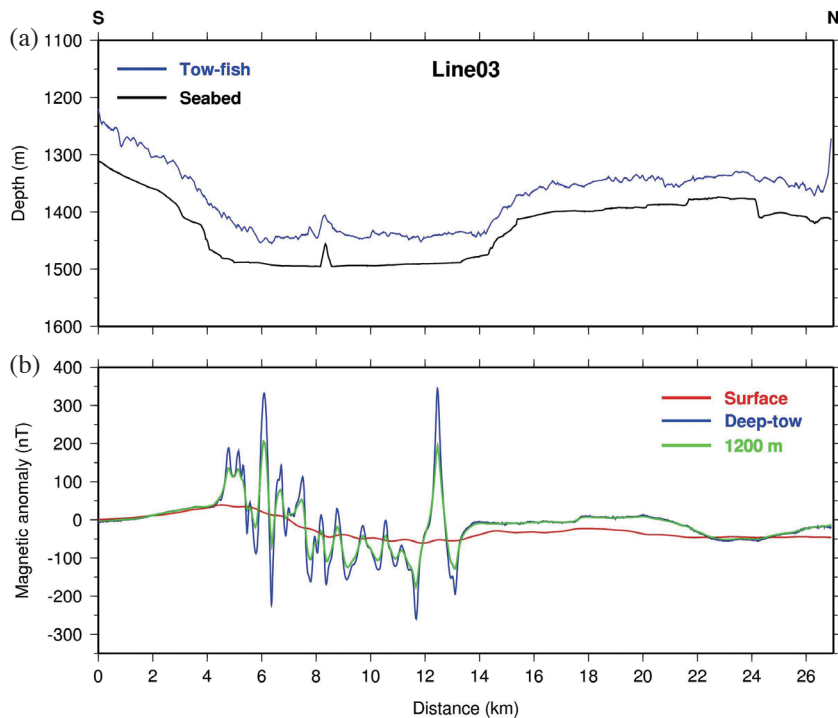


Fig. 4. (a) Line 03 topographic profile. Blue line indicates the altitude of the deep-towed instrument. (b) Magnetic anomalies along profile line 01. Red line indicates surface-towed magnetic anomalies; blue line indicates deep-towed magnetic anomalies; green line indicates observation plane at 1200 m depth magnetic anomalies.

same profiles from Doo et al. (2015) dataset. As shown in Fig. 4b (red line), the variation in the surface-towed magnetic anomalies is small, which roughly reveals long-wavelength regional structural signals. For the convenience of data analysis, a fixable observation level is necessary. A correction for the instrument altitude above the seafloor was performed by upward continuation technique (Ciminale and Loddo 1989; Blakely 1995) from the uneven observation plane to a level plane at a depth of 1200 m (green line shown in Fig. 4b). After data processing, we obtained a magnetic anomaly map, as shown in Fig. 5.

To minimize edge effects, the deep-towed magnetic data were bordered with surface magnetic data (Doo et al. 2015) that had been downward continued to the level plane at a depth of 1200 m. Then, before calculating the crustal magnetization, a bandpass filter with wavelength cutoffs of 10 and 0.1 km and a pass-band from 5 - 0.5 km were

used to ensure the convergence of the solution. In order to obtain the equivalent magnetization map in the study area, we have performed a magnetic inversion (Hsu et al. 2001). We assumed that the magnetic anomalies were attributed to an equivalent layer with a constant thickness of 500 m and that the top of each block was the seafloor. The magnetization direction was assumed to be the same as the present-day geomagnetic field (the inclination is set to 36.8° and the declination is set to -4.5° based on the IGRF-12 model). The equivalent magnetization of each block was obtained by inverting the magnetic data using the least-square method (Menke 1984), and the inversion calculation is accomplished using the LSQR algorithm (Paige and Saunders 1982). The resulting magnetization map is shown in Fig. 6.

In addition, single-beam bathymetry data were collected in the southern OT during 2016 - 2018 using the onboard echo sounder (EK-60 system) mounted on the R/Vs OR1

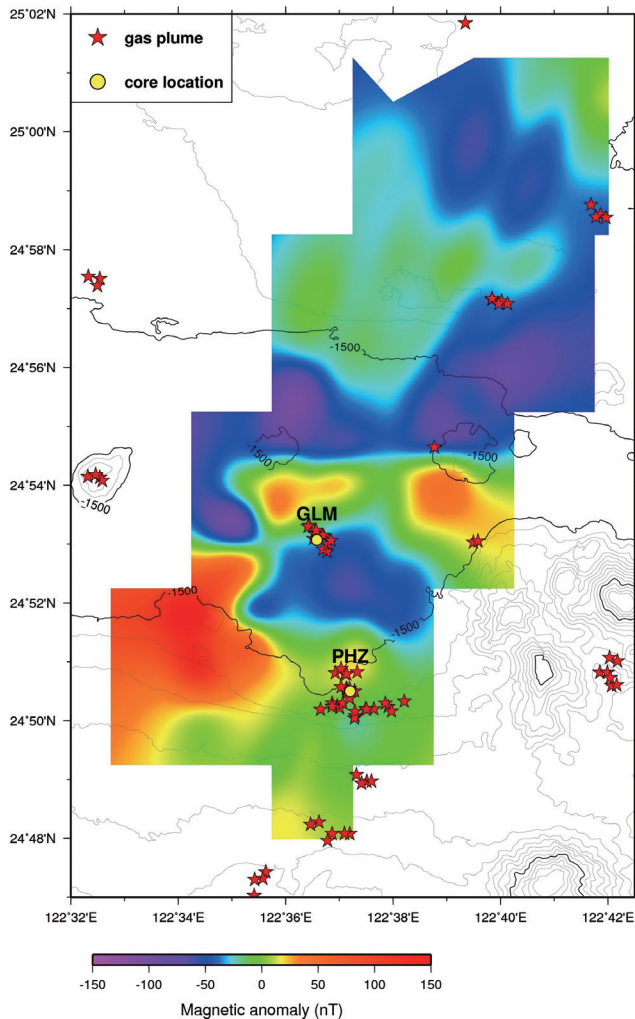


Fig. 5. Magnetic anomaly map of the study area. Red stars indicate gas plumes locations identified by EK-60 system. Yellow circles indicate the location of gravity code sites. Black and gray lines indicate bathymetric contours. GLM: Geolin Mounds; PHZ: Penglai Fault Zone.

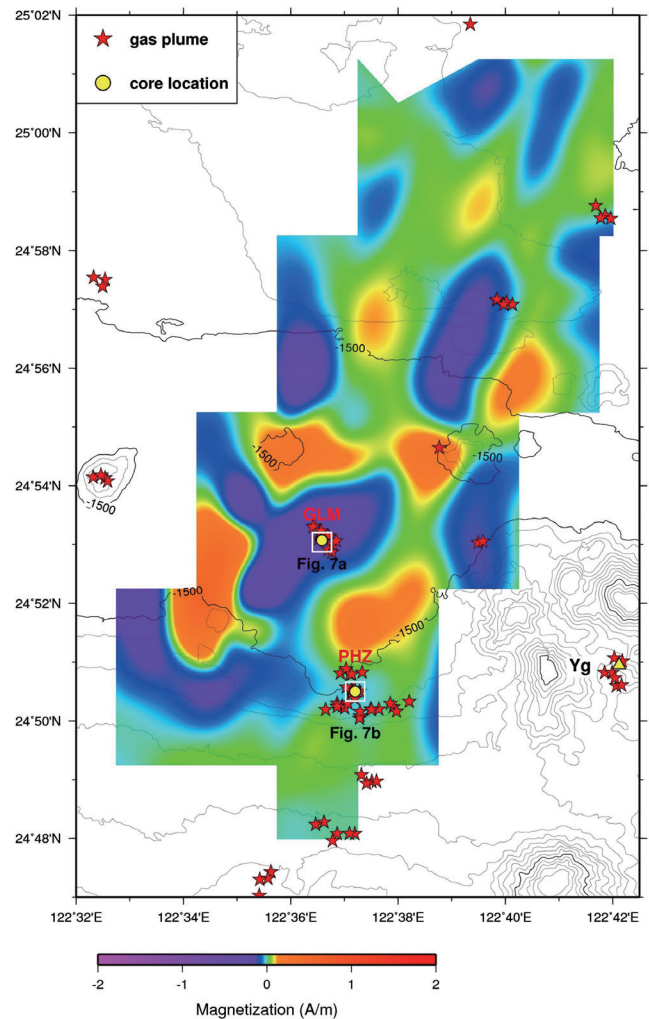


Fig. 6. Magnetization distribution map of the study area. Red stars indicate gas plumes locations identified by EK-60 system. Yellow circles indicate the location of gravity code sites. Black and gray lines indicate bathymetric contours. GLM: Geolin Mounds; PHZ: Penglai Fault Zone; Yg (yellow triangle): Yonaguni Knoll.

and OR2. The EK-60 system is useful for several investigations in the water column, including those conducted to determine fish distributions and marine creature activity, and for fields as ocean physics, marine geology and geophysics. Gases or bubbles can be detected in terms of gas flares or gas plumes in the water column. Venting is an obvious feature of hydrothermal fields. Thus, if gas flares (or plumes) in the seawater column are emitted persistently from the seafloor, they can be detected using the EK-60 system. In terms of the features of hydrothermal fields, the onboard EK-60 system could represent a relatively quick and economic tool for elementary investigations. Furthermore, geophysical, geological, and geochemical observation results in the study area are integrated for detecting new hydrothermal systems.

4. RESULTS AND DISCUSSION

Previous studies have shown that the OT lacks oceanic lithosphere (Nagumo et al. 1986; Hirata et al. 1991; Oshida et al. 1992), and a recent seismic study revealed a minimum crustal thickness of 8 km at the southernmost part (Klingelhoefer et al. 2009). Although this thickness might be thin compared with typical continental crust, the velocity gradient of the layer is too low to be interpreted as oceanic crust (Ishibashi et al. 2015). The nature of the crust in the southern OT suggests the presence of extended continental crust. Consequently, no magnetic reversals have occurred

in the study area, and the equivalent magnetization patterns could actually reflect the magnetic characteristics of subsurface materials. Thus, some small areas in Fig. 6 with magnetization lows could reflect the characteristics of shallow subsurface materials. A number of studies have reported that hydrothermal systems are typically associated with low magnetization. However, some other factors may also result in this type of magnetic feature. To ensure that these magnetization lows are related to hydrothermal systems, we need to compare their characteristics with other geophysical, geological, and geochemical observations.

The EK-60 system detected several gas plumes in the study area (Hsu 2017; Tsai et al. 2019), some of which were concentrated in several small areas that correlate well with magnetization lows (Fig. 6). Geochemical investigation results reveal that high methane concentrations, high He isotope ratios, and high $^3\text{He}/^4\text{He}$ ratios (Su 2017) were observed at both site GLM and site PFZ. Furthermore, active hydrothermal vent images were found around site GLM (observed by a Fiber-optical Instrumentation Towed System) and mineral deposits with metallic reflections were observed around site P1 (Chen 2017; Chou et al. 2019). Apparently, the locations of sites GLM and PFZ both coincide with magnetization lows and gas plumes. Furthermore, gas escape features are observed from the high-resolution deep-towed side-scan sonar images (Fig. 7) (Hsu 2017). All of these results indicate intense hydrothermal activity at these

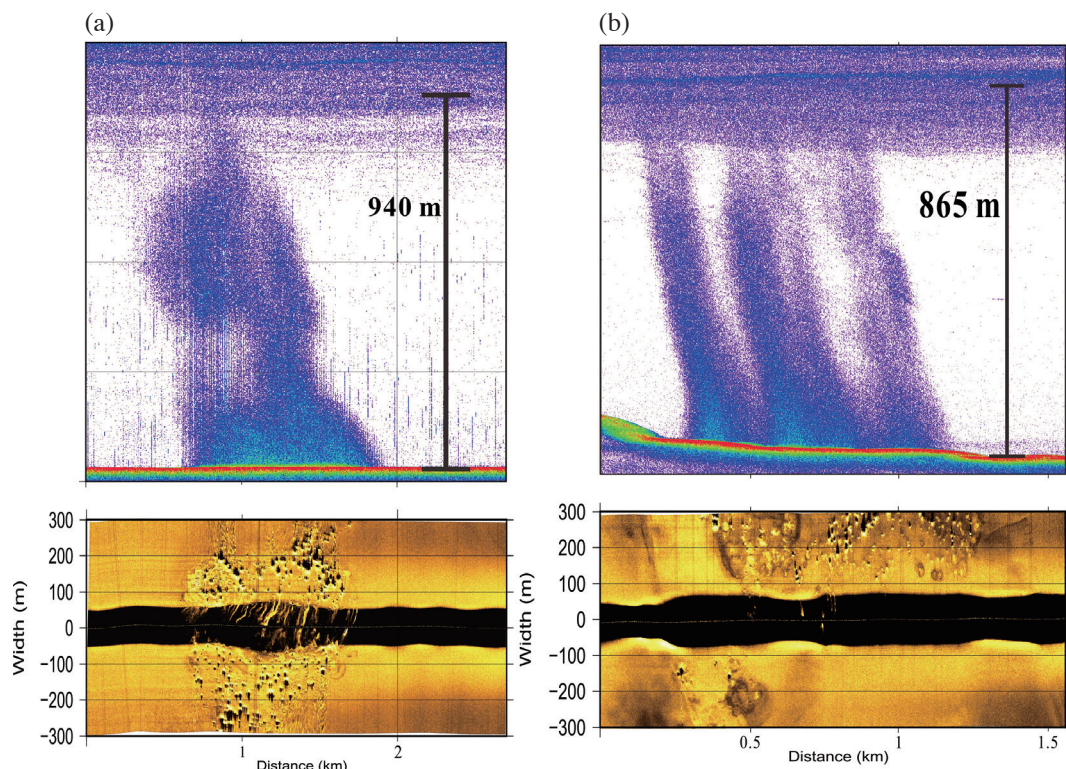


Fig. 7. (a) EK-60 echo sounder image (upper panel) and side-scan sonar image (lower panel) around site GLM in Fig. 6. (b) EK-60 echo sounder image (upper panel) and side-scan sonar image (lower panel) around site PFZ in Fig. 6.

two sites (GLM and PFZ), although additional, more detailed investigations are needed.

Several obvious features such as fluid emanations, high heat-flows, and high $^3\text{He}/^4\text{He}$ ratios could be the useful indicators for detecting hydrothermal systems. However, if a hydrothermal system is inactive (or extinct), these features may not exist. In terms of the exploration for metalliferous ore resources, both active and extinct hydrothermal vent sites are important. The reduced magnetization characteristics are still preserved after the cessation of hydrothermal venting (Tivey and Johnson 2002). Thus, we can detect inactive hydrothermal fields based on high-resolution deep-towed magnetic surveys.

5. CONCLUSION

Compared with a surface-towed magnetic survey, deep-towed magnetic data contain short-wavelength signals (Fig. 4) that can provide the opportunity to image shallow, small subsurface structures. In terms of the detection of hydrothermal systems, therefore, near-bottom surveys are indeed necessary. Our observation results reveal strong correlations between magnetization lows and some hydrothermal system-associated features, such as gas plumes, high heat flow, and high $^3\text{He}/^4\text{He}$ ratios (Fig. 6). These results are consistent with several previous near-bottom magnetic studies. However, some areas have magnetization lows but do not reveal other hydrothermal features, and thus, they need to be investigated further. Combining the geochemical and geophysical investigation results in the study area, we propose that the GLM site and site PFZ are the highly potential hydrothermal areas in the southern OT. Consequently, additional investigations would be worthwhile.

Acknowledgements Constructive reviews from Dr. F.C. Tontini and one anonymous reviewer are appreciated. We thank the crew of the R/Vs OR1 and OR2 for their efforts in collecting deep-towed magnetic and EK-60 data. This study was conducted as an investigation of mineral resource project funded by the Central Geological Survey, Ministry of Economic Affairs, Taiwan. Most of the figures are generated using the GMT software of Wessel and Smith (1998).

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