Title:

Embryonic rifting zone revealed by a high-density survey on the southern margin of the southern Okinawa Trough

Ayanori Misawa[1・†]

Masahiko Sato[1,2]

Seishiro Furuyama[1, 3]

Jih-Hsin Chang[1]

Takahiko Inoue[1]

Kohsaku Arai[1]

1: Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST)

2: Department of Earth and Planetary Science, The University of Tokyo

3: Department of Marine Resources and Energy, Tokyo University of Marine Science and Technology,

Corresponding author: Ayanori Misawa (ayanori-misawa@aist.go.jp)

Key Points

- A graben controlled by a normal fault was discovered in the southern Okinawa Trough offshore northern Ishigaki-Jima Island.
- Magnetic anomaly and seismicity data indicate relatively shallow magma acting as a heat source.

- The graben likely manifests an embryonic rifting on the southern margin of the southern Okinawa Trough.

Abstract

Offshore northern Ishigaki-Jima Island, in the southern Okinawa Trough, offers outstanding opportunities to explore the rifting stage of a backarc system. We report the results of integrated marine geological and geophysical surveys with high-density survey lines in this area. We identify a graben bounded by normal faults and extending approximately 59 km in an ENE-WSW direction off-axis of the southern Okinawa Trough. Submarine volcanoes with active hydrothermalism and associated intrusive structures lie in the graben. Magnetic anomaly and seismicity data in and around the graben suggest the presence of relatively shallow magma acting as a heat source. All features identified in and around the graben suggest active rifting in the southern Okinawa Trough.

Plain Language Summary

The Okinawa Trough, adjacent to the southwesternmost Japanese islands, has experienced rifting of its continental crust since 2Ma. The southern part of the Trough includes a rift valley, the Yaeyama Rift, where rifting is active. Herein, using marine geological and geophysical data, we report the discovery of a graben bounded by normal faults on the southern margin of the southern Okinawa Trough. The graben hosts several submarine volcanoes, under which magnetic anomalies suggest relatively shallow magma. Because these geologic features resemble graben in the axial trough, we propose that the newly identified graben represents a rifting episode previously undocumented for the geological evolution of the Okinawa Trough.

Keywords:

Okinawa Trough, Backarc basin, Normal fault, Graben, Submarine volcano

1. Introduction

Backarc basins on continental margins are important constituents of the plate tectonic paradigm, and knowledge of their evolution is key to understanding the development of the lithosphere. A backarc system typically evolves from rifting to seafloor spreading. Compared to seafloor spreading, rifting on continental margins is not well understood due to the current rarity of such deformations. Among backarc basins located on continental margins, the Okinawa Trough (OT) is unique in that the backarc system is actively rifting, but no seafloor spreading has occurred (e.g., Lee et al., 1980; Raju et al., 2004; Keller et al., 2002; Jourdain et al., 2016). Intermitted rifting of the OT has been occurring since 2 Ma (e.g., Sibuet et al., 1987; 1995; 1998).

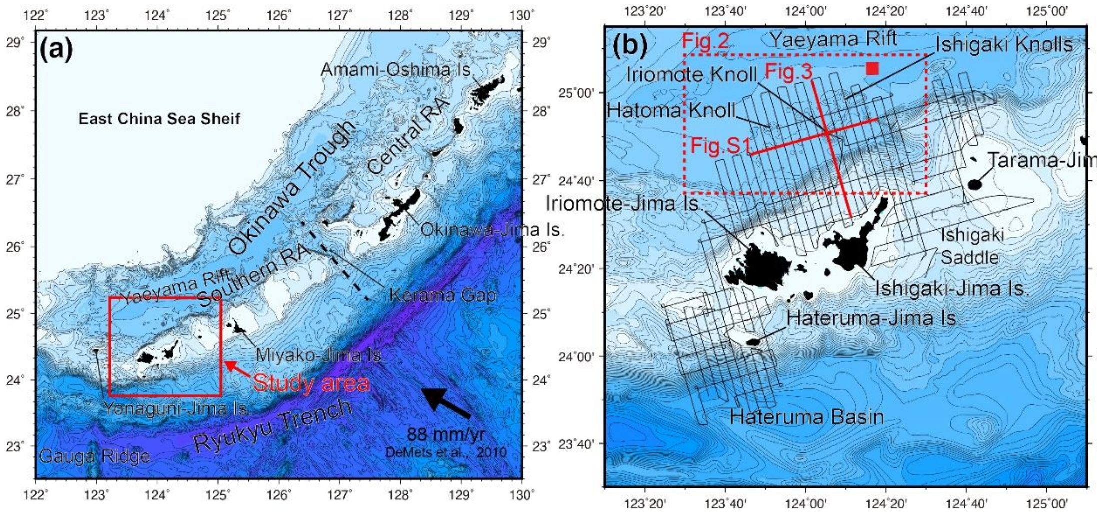

Figure 1 Tectonic map of the south Okinawa Trough area. (a) Bathymetry of the Ryukyu Island arc. The inset shows the main study area offshore northern Ishigaki-Jima Island. Black arrows indicate Philippine Sea plate motions (DeMets et al., 2010). Dashed black lines indicate the position of the Kerama Gap, which is deemed to be the boundary between the Southern Ryukyu Arc and the Central Ryukyu Arc (Konishi, 1965). (b) Bathymetry offshore

northern Ishigaki-Jima Island and GH18 cruise survey lines. Bold red lines indicate seismic profiles used in this study. The red square represents the position of a magma chamber (Arai et al. 2017). Both bathymetric maps used JTOPO30 grid data. RA: Ryukyu Arc.

The area offshore northern Ishigaki-Jima Island, located in the southern OT, is ideal for investigating rifting of a backarc system on a continental margin (Fig. 1). Previous seismic refraction surveys show no evidence of basaltic crust associated with seafloor spreading (e.g., Hirata et al., 1991; Nakahigashi et al., 2004), and numerous submarine volcanos suggest active magmatism associated with OT rifting (e.g., Sibuet et al., 1987; 1995; 1998). Among the submarine volcanoes, hydrothermal activity has been observed at Hatoma Knoll, the Yonaguni Knoll Ⅳ field, and Yaeyama Knoll on the trough axis (e.g., Toki et al., 2016; Konno et al., 2006; Miyazaki et al., 2017).

To investigate the geological structure along the island arc and the southern margin of the OT, an integrated marine geological and geophysical survey with high-density lines was conducted offshore northern Ishigaki-Jima and Hateruma-Jima islands (Fig. 1b). We report on newly discovered embryonic rift features offshore northern Ishigaki-Jima Island in the OT.

2. Geological setting

The Ryukyu subduction system consists of the Ryukyu Trench, the Ryukyu arc, and the OT, and is a typical trench-arc-backarc system (Fig. 1a). In the Ryukyu Trench, the Philippine Sea (PHS) plate is obliquely subducting beneath the Eurasian plate. The subduction rates of the plates differ in the northern and southern parts of the arc region, and the PHS plate subducts at 88 mm/yr in the southern OT (DeMets et al., 2010). Major components of the Ryukyu Islands are considered to be a forearc (outer arc) high, composed of pre-Cretaceous high-pressure metamorphic rocks, Eocene volcanic rocks, and Miocene sediments (Kizaki, 1976; Letouzey and Kimura, 1986). Various theories have been proposed for the timing of southern OT backarc rifting. Sibuet et al. (1987) suggested that the first phase of rifting occurred after a major early Miocene change in PHS plate motion with respect to Eurasia, and ceased during the Pliocene. Subsequently, a second rifting phase started at the Plio-Pleistocene transition and has continued to the present (Sibuet et al. 1987). In contrast, Miki (1995) proposed a two-phase opening model, the first phase lasting from 10 to 6 Ma, and the second occurring at ~1 Ma. Seismic data from the Yaeyama Rift in the OT axis indicates active rifting (Lee et al., 1980). On the basis of seismic profiles from the Yaeyama Rift, Arai et al. (2017) and Nishizawa et al. (2019) interpreted normal faults bounding the Yaeyama Rift and the stratigraphy of well-stratified trough-fill sediments. Arai et al. (2017) identified a less reflective zone and a low-velocity zone in the trough-fill sediments, and suggested the presence of an off-axis magma chamber in the OT (Fig.1b). Southwards, several knolls are distributed in the OT offshore northern Ishigaki-Jima Island, including the Ishigaki Knolls, Minna Knoll, Iriomote Knoll, Daini-Kobama Knoll, Daiichi-Kobama Knoll, Hatoma Knoll, and the Hatoma Hill Chain (Fig. 2a). These knolls are reported to be submarine volcanos (Watanabe et al., 1995).

3. Method and materials

We conducted integrated marine geological and geophysical surveys around Ishigaki-Jima Island in the Ryukyu Islands using research vessel (R/V) *Hakurei* operated by the Japan Oil, Gas and Metals National Corporation (JOGMEC) in August 2018. We acquired high-resolution multi-channel seismic (MCS) reflection, multi-beam echo sounder (MBES) swath bathymetry, sub-bottom profiler, gravity, and magnetic field data. Survey line spacings were 2 nautical miles (nm) in the NNW-SSE direction and 4 nm in the WSW-ENE direction (Fig. 1b). Combined, these data illuminate the geological structure offshore northern Ishigaki-Jima Island.

The seismic source was a GI gun (*Sercel*) comprising a total volume of 355 cubic inches (G: 250 cubic inches; I: 105 cubic inches). The shot interval of 6.1 s corresponded to ~25 m at a ship speed of ~8 knots. The receiver array used a 200 m-long, 32-channel solid digital streamer with group intervals of 6.25 m. The recording length was 5.9 s and the sampling rate was 2.0 ms. GPS data were used for positioning. Digital data were recorded with a CNT-2 seismic system (*Geometrics Inc.*) and then saved in SEG-D format on board. The SEG-D format data were subsequently converted to SEG-Y format, and the following data processing was performed using Seismic Processing Workshop (SPW) software (*Parallel Geoscience Corp.*): common-mid point (CMP) sorting, trace editing, bandpass filtering, gain recovery, deconvolution, velocity analyses, normal moveout (NMO), and CMP stack.

Bathymetric data were collected with a multi-beam echo sounding system (EM122, *Kongsberg Maritime AS*) at an operating frequency of 12 kHz from R/V *Hakurei*. Additional EM122 data were acquired from R/V *No.1 Kaiyo-Maru*. Sound velocity correction used real-time data from a surface water velocity meter, and sound velocity profiles from conductivity, temperature, and depth instruments (CTD) and expendable CTDs (XCTD) during the MBES observations. HIPS and SIPS software (*CARIS, Ltd.*) was used to edit the raw bathymetry data.

Total magnetic field data were acquired at 0.1-s intervals with a surface-towed cesium magnetometer (G-882, *Geometrics Inc.*). The sensor was towed 300 m behind the ship to minimize magnetization effects from the ship. Magnetic anomalies were calculated by subtracting the 13th Generation International Geomagnetic Reference Field (IGRF-13) from the observed magnetic field intensity. Magnetic diurnal variation was corrected using data from the Gesashi magnetic observatory on Okinawa-Jima operated by the Geospatial Information Authority of Japan. Crossover error, assumed to be mainly caused by ship magnetization, was minimized by using the Generic Mapping Tools software package x2sys (Wessel, 2010).

4. Results

Bathymetry data

The detailed seafloor morphology offshore northern Ishigaki-Jima Island obtained from the two survey cruises reveals numerous knolls and seafloor lineaments trending ENE-WSW (Fig. 2). An elongated depression between Hatoma Knoll and the Ishigaki Knolls is bounded by two rows of ENE-WSW-trending lineaments (Fig. 2). We interpret these lineaments as active faults bounding a developing graben. The graben is ~59 km long and 6–10 km wide, with a maximum depth of ~100 m. These lineaments likely extend across to the Ishigaki Knolls, located on the eastern side of the graben. Knolls and topographic highs inside the graben (Fig. 2b) are consistent with a regional interpretation of submarine volcanoes (Watanabe et al., 1995). Hatoma Knoll, characterized by active hydrothermal activity, is a submarine volcano within the graben (Fig. 2).

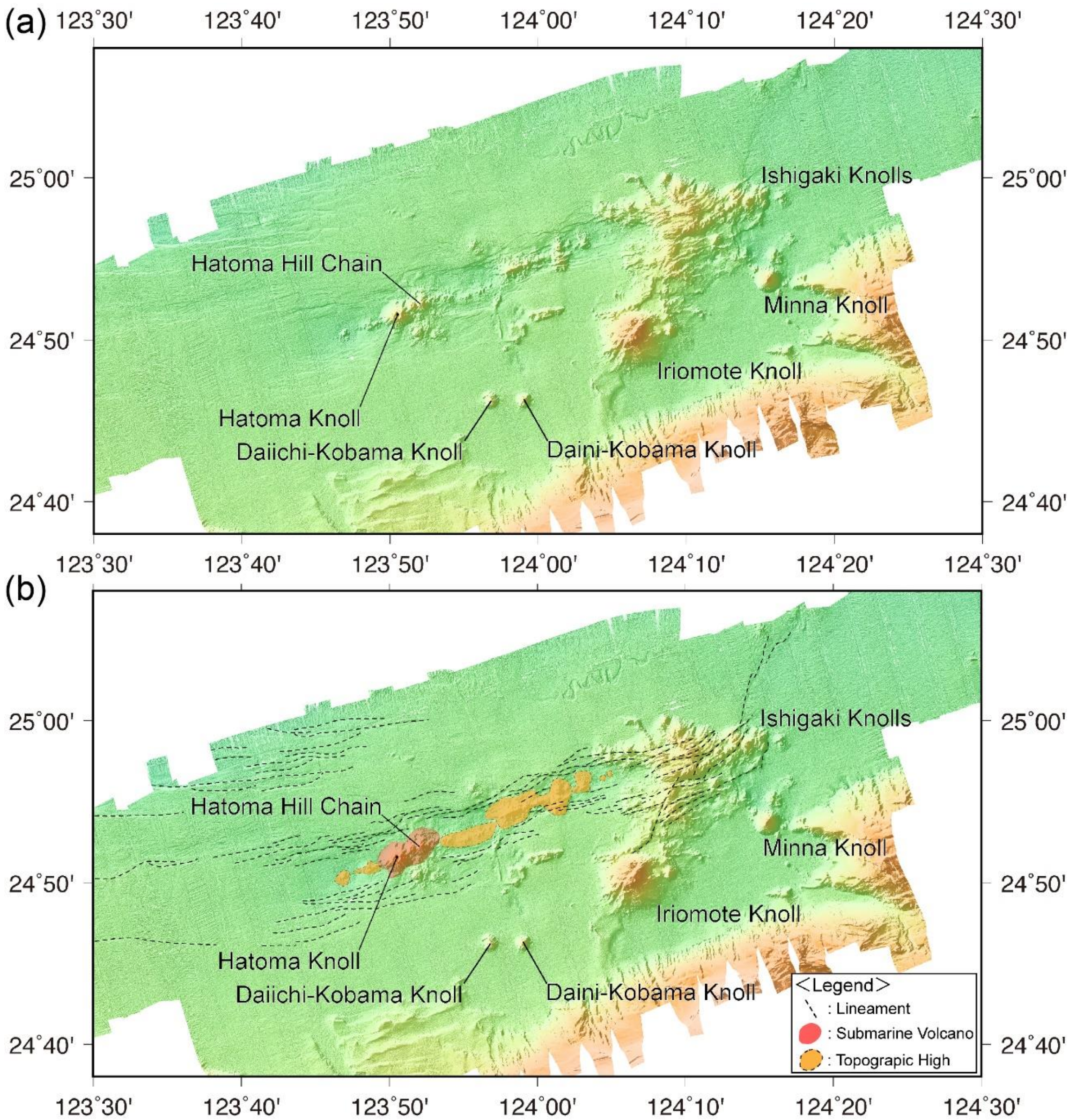

Figure 2 New high-resolution bathymetric map offshore northern Ishigaki-Jima Island. (a) Bathymetric maps were created using 20-m grid data from the two cruises. (b) Morphological interpretation. This new high-resolution bathymetric map reveals the ENE-WSW trending lineaments and an elongated depression between the Hatoma Knoll and Ishigaki Knolls. The dashed black lines are lineaments interpreted from the bathymetry.

Seismic profiles

Based on our seismic data, the sedimentary sequence of the OT is roughly divided into Unit A and overlying trough-fill sediments, with an unconformity (Fig. S1). Unit A is found from the slope region of the island arc to the OT. It seems the stratification of Unit A gradually increases up-section. The seafloor observation via Remotely Operated Vehicle (ROV) in this slope region confirmed that the exposed outcrop of Unit A is composed of siltstones. Thus, we consider Unit A to be as a stratified sedimentary sequence that partially extends from the island arc to the OT. The internal structure of the trough-fill sediments is characterized by continuous, high-amplitude parallel reflectors, onlapping Unit A. The thickness of the trough-fill sediments has a two-way travel (TWT) time of 1.3 seconds (Fig. 3). In the NNW-SSE seismic profile (Fig. 1b), the thickness of the trough-fill sediments generally increases toward the Yaeyama Rift (Fig. 3). Our seismic data also show that the internal structure of the Iriomote and Minna Knolls is characterized by a chaotic structure, seemingly associated with submarine volcanic process. It seems possible that the structure resulted from igneous intrusion and magma emplacement into Unit A and the trough-fill sediments. In addition, some sections of the trough-fill sediments show chaotic patterns indicating disturbance (Fig. S1). Furthermore, the unconformity is interrupted immediately beneath the chaotic structure, also suggesting that the chaotic pattern results from igneous intrusion and magma emplacement.

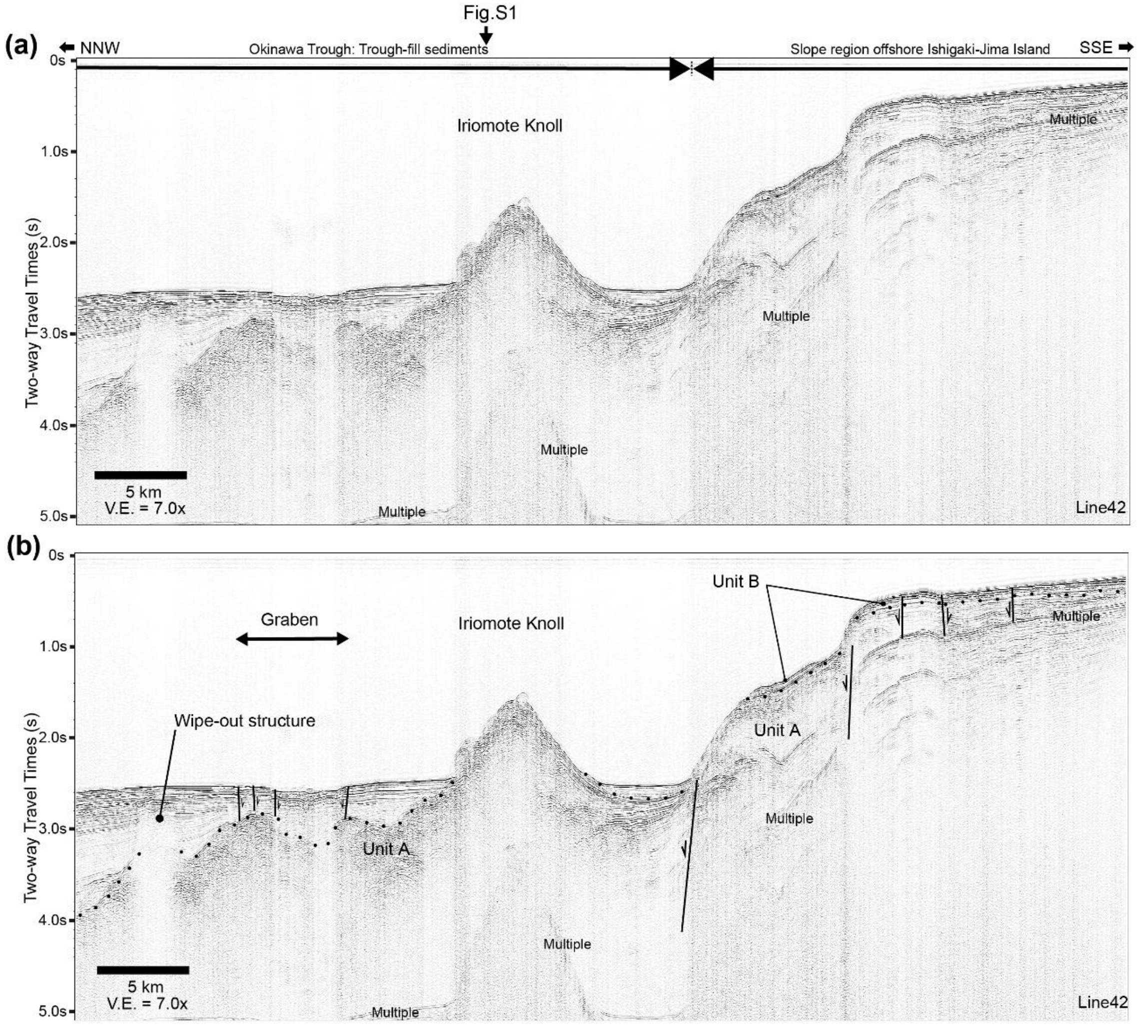

Figure 3 Stacked seismic profile of the Okinawa Trough and backarc slope offshore northern Ishigaki-Jima Island. (a) Stacked seismic profile of MCS Line42. (b) Interpreted seismic profile. This profile shows sedimentary sequences (Unit A, Unit B, and trough-fill sediments) across the graben and wipe-out structure in the OT. Unit A is characterized by the stratified internal reflector gradually increaseing up-section. Unit B is characterized by the continuous high-amplitude stratified internal reflector, while it is limited within the upslope area. The trough-fill sediments of the OT are characterized by continuous high-amplitude parallel stratified internal reflectors. The locations

of the profiles are shown in Fig. 1b. The dotted line indicates the unconformity surface. VE is calculated using Vp = 1,500 m/s.

Northward-dipping normal faults dominate the slope region, and northward-dipping and southward-dipping normal faults have developed in the trough-fill sediments of the OT (Fig. 3). Most normal faults offset the seafloor: the vertical offsets of the northern and southern bounding faults are estimated to be ~25 m and ~20 m, respectively (Fig. S2). The positions of these normal faults coincide with the lineaments flanking the graben (Figs. 3 and 4), indicating that the normal faults controlgraben formation (e.g., Lee et al., 1980; Lizarralde et al., 2007). Several intrusive structures within the graben coincide with topographic highs (Fig. 4), indicating a causal relationship.

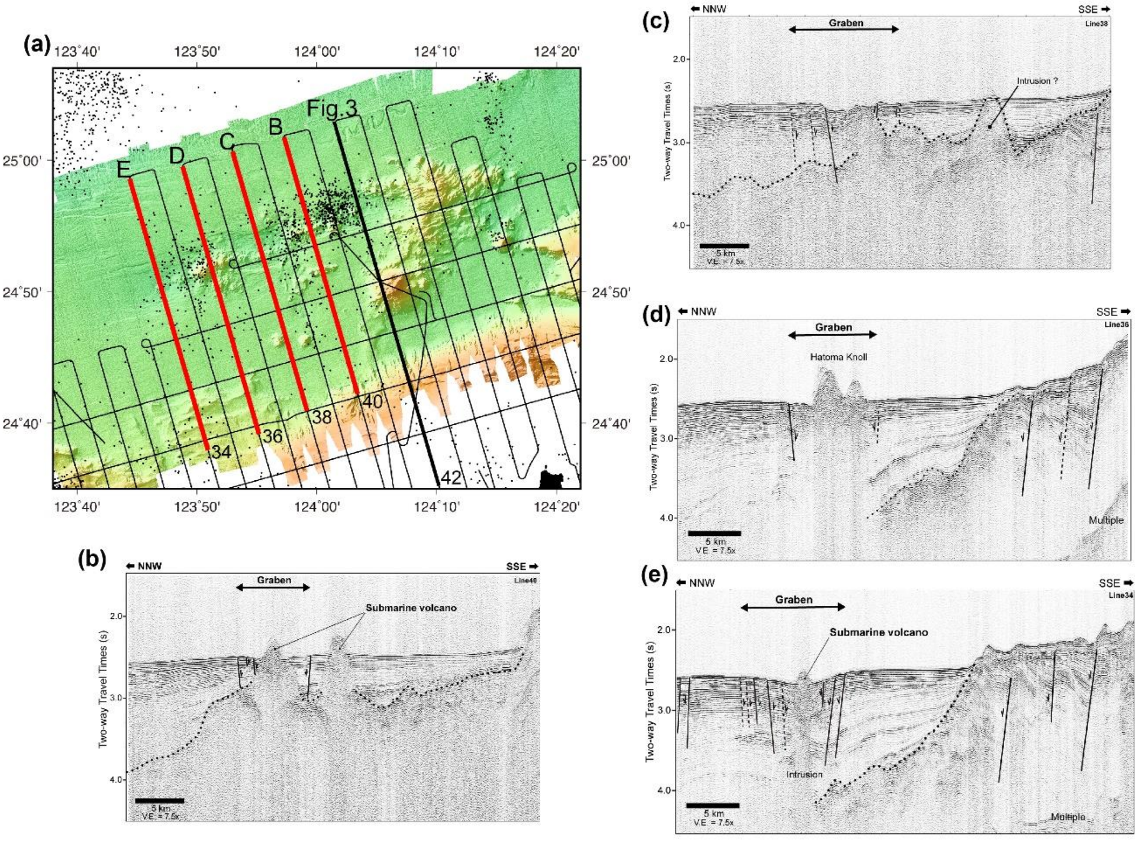

Figure 4 Seismic profiles across the graben. (a) Bathymetric map showing survey lines. Bathymetric maps were created using 20 m grid data. Black dots show epicenters determined by the Japan Meteorological Agency (JMA) (1998 - April 2018). Hypocenter depths range from 0 to 20 km, but uncertainties are large due to the limited number of seismic stations around the OT. Note that seismic activity is concentrated around Hatoma Knoll and the topographic highs inside the graben. (b) (c) (d) and (e) Interpreted stacked seismic profile of Lines 40, 38, 36, and 34, respectively. The graben is recognizable in several seismic profiles. In addition, several intrusive structures are recognized inside the graben, and submarine volcanos is formed due to these intrusions. Dotted lines in the interpreted profiles indicate the unconformity surface. VE is calculated using Vp = 1,500 m/s.

At the western margin of the Ishigaki Knolls, a vertical zone is acoustically transparent with comparatively weak reflectors in part of the trough-fill sediments (Fig. 3). This feature is interpreted as a wipe-out structure, which commonly indicates the presence of fluid and/or gas, or of mud diapirs (e.g., Dillon et al., 1993, Bouriak et al., 2000, Sager et al., 2003, Hornbach et al., 2007). The wipe-out structure at the western margin of the Ishigaki Knolls occur within the trough-fill sediments and does not reach the seafloor. Its structure is characterized by a high-amplitude reflector at its top, and its base is not recognizable (Fig. S3b). The high-amplitude reflector has negative-polarity, the opposite of the polarity of the seafloor (Fig. S3d). These characteristics indicate the presence of gas and/or fluid (e.g., Shipley et al., 1994). The wipe-out structure lies within the trough-fill sediments (Fig. S3b), suggesting pervasive gas and/or fluid. In addition, a flare (acoustic water column anomaly) emanating from the seafloor above the wipe-out structure was recorded in the MBES data (Fig. S3e). This suggests that some gas and/or fluid is emanating from the seafloor (e.g., Nakamura et al., 2015; Miyazaki et al., 2017).

Magnetic data

A magnetic anomaly map (Fig. 5) shows clear dipole-shaped magnetic anomalies, or pairs of negative and positive anomaly regions, in this region (M1–M6). The negative regions of these anomalies are located to the north of the positive anomalies, indicating that induced magnetizations and/or remnant magnetizations almost parallel to the present field direction are the dominant source. Relative to bathymetry, all six anomalies are distributed around the knolls; anomalies M1, M2, M3, M4, M5, and M6 are associated with Hatoma Knoll, topographic highs, Daini-Kohama Knoll, Iriomote Knoll, Minna Knoll, and the Ishigaki Knolls, respectively. For magnetic anomalies that originated from isolated dipole sources in the survey area, the interval between the negative and positive anomaly peaks is nearly identical to the distance from the survey plane to the dipole position. The negative-to-positive peak intervals for magnetic anomalies M1–M5 have similar values from 3 to 7 km (M1: 4–5 km; M2: ~4 km; M3: 6–7 km; M4: 5–6 km; M5: ~3 km), suggesting that the source positions of these anomalies assuming dipole sources, are located 3–7 km from the sea surface. Considering the water depth of ~2 km in the survey area, the dipole sources are probably located 1–5 km beneath the seafloor.

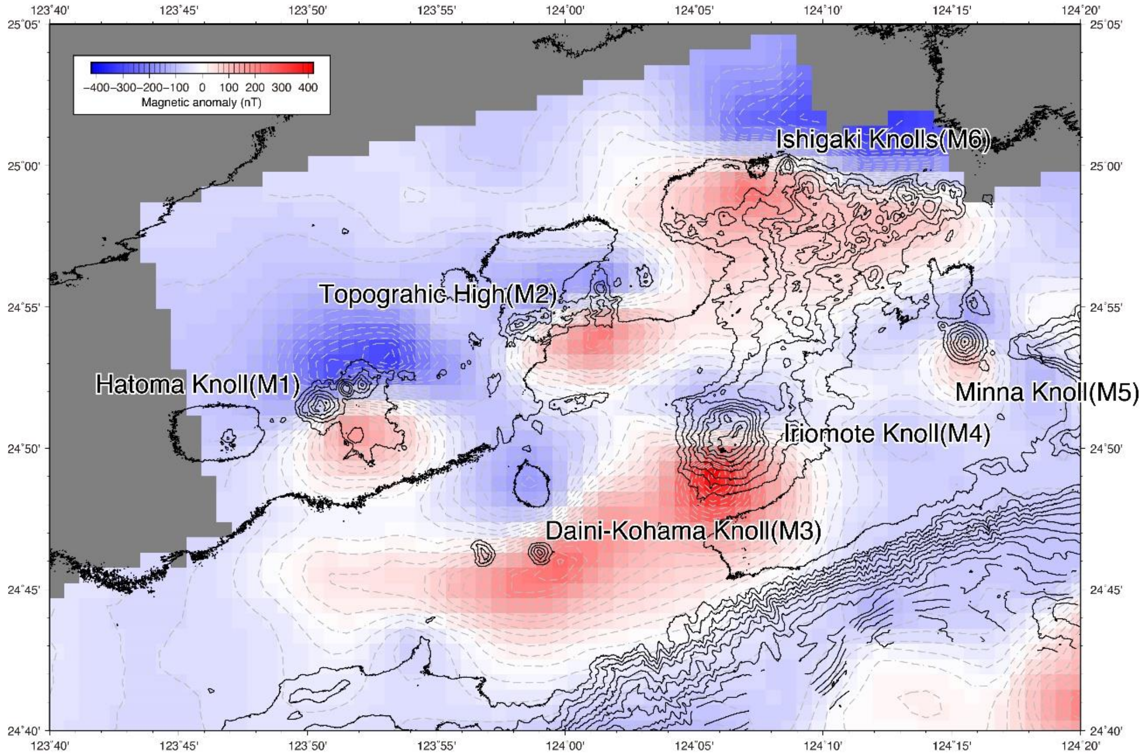

Figure 5 Magnetic anomaly map offshore northern Ishigaki-Jima Island. The magnetic anomaly map grid interval is 1 km, and the contour interval is 20 nT. Dipole anomalies lie around the knolls, which are submarine volcano. They are characterized by a narrow interval between the positive and negative dipole anomalies. Bathymetry contours are shown as black lines. The bathymetry contour interval is 100 m.

5. Discussion

The graben identified in this study has developed by normal faulting and contains intrusive structures (Figs. 2 and 4). It resembles the Yaeyama Graben in the southern OT in terms of both bounding normal faults and intrusions (Lee et al., 1980; Arai et al., 2017). In the Bransfield Strait along the Antarctic Peninsula, where the continental margin backarc system is also in the rifting stage, a graben bounded by normal faults and a relatively homogeneous intrusion into the sedimentary basins have been observed

(Grad et al., 1992). A rift graben bounded by normal faults with several sills has been documented in the Guaymas Basin in the Gulf of California, where seafloor spreading has commenced (Lizarralde et al., 2007; Kluesner et al., 2014). The characteristics of the graben identified in this study are similar to those of other rift grabens in different stages of backarc system evolution in diverse tectonic settings.

Topographic highs with chaotic seismic characteristics are located along the axis of the graben. We interpret these highs as submarine volcanos formed by magma extrusion from the seafloor (Figs. 2 and 4). Dipole-shaped magnetic anomalies around Hatoma Knoll (M1) and the topographic highs within the graben (M2) suggest the existence of strong anomalous sources 2–3 km below the seafloor (Fig. 5). Such strong anomalous sources at relatively shallow depths further support this interpretation. The gas and/or fluid emanation on the north side of the graben may represent hydrothermal activity associated with magmatism (Fig. S3). Shallow seismicity clusters with hypocenter depths from 0 to 20 km along the graben indicates considerable seismic activity around Hatoma Knoll and the topographic highs (Fig. 4a). It should be noted that the accuracy of hypocenter locations in offshore areas is inferior to that for those on land due to the limited number of seismic stations around the OT. These features and characteristics suggest shallow magma as a heat source beneath the graben.

The southern margin of the OT is underlain by a heat source. Magma intrusion has been recognized on the northwest side of the graben shown in this study (Fig.1b) (Arai et al., 2017). The heat source is likely associated with the axial magma chamber below the Yaeyama Rift (Fig. S4). Although more details of the structure should be investigated by future geophysical surveys in the southern OT, the graben and associated subseafloor structures can be regarded as embryonic rifting preceding seafloor spreading. The features revealed in this study suggest that small-scale magmatic activity and associated intrusive structures play an important role in the development of normal faults, submarine volcanoes, and the graben in this early stage of the backarc system.

6. Conclusions

Integrated marine geological and geophysical surveys incorporating high-density survey lines were undertaken offshore northern Ishigaki-Jima Island. We identify a graben bounded by normal faults off-axis of the southern OT. This graben extends ~59 km in the ENE-WSW direction. Submarine volcanoes such as Hatoma Knoll display active hydrothermal activity, and associated intrusive structures lie within the graben. The source depth of dipole-shaped magnetic anomalies and active seismicity shallower than 20 km in and around the graben indicate relatively shallow magma acting as a heat source. These features suggest active rifting in the graben, and that the graben likely manifests embryonic rifting along the southern margin of the OT.

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Most bathymetry was plotted using GMT software (Wessel and Smith,1991). The data used in this paper are available online (http://doi.org/10.6084/m9.figshare.11993520).

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