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Structural characteristics of the Bayonnaise Knoll caldera as revealed by a high-resolution seismic reflection survey

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Abstract

The Bayonnaise Knoll caldera is a conical silicic caldera located on the eastern part of the back-arc rift zone of the Izu-Ogasawara arc. Many geological and geophysical surveys have shown that the Bayonnaise Knoll caldera contains hydrothermal sulfide deposits. The Japan Agency for Marine-Earth Science and Technology conducted high-resolution multi-channel seismic reflection surveys across the Bayonnaise Knoll caldera to ascertain details of the crustal structure, such as the configuration of faults around the caldera. A reflection profile of excellent quality was obtained by high-density velocity analysis at about 150-m intervals. We applied prestack depth migration by using the results of the high-density velocity analysis and further analyzed this region. The depth-migrated profile shows many faults, which correspond to bathymetric lineations, on the eastern side of the Bayonnaise Knoll caldera. The velocity structure of the Bayonnaise Knoll caldera resembles that of the Myojin Knoll caldera, which has been well surveyed and is associated with the hydrothermal deposit. The depth-migrated profile shows a clear reflective zone that is distributed asymmetrically to the Bayonnaise Knoll caldera center. These data suggest that caldera formation was controlled by back-arc rifting activity in the Izu-Ogasawara arc. The hydrothermal fluid migration path in the Bayonnaise Knoll caldera is estimated to be the result of faulting and magmatic intrusion on the eastern side of the structure. It is assumed that these fluids formed the Kuroko-type sulfide deposit in the eastern part of the caldera structure.

Keywords: Bayonnaise Knoll caldera; Multi-channel seismic reflection survey; Hydrothermal deposit; Back-arc rift; Prestack migration

Correspondence/findings

Introduction

The Izu-Ogasawara (Bonin) arc extends over 1,200 km from the Honshu island of Japan to Guam on the northeastern margin of the Philippine Sea plate. The Izu-Ogasawara arc is a region that is beneficial for understanding intra-oceanic evolution, and it has been investigated well in many geological and geophysical studies (e.g., Taylor 1992; Suyehiro et al. 1996; Kodaira et al. 2007). Not only large-scale surveys, but also detailed analyses and surveys have specifically investigated its structural characteristics (e.g., Tsuru et al. 2008; Fujiwara et al. 2009).

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Paleo-volcanic arrangements are known to exist along the north-south direction; these are known as the outer-arc high or frontal-arc high by geographic characteristics in the forearc basin. Since the spreading suspension of the Shikoku Basin in 15 Ma (Okino et al. 1994), many active volcanoes have developed in the Izu-Ogasawara region (e.g., Ishizuka et al. 2002). Additionally, several basins developed in the so-called back-arc rift zone between the current volcanic front and the paleo-volcanic arrangement in the west (Murakami 1996).

A large Kuroko-type polymetallic sulfide deposit was discovered on the caldera floor of the Myojin Knoll caldera (Iizasa et al. 1999) along the back-arc rift. Kuroko, which is a black ore produced in submarine volcanoes, includes minerals such as copper, lead, silver, and gold that are useful for industrial activities. The Kuroko deposit distribution is known to be restricted in island arcs.

New hydrothermal deposits on the Bayonnaise Knoll caldera located west of the Myojin Knoll caldera have been reported from many surveys (Tanahashi et al. 2006). The configuration of the Myojin Knoll and Bayonnaise Knoll caldera region resembles that of formerly submarine onshore large deposits of the Hokuroku region in the Akita Prefecture (Tanahashi et al. 2008). Many ongoing hydrothermal activities have been recognized along the Izu-Ogasawara volcanic front (e.g., Nagaoka et al. 1992). Understanding the model of hydrothermal deposit formation is crucially important for the exploration of new hydrothermal deposits. Specifically, a better understanding of the internal structures of these calderas will give a new perspective as to the formation of Kuroko-type hydrothermal deposits. Because investigating the internal structure is necessary to ascertain the formation processes related to hydrothermal sulfide deposits of the Bayonnaise Knoll caldera, we conducted a high-resolution multichannel seismic reflection (MCS) survey to find the relation between the hydrothermal deposit and crustal structure. As described in this paper, we investigated the fault configuration and the crustal structure of the Bayonnaise Knoll caldera with a high-density velocity analysis of newly obtained MCS data. Based on our analyses and interpretations of the results, we discuss the relationship between hydrothermal deposit formation and fault configuration in and around the Bayonnaise Knoll caldera.

Geological setting of the Bayonnaise Knoll caldera

The Bayonnaise Knoll caldera is a typical submarine volcano with a caldera structure that is located on the eastern part of the back-arc rift zone, which is distributed 20 km west of the Myojin-sho caldera in the Izu-Ogasawara arc (Figure 1). The Bayonnaise Knoll caldera is also located on an extended ridge northeast from the Enpo ridge in a series of back-arc ridges in en-echelon arrangement. One of the well-surveyed submarine volcanoes, namely, the Myojin Koll caldera that contains hydrothermal deposits (e.g., Fiske et al. 2001; Tsuru et al. 2008), is also located on the Enpo ridge. The water depth at the top of the Bayonnaise Knoll caldera is about 600 m. The caldera slope height is about 400 m. The east-west and north-south diameters of the Bayonnaise Knoll caldera are 2,000 and 2,800 m around the top of caldera rim, respectively (Tanahashi et al. 2006). The activity of the submarine volcanoes in the Izu-Ogasawara current arc comprises bimodal magmatism with basaltic and dacitic-rhyolitic magma (Tamura and Tatsumi 2002). The Bayonnaise Knoll caldera has been classified as a silicic volcano. The caldera floor is comprised of volcanic breccia and sediments, as indicated by deep sea camera observations (Tanahashi et al. 2006). Additionally, lava has been recognized on the southern slope of the center cone. Iizasa et al. (1999) reported a large Kuroko-type sulfide deposit, called the Hakurei deposit, on the southeastern margin of this caldera floor that is associated with hydrothermal activity. Minerals such as Au, Ag, and Zn are abundant not only in active hydrothermal sulfide deposits on the current volcanic front such as at the Myojin Knoll caldera (Iizasa et al. 1999, 2004) and Suiyo Seamount (Watanabe and Kajimura 1994), but they are also present in inactive hydrothermal sulfide deposits on the Bayonnaise Knoll caldera. Thus, detailed investigation of the Bayonnaise Knoll caldera structure is important to elucidate the characteristics of the hydrothermal deposits.

Data acquisition and processing

The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) conducted a new multi-channel seismic reflection survey (standard fold number 55.5) across from the current volcanic front to the Eocene volcanic arrangement (Taylor 1992). For this study, we extracted data from part of the Bayonnaise Knoll caldera (Figure 1) to investigate the detailed crustal structures with a high-density velocity analysis. The seismic source used was an annular port array of 32 air guns with a total volume of 7,800 in^3 (130 L) operating at a standard air pressure of 2,000 psi (14 MPa). The frequency spectrum was flat at the frequency range of 5 to 80 Hz. The hydrophone streamer cable used as a receiver was ca. 5,700 m long, and it had 444 channels spaced at intervals of 12.5 m. The air gun was fired every 50 m at a time interval of ca. 20 s along the survey line. Seismic reflection records of 15-s length with a 1-ms sampling interval were obtained for deep crustal imaging. The MCS data were processed through the standard seismic data processing flow of JAMSTEC, which consists of noisy-trace editing, 30- to 80-Hz band-pass filtering, velocity analysis, normal moveout (NMO) correction, common depth point (CDP) stacking, and poststack time migration. Especially, we applied high-density picking to the reflectors at every 25 CDP intervals (156.25 m) for velocity analysis to resolve the internal structure of the caldera.

It is difficult to image the precise crustal structure of the Bayonnaise Knoll caldera using the CDP stacking method assuming horizontally layered media because submarine calderas such as the Myojin Knoll caldera and Bayonnaise Knoll caldera have steep slopes, as evidenced by their rough sea floor topography (Tsuru et al. 2008). Therefore, we applied high-resolution imaging using prestack depth migration (PSDM; Sattlegger and Stiller 1974) with a high-density velocity model derived from the detailed velocity analysis. Additionally, we optimized the PSDM method to produce images of steep structures such as calderas or faults (Yamashita et al. 2007). The PSDM method, which is a powerful tool for imaging complicated structures, improved the precision of the reflector identification data. The imaging quality of

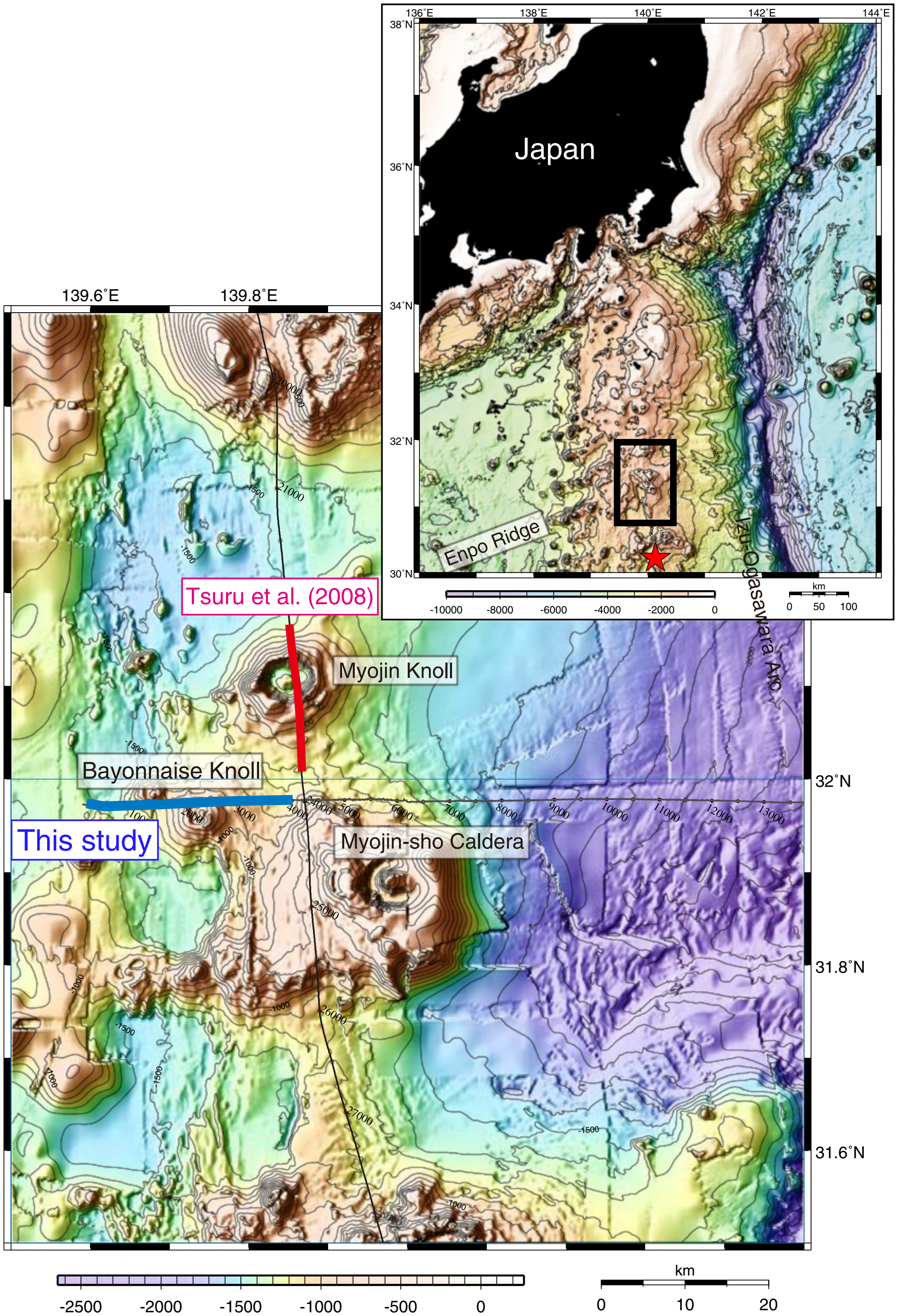

Figure 1 Map showing the location of the study area. The blue line represents a part of our survey line along the Bayonnaise Knoll caldera. The red line shows the survey line along the Myojin Knoll caldera reported by Tsuru et al. (2008). The red star in the small figure shows the Ocean Drilling Program (ODP) site 788 (Taylor 1992).

crustal structures using reflection survey data depends on the reliability of applied velocity structures (Lines et al. 1993). For conventional reflection survey data processing, velocity information is observed using NMO correction and CDP stacking; it cannot address lateral variations of the structure because the algorithm defines the subsurface structure as a flat multilayered structure (e.g., Al-Yahya 1989; Stork and Clayton 1992). Back-arc basins are known to have widely variable normal faults, folds, and deformations in a shallow crustal structure. Therefore, the PSDM technique is useful to improve imaging in these settings. We used the smoothed velocity model of high-density picking for the initial velocity model in the PSDM analysis. The final velocity model was updated two times by iteration through repeated tomographic inversion.

Results

Figure 2 shows the final poststack time-migrated profile (above) and its interpretation (below) for the Bayonnaise Knoll caldera. The reflection profile shows a clear image of a deeper zone under 1.5 s beneath the summit area of the caldera. The well-formed conical-shaped caldera with a central dome is evident in the profile. Although our survey line crossed the north side of the Bayonnaise Knoll caldera, the center dome of the Bayonnaise Knoll caldera appeared on the profile because of the spatial effect from using a 6,000-m-long streamer. The profile shows numerous faults over the entire caldera structure and its surroundings. Large faults can be recognized over 1 s in the profile beneath the seafloor. Numerous reflectors were also identified under the caldera, and these extended horizontally for 2,000 m at most. These reflectors are well

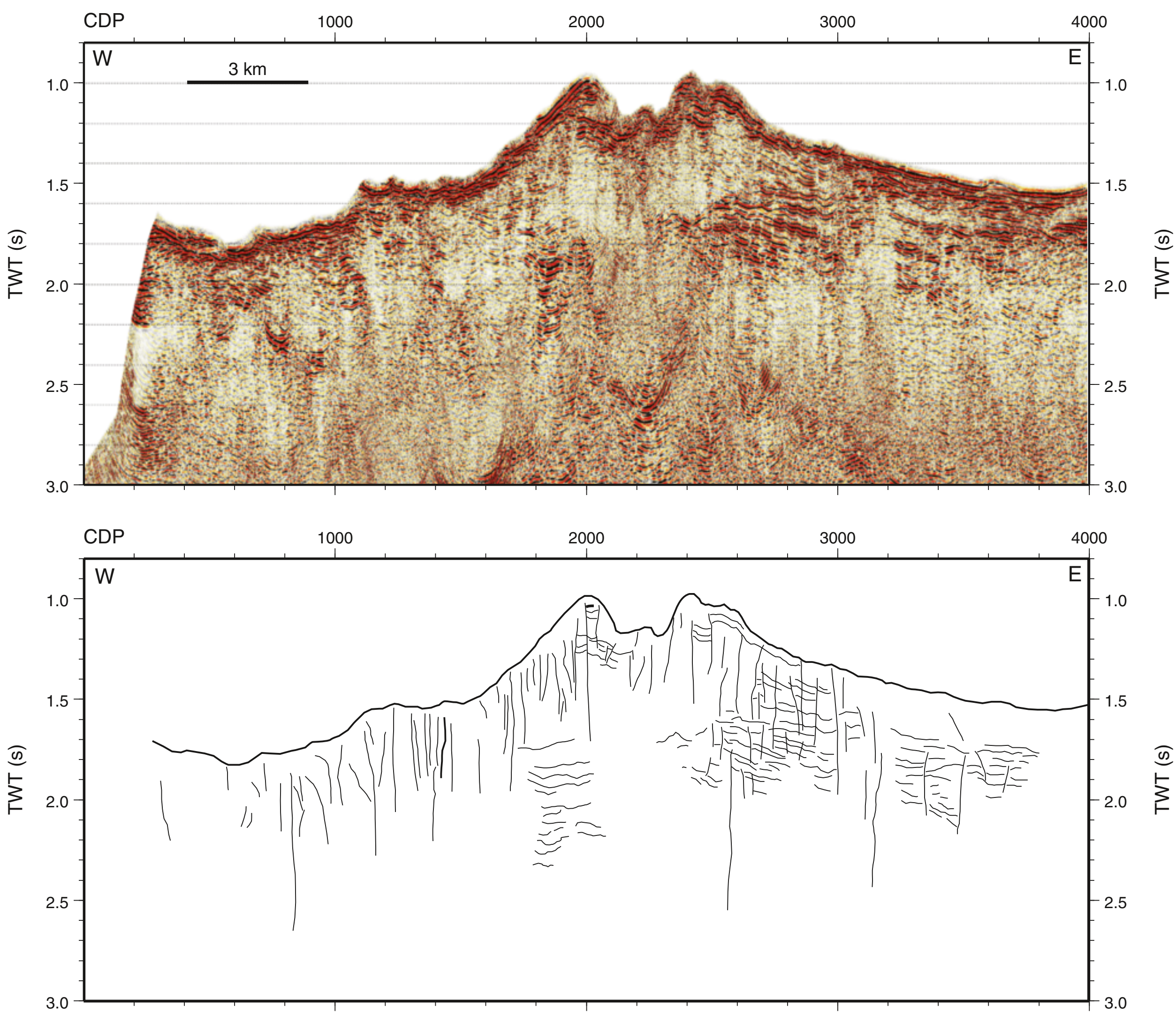

Figure 2 Poststack time-migrated profiles of the Bayonnaise Knoll caldera (above) and its interpretation (below). The horizontal axis is common depth point (CDP) number. The CDP interval is 6.25 m in this survey. The vertical axis shows the two-way travel time (TWT) in seconds.

developed in the eastern part compared with the western part of the caldera. Some transparent zones were recognized under the caldera. Presumably, they show the effects of structural heterogeneity caused by the magma supply path, which was interpreted using the Sakurajima volcano (Tsutsui et al. 2013).

Herein, we describe the depth and velocity structure that was obtained via the PSDM analysis. Although the picking of the velocity analysis was conducted at depths corresponding to the lower crust, we applied the PSDM analysis to the 2,500-km depth to improve and stabilize the seismic profile quality. The PSDM profile is depicted in Figure 3. The imaged structure of the deep section recreated by this analysis was clearer than that of the results for the Myojin Knoll caldera (Tsuru et al. 2008); this was likely because of the effective use of a tuned air gun array, a long streamer, and the high-density velocity analysis in this study. Reflectors beneath the caldera have a center-dipping character. The P-wave velocity model obtained using the PSDM analysis had a range of 1,570 to 2,500 m/s from the seafloor to 2,100-m depth. The data were poorly resolved by our detailed analysis below 2,100-m depth. The velocity structure beneath the caldera displayed asymmetric characteristics. We identified a reflective zone around the caldera (gray zone in Figure 3). The reflective zone in the eastern part of the Bayonnaise Knoll caldera (CDP number 2200-3050, 3100-4000) corresponds to the velocity zone of 1,580 to 1,800 m/s. This velocity suggests that the reflective zone represents the formation of stratified and/or massive volcanic breccias, as similar results were found with survey result at the Myojin Knoll caldera by Tsuru et al. (2008) and geological study (Naka et al. 1995). This layer is estimated to be a porous and permeable layer. The velocity beneath this reflective zone was high (over 2,300 m/s), and this could be indicative of the effects of some magma intrusion as similar findings were obtained for an onshore active volcano (e.g., Aoki et al. 2009). The reflective zone at the 1,500-m depth under the western caldera wall (CDP number 1700-2100) had a velocity higher than 2,200 m/s,

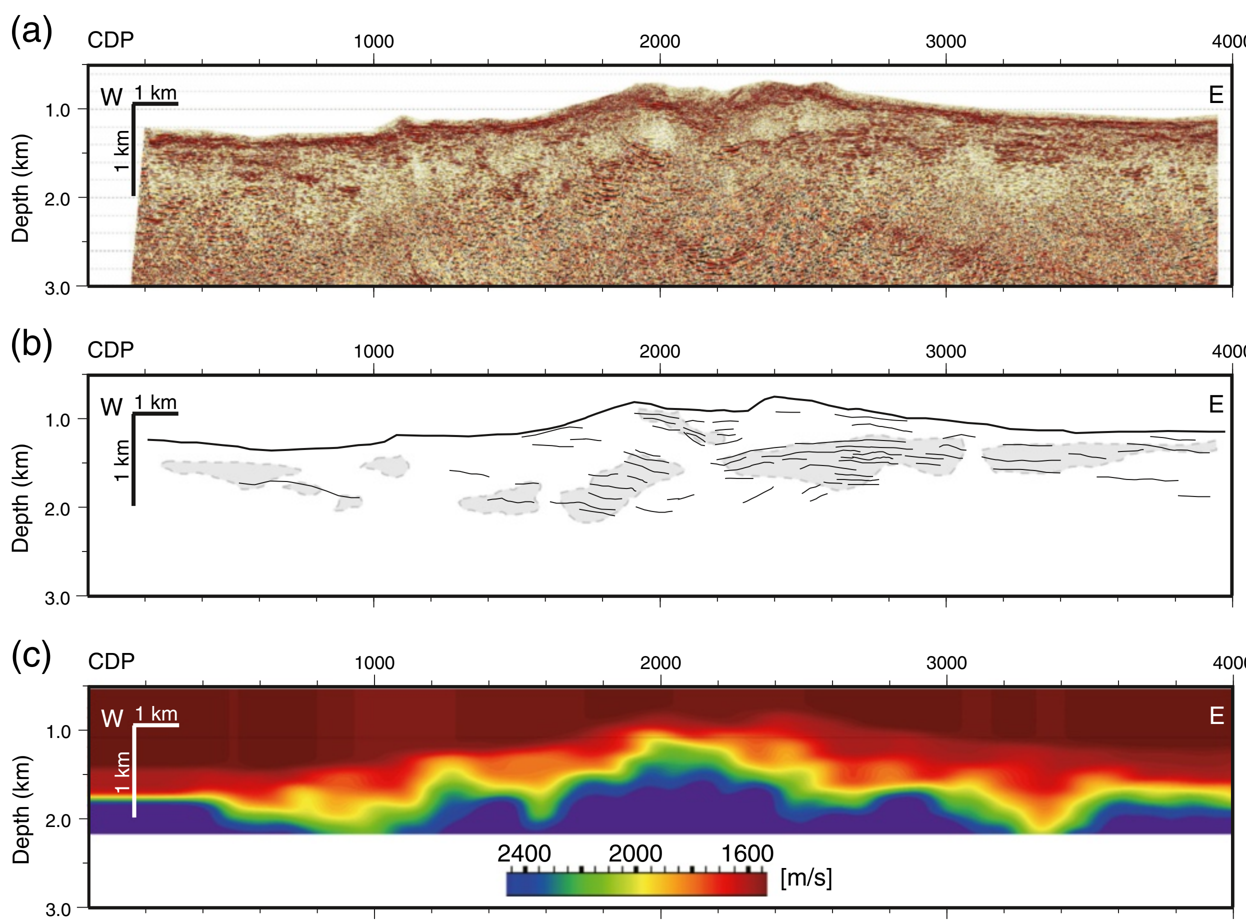

Figure 3 Depth profiles and final velocity model. Depth profiles of the Bayonnaise Knoll caldera; vertical exaggeration is two for the **(a)** prestack depth-migrated (PSDM) section and **(b)** its interpretation. The gray area shows the reflective zone. **(c)** Final velocity model of the PSDM analysis. The PSDM analysis was applied down to a depth of 2.5 km. CDP, common depth point.

which is suggestive of fractured rhyolitic lava, according to estimations from the survey results at the Myojin Knoll caldera by Tsuru et al. (2008). The seismic facies beneath this reflective zone are relatively transparent (Figure 2), and they likely correspond to seismic facies of volcanoclastic sandy silt and/or rhyolite lava as was seen at the Myojin Knoll caldera (Tsuru et al. 2008). The higher velocity beneath the caldera center is suggestive of the existence of shallow magma materials, as a similar velocity was interpreted in such a way by Tsuru et al. (2008). In the western part of the caldera (CDP number 1200), a high-velocity zone exists in the shallow part. It may be suggestive of the possible next stage of volcanic activity in this region.

Discussion

The knoll chain, which displays a north-south trend in the center of the caldera, is interpreted to have been formed in the back-arc rift fault zone (Tanahashi et al. 2008). Tanahashi et al. (2008) noted that a hydrothermal sulfide deposit can be observed along this fault zone. The results of a deep sea magnetic survey, which was conducted using autonomous underwater vehicles, also revealed a high-magnetic anomaly on the caldera wall (Honsho et al. 2010, 2012, 2013) This implies the existence of a fault in this part. Figure 4b presents a detailed bathymetry map around the Bayonnaise Knoll caldera that was constructed along the MCS survey line. Some topographic lineation with a north-south trend was identified around this region. Many faults were identifiable in our MCS profile (Figure 2), and these are extended along the bathymetric features. The lineations are concentrated on the eastern side of the back-arc rift zone. This result suggests that activity at the Bayonnaise Knoll caldera was induced by faulting during the spreading of the back-arc rift zone. According to the structural classification of Murakami (1996) for the Izu-Ogasawara arc, a narrow half-graben structure that was formed by rifting is developed on the north side of the Izu-Ogasawara arc. This suggests that hydrothermal activity can likely be found on the north side of the Izu-Ogasawara arc.

To elucidate the evolutionary process of Kuroko deposits, one must understand the caldera and fault structural configuration and formation process. Unfortunately, few geological samples have been collected from the Bayonnaise Knoll caldera. Ishizuka et al. (2003) identified temporal variation in the volcanism along the en-echelon arrangements in the Izu-Ogasawara arc and constructed a location versus 40Ar/39Ar age plot for the rear-arc volcanoes. According to Ishizuka et al. (2003), the volcanoes around the volcanic front, including the Bayonnaise Knoll caldera and Myojin Knoll caldera, have the same geochemical characteristics along the Enpo chain. This suggests that the Bayonnaise Knoll caldera has similar geology to the Myojin Knoll caldera. The subsurface structure of the Myojin Knoll caldera has already been reported by Tsuru et al. (2008). They described the relationship between the deposition of Kuroko-type deposits and the configuration of faults in detail. We have summarized the scale characteristics of the Myojin Knoll caldera and Bayonnaise Knoll caldera in Table 1. The Bayonnaise Knoll caldera and Myojin Knoll caldera are located on the eastern edge of the back-arc rift zone and on the current volcanic front, respectively. The total size of the Bayonnaise Knoll caldera is only half that of the Myojin Knoll caldera. Velocity structure variations of both calderas are very similar. The Myojin Knoll caldera is estimated to have similar lithologies along the Sumisu rift, as indicated by geophysical and geological observations (Fiske et al. 2001; Tani et al. 2008; Tsuru et al. 2008). This suggests that the Bayonnaise Knoll caldera and Myojin Knoll caldera also have similar lithologies, which are mainly composed of pumiceous sand and gravels; the data suggestive of this were revealed at the eastern margin of the Sumisu rift in the Izu-Ogasawara back-arc, i.e., Ocean Drilling Program (ODP) site 788 of Leg 126 (Taylor 1992). The Sumisu rift is located approximately 130 km south of this region. According to the drilling results (Nishimura et al. 1991, 1992), there are pumiceous deposits with a thickness of more than 250 m from 0.2 Ma to present. Tani et al. (2008) suggested that the source of these pumiceous deposits was produced in the Sumisu volcano. Tanahashi et al. (2006) recognized many tuffaceous volcanic breccia in and around the Bayonnaise Knoll caldera via seafloor camera observations. The Bayonnaise Knoll caldera walls are mainly composed of thick volcanic breccia, as estimated from data similar to the comparisons between the velocity structure (Tsuru et al. 2008) and geological sampling data (Naka et al. 1995) in the Myojin Knoll caldera. In the case of the Sumisu caldera, there are symmetric characteristics along the north-south profile and asymmetric characteristics along the east-west profile that were discovered by a single-channel seismic survey (Tani et al. 2008). Regarding the structural symmetry of the caldera, it presents different characteristics that include uncertainties of the effect of the direction for volcanic arrangement. Asymmetric structures such as the reflective zone suggest that there are different volcanic activities across the back-arc rift zone.

Based on our results, we now propose a strategy for how to locate the hydrothermal deposit in the Bayonnaise Knoll caldera. The hydrothermal activity implies that there is intrusion of high-temperature materials such as hot water or magma beneath the caldera. Input of water may also occur around the caldera. Honsho et al. (2010, 2012) present the distribution of the magnetic anomaly, and these data likely correspond to the hydrothermal deposit

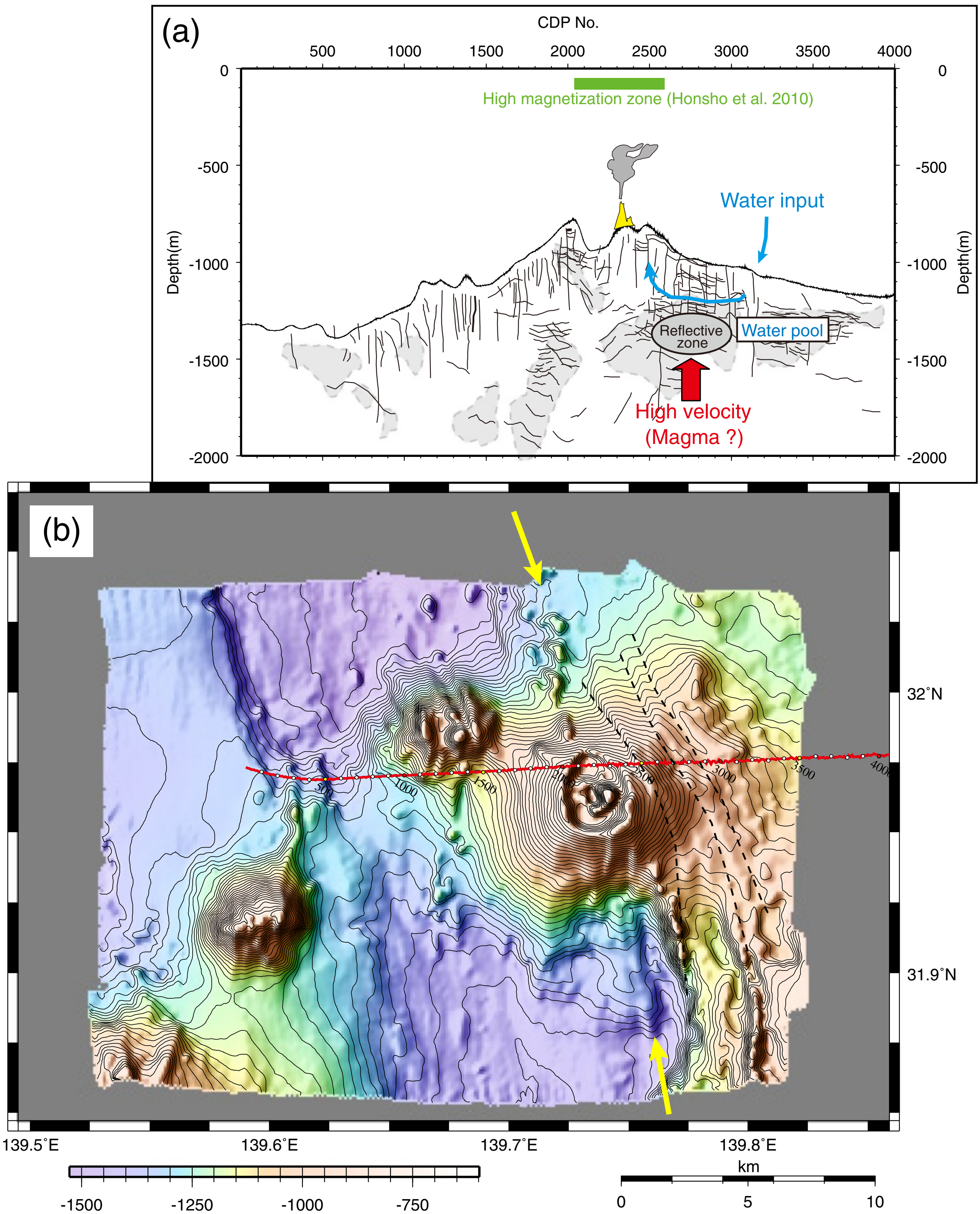

Figure 4 (See legend on next page.)

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Figure 4 Interpreted section compiled from time-migrated and PSDM profiles and detailed bathymetry map (Bayonnaise Knoll caldera). (a) Interpreted section compiled from time-migrated and prestack depth-migrated (PSDM) profiles in the Bayonnaise Knoll caldera with the model of hydrothermal fluid migration. The green horizontal bar shows the high-magnetization zone over 4 A/m, as projected from mapping results by Honsho et al. (2010). **(b)** Detailed bathymetry map around the Bayonnaise Knoll caldera. The red line shows our multi-channel seismic reflection (MCS) survey line. Dotted lines represent the fault inferred from the present study results and bathymetric lineation features. Yellow arrows indicate the knoll chain in the center of the Bayonnaise Knoll caldera that was described in Honsho et al. (2010). CDP, common depth point.

distribution in the Bayonnaise Knoll caldera. A high-magnetization zone exists in the crater of the Bayonnaise Knoll caldera according to their results (Figure 4). They also suggest that the magnetic anomalies are distributed along the inferred fault with a north-south trend. According to our results, not only is there a fault in the center of the Bayonnaise Knoll caldera, but major faults also exist outside of the caldera rim. These faults are assumed to have strongly affected the formation process of the hydrothermal deposit. We now discuss the circulation of the hydrothermal fluid that influenced the growth process of the hydrothermal deposit in the Bayonnaise Knoll caldera. The locations of the hydrothermal deposit are concentrated along the caldera wall (Tanahashi et al. 2006). Regarding the hydrothermal activity in the Suiyo Seamount, Watanabe and Kajimura (1994) proposed a model of hydrothermal fluid circulation. The model shows that seawater is injected inside of the Suiyo caldera wall and is heated by either the dyke or magma intrusion at the caldera center; this has resulted in the formation of hydrothermal mounds and chimneys at present. Tsuji et al. (2012) proposed a hydrothermal fluid circulation model around the Iheya North Knoll of the Okinawa Trough, which is located at the continental back-arc basin. Their model shows the water input from the normal fault and ridge at the seafloor and fluid migration driven by the heat source beneath the hydrothermal field. Figure 4 depicts the hydrothermal fluid circulation model in the Bayonnaise Knoll caldera as inferred from the interpretation of data obtained from seismic time and depth sections and the velocity model. The reflective zone in the eastern part of the caldera is believed to comprise porous and permeable volcanic sediments that have low velocity. The high-velocity layer below the reflective zone is interpreted to be the result of magma intrusion. The hydrothermal fluid circulation model is estimated as follows. 1. The water intrudes along the major fault on the eastern outside edge of the Bayonnaise Knoll caldera. 2. The water passes through a porous and a permeable layer. 3. The fluid is heated by magma intrusion and forms a hydrothermal field in the Bayonnaise Knoll caldera. A similar type of volcanic activity seems to be distributed along the east side of the back-arc rift zone in the Izu-Ogasawara arc.

Table 1 Characteristics of the Bayonnaise Knoll caldera and the Myojin Knoll caldera

Caldera	Bayonnaise Knoll	Myojin Knoll
Summit water depth	600 m	336 m
Basal diameter	10 km	15 to 22 km
Caldera rim diameter	2.5 to 3 km	5 to 7 km
Wall height	400 m	1,000 m
Structure	Asymmetry (E-W)	Symmetry (N-S)
Velocity (Vp)	1,570 to 2,400 m/s	1,590 to 2,460 m/s

Bayonnaise Knoll caldera: Tanahashi et al. 2008; Honsho et al. 2010. Myojin Knoll caldera: Iizasa et al. 1999; Tsuru et al. 2008.

Conclusions

We conducted a velocity analysis by applying high-density picking and prestack depth migration to newly acquired MCS survey data to investigate the crustal structure of the Bayonnaise Knoll caldera. A summary of the results is presented below.

1. Faults along the bathymetric lineation have developed on the east side of the Bayonnaise Knoll caldera, and their locations correspond to the distribution of hydrothermal sulfide deposits.
2. The asymmetric structure of reflective zones beneath the Bayonnaise Knoll caldera was identified.
3. The velocity structure obtained by prestack depth migration of the Bayonnaise Knoll caldera data resembles that of the Myojin Knoll caldera.
4. The hydrothermal migration path is estimated to be the result of faulting and magma intrusion on the east side of the Bayonnaise Knoll caldera.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

MY, NT, and SK designed the seismic reflection survey line. MY and KT analyzed the seismic reflection data. MY drafted the manuscript. TK acquired the bathymetric data. MY and TK interpreted the seismic reflection data. KT conducted the high-density velocity analysis. All authors read and approved the final manuscript.

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