Deep-sea magnetic survey using autonomous underwater vehicle r2D4 on Bayonnaise knoll caldera

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ABSTRACT

In March and October in 2008 deep-sea surveys by using the autonomous underwater vehicle (AUV) r2D4 developed by Institute of Industrial Science, The University of Tokyo, were conducted on the northern and southeastern parts of the Bayonnaise knoll caldera, located on the eastern margin of the rift zone of the Izu-Ogasawara island arc. The magnetic vector field data collected during the two dive surveys were used for magnetic inversion to reveal the magnetization distribution on the seafloor. The inversion result imaged two areas of high magnetization in the northern margin of the caldera floor and in the southeastern caldera wall. The magnetization highs found in the caldera seem to lie on an inferred line of a basaltic knoll chain running to the north and south of the Bayonnaise knoll, suggesting that they may represent intrusive basaltic rocks produced by the volcanic activity of the knoll chain, that could not come up to eruption blocked by the thick crust of the Bayonnaise knoll. One of the high magnetization areas is located adjacent to the Hakurei deposit, indicating that the basaltic magma intrusion may have induced the hydrothermal activity of the Hakurei site. It has been found that some hydrothermal sites are associated with low crustal magnetization, which is considered resulting from the alteration of magnetic minerals and reduction in magnetization of crustal rocks due to the hydrothermal circulation. However, the Hakurei site is apparently not associated with obvious low magnetization. That is probably because the Bayonnaise knoll almost consists of dacite lava and fragments which have weak magnetization and altered and demagnetized basaltic rocks would be indistinguishable from nearby dacite rocks. The high magnetization may represent only the unaltered part of the intrusive body that is relatively far from the hydrothermal site and the Hakurei site may be underlain by the altered and demagnetized part. The lateral resolution of the magnetization distribution obtained in this study is limited by the high-cut filter applied in the analysis process, not by the resolution of data itself. The focus of marine magnetic survey has been shifting from sea-surface to deep-sea and it is imperative to progress the analysis method to make the most of high resolution data.

Keywords: Deep-sea magnetics, AUV, Bayonnaise knoll caldera, Hakurei hydrothermal deposit

1. Introduction

Recent extensive marine surveys on the Izu-Ogasawara island arc and the Okinawa trough, Japan reveal the existence

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of many Kuroko-type deposits accompanying seafloor hydrothermal activity on the volcanic front and the backarc rift zone (Iizasa et al., 2004; Iizasa et al., 1999; Ishibashi and Urabe, 1995). The metal content of hydrothermal sulfide samples from these island arc deposits is characterized by the enrichment of Au, Ag and Zn compared with those from mid-ocean ridges (Iizasa et al., 1999). Understanding of the structure of these deposits and the processes of their formation is necessary not only for our geoscientific interests in these phenomena but also for their economic importance.

The magnetic field measurement has been considered as one of the means to approach the subsurface structure of hydrothermal deposits. In this paper we report the results of deep-sea magnetic field study on Bayonnaise knoll caldera, a submarine silicic caldera on the rift zone of the Izu-Ogasawara island arc, using the autonomous underwater vehicle (AUV) r2D4 (Ura et al., 2007). One dive surveyed the northern part of the caldera, and another dive explored the southeastern margin of caldera floor, the site of a large sulfide deposit associated with the active hydrothermal field. We discuss the magnetic structure of the caldera in relation to the regional settings and the hydrothermal field.

2. Geologic Settings of Bayonnaise Knoll Caldera

The Izu-Ogasawara island arc has been formed by the backarc volcanic activity accompanied by the continuous subduction of the Pacific plate under the Philippine Sea plate. It is composed of, from east to west, the NS trending volcanic front, the backarc rift zone and the WSW-ENE trending backarc echelon seamount chains (Fig. 1). The Bayonnaise knoll caldera is located on the eastern margin of the backarc rift and also located at the northeastern end of the Enpo seamount chain, one of the backarc echelon seamount chains to the west of the rift zone. In the vicinity of the Bayonnaise knoll caldera there are two calderas lying along the volcanic front: the Myojin knoll caldera and the Myojinsho caldera.

The rim of the Bayonnaise knoll caldera has EW and NS diameters of 2.5 and 3 km, respectively (Fig. 2). The caldera floor is 840-920 m deep. The caldera rim is slightly open to the north and varies in depth from 640 m on the southeast to 860 m on the north. A post-caldera dome with its top 580 m deep occupies the eastern part of the floor. A large active hydrothermal field associated with sulfide deposit, called the Hakurei deposit, has been found on the southeastern margin of the caldera floor (Iizasa et al., 2004).

3. Data Acquisition and Initial Processing

Fig. 1. Index map showing the location and the geological settings of the Bayonnaise knoll caldera.

r2D4 (Fig. 3) is a 4.4 m long, 0.96 m wide AUV equipped with a side scan sonar, an interferometry receive sonar, a conductivity-temperature-depth-oxygen (CTDO) sensor, a geochemical anomalies monitoring system (GAMOS) and a three-axis magnetometer sensor (Ura and Obara, 2005). Magnetic data were collected at 8 Hz together with the attitude data of the vehicle sampled at 2 Hz. The attitude data were interpolated to give 8 Hz data before compiled with the magnetic data.

Dive surveys using the AUV r2D4 were conducted on the Bayonnaise knoll caldera during the two research cruises in 2008: the first cruise in March using the R/V Natsushima (dive #36) and the second in October using the R/V Hakurei-maru No.2 (dive #51). Data distribution along the dive tracks is shown in Fig. 2. Dive #36 explored the north part of the caldera using the six ~3 km long profiles running in the WE direction. Data during turns were excluded. The dive track roughly goes along the topography and the average altitude of the vehicle is 104.8 m varying from 59.9 to 189.7 m. Dive #51 surveyed the southeastern margin along a spiral track. The vehicle did not completely run as planned because of a navigation accident. Some parts of the track that overlap or cross at different altitudes were removed for subsequent analyses. The average altitude is 84.6 m, varying from 33.9 to 219.5 m.

The observed magnetic field data were first calibrated for the magnetic field produced by the vehicle using the processing method for shipboard three-component magnetometer (STCM) data (Isezaki, 1986). In the case of shipboard measurements, a 360 degree rotation of ship (an operation to collect data utilized for the calibration) need to be carried out several times at different latitudes for stable calibration (Isezaki, 1986). As regards AUV measurements the operation is usually needed only once a survey by varying the pitch in a wide range ($\sim \pm 30^\circ$) as well when the vehicle

Fig. 2. Bathymetric map around the Bayonnaise knoll caldera. Contour interval is 25 m. Bold lines show data distribution along dive tracks used in this study. Boxes show the areas of Figs. 5 and 6.

Fig. 3. Autonomous Underwater Vehicle (AUV) r2D4.

Fig. 4. An example of the vehicle positioning (dive #36). A blue line shows the original track obtained by the inertial navigation system, and a red line shows the corrected one based on the data from the acoustic navigation system (crosses).

makes the lateral rotation. The three-component magnetic data were vector summed to give total field and an ambient field based on the International Geomagnetic Reference Field (IGRF) was removed from it. The obtained total intensity anomalies were filtered using the Gaussian function 60 s wide to give values every 5 s, corresponding to ~8 m along the track as the vehicle was running at ~3 knots. Finally 2666 data were obtained along dive #36 and 1785 data along dive #51.

We took advantage of two kinds of positioning system during the surveys: the positioning using the inertial navigation system of the vehicle and that using the acoustic communication with the mother ship. The former gives continuous position data but is inherent in the accumulation of error, whereas the latter gives individual but intermittent position data at the time of communication. We used the continuous position data of inertial navigation system after correction of the accumulating error by fitting them to the absolute locations obtained by the acoustic navigation system (Fig. 4).

4. Analyses and Results

The total intensity anomaly data were interpolated onto a 20 m grid (Figs. 5a and 6a). As for dive #36 the mean and trend of each profile were removed before gridding. The mean value of all data was also removed for dive #51. The gridded magnetic data were then upward continued to a level plane, that is taken deepest but above the seafloor (Parker and Huestis, 1974), by using the iterative Fourier procedure developed by Guspi (1987). For the data of dive #36, the magnetic field was upward continued to a level of 730 m water depth (Fig. 5b) using a cosine-tapered high-cut filter

Fig. 5. Magnetic inversion of dive #36 showing (a) observed anomalies, (b) upward continued anomalies on a level plane of 730 m water depth, (c) computed magnetization assuming a 100-m-thick source layer, and (d) computed magnetization assuming a 300-m-thick source layer (note that the color scale differs from that of (c)). Unit of the horizontal axes is km with the origin taken at ($139^{\circ}44'20''\text{E}$, $31^{\circ}58'30''\text{N}$). See Fig. 2 for the analysis area.

beginning at a wavelength 500 m and reaching zero at 400 m to ensure the convergence of calculation. For dive #51, the level plane was taken at 580 m depth (Fig. 6b) and the same kind of filter beginning at 600 m and cutting off at 500 m was

Fig. 6. Magnetic inversion of dive #51 area. Panels arranged as Fig. 5. Level plane of (b) is taken at 580 m water depth. See Fig. 2 for the analysis area.

applied; the cutoff to longer wavelengths was needed because of the more variable depth of the vehicle during this dive survey. Ten iterative procedures brought sufficient

convergence.

The magnetic anomalies reduced to each level plane were then inverted for crustal magnetization by using the method of Parker and Huestis (1974) (Figs. 5c and 6c). Multibeam bathymetric data obtained by the R/V Kairei in August 2005 (Chief scientist: Kensaku Tamaki) were used in the calculation. The water depths obtained during the dive surveys (from depth and altitude of the vehicle) are in good agreement with the multibeam data (the difference is < 10 m for more than 90 % of the data). A bandpass filter was applied to ensure the convergence of calculation (pass band of 3000 to 500 m with cutoffs of 4000 and 400 m for the data of dive #36 and pass band of 2000 to 600 m with cutoffs of 2500 and 500 m for dive #51, depending on the dimensions of each area and the high-cut filters used in the preceding procedure). Twenty iterations were executed to achieve the convergence.

The inversion solution has the nonuniqueness represented by the annihilator, a magnetization distribution which produces no external magnetic field when convolved with the topographic relief (Parker and Huestis, 1974). Arbitrary times of annihilator can be added to the solution without affecting the resultant magnetic field. Adding the annihilator almost results in a DC-level shift in the magnetization solution. Because the age of the Bayonnaise knoll caldera is not yet known, we have no means to guess the dominant polarity of the caldera. However, it has been reported that the wall and central cone of the caldera consist of dacite lavas (Iizasa et al., 2004). Moreover, sea-surface or aero magnetic surveys in a wider area (Honsho et al., in manuscript preparation; Nishizawa et al., 2000) show no remarkable magnetic signal associated with the Bayonnaise knoll, indicating the caldera as a whole holds weak magnetization. We tentatively added 2.4 or 2.3 times of the annihilator for the results of dives #36 or #51 respectively, to make the magnetization nearly zero in the most part of the analysis areas except for the zones of localized magnetization high. But a few A/m DC-level shift in the magnetization solutions remains still possible considering that the surrounding dacite may have some weak positive or negative magnetization.

It should be noticed that the amplitude of resultant magnetization depends on the assumed thickness of source layer: more reduced magnetization is obtained as the source layer becomes thicker. Figs. 5d and 6d show the inversion solution assuming the source layer 300 m thick instead of 100 m. It can be confirmed that the pattern of distribution is little affected by the assumption of the layer thickness, but the magnitude is reduced. The maximum intensity is reduced from 7.1 to 3.3 A/m for dive #36, from 5.7 to 3.0 A/m for dive #51. Because the contribution of deeper source becomes

smaller, not only the distribution pattern but also the magnitude has a slight difference if the source layer is assumed thicker than 500 m. The maximum intensity calculated with the assumption of the half-infinite source is 2.2 A/m for dive #36 and 2.5 A/m for dive #51.

5. Discussion

The magnetic inversion results of the two dives are shown together in Fig. 7. Two areas of high magnetization are found in the northern margin of the caldera floor and in the southeastern caldera wall. The northern one is located at the deepest part of the caldera floor and seems to have two peaks within (larger one in the north and smaller in the south). Another magnetization high in the southeastern caldera wall has almost circular shape and is smaller than the northern one both in the dimension and intensity. In the Myojinsho caldera and the Myojin knoll caldera, though there are variations of size and intensity, also have observed local magnetic anomalies in the caldera wall or the caldera rim generated by intrusive rocks that have stronger magnetization than knoll bodies (Murakami, 1997; Ueda et al., 2001). This magnetization is considered to be the thermal remanent magnetization acquired in the direction of the earth magnetic field when it cooled. Though the central cone which occupies the eastern part of the caldera floor has remarkable positive magnetic anomalies in its southern slope (Fig. 6a), the magnetic inversion result shows the magnetic anomalies are

Fig. 7. Magnetization distribution on the Bayonnaise knoll caldera. The area surrounded by dashed lines indicates the caldera wall.

Fig. 8. A summary of the geological features and the high magnetization areas in the caldera, showing the same area of Figure 2. Bathymetric contour interval is 25 m. Location of the Hakurei deposit is from Iizasa et al. (2004). The two areas of high magnetization (> 4 A/m) are shown by shade with 'H'.

almost explained by the topographic effect and it has as small magnetization as the caldera wall and rim. The result is consistent with the observation that the caldera wall and central cone consist of dacite (Iizasa et al., 2004).

Fig. 8 shows the regional bathymetric map together with the locations of the Hakurei deposit and the two areas of high magnetization found by our survey. In the north and south of the Bayonnaise knoll exists a NS trending, small knoll chain. Iizasa et al. (2004) pointed that the Hakurei deposit occurs on the inferred intersection of the knoll chain and caldera boundary faults. The result of the sea-surface magnetic survey in the region (Honsho et al., in manuscript preparation) shows a weak and broad NS trending magnetization high along the knoll chain, and fifteen rock samples dredged on one of the knolls were confirmed to be all basaltic lava (from the cruise report of KT09-12 by the R/V Tansei-maru in 2009). Another knoll chain located south of

our survey area, which has similar NS trend to the one crossing the Bayonnaise knoll but is longer and more remarkable, also has clear high magnetization (Ueda et al., 2001; Honsho et al., in manuscript preparation) and basaltic rocks were also sampled from three dredge sites in the knoll chain (from the cruise report of KT09-12 by the R/V Tansei-maru in 2009). Considering that the two areas of high magnetization seem to lie on an inferred line of the knoll chain running to the north and south of the Bayonnaise knoll and that the existence of basaltic rocks is inferred from the clearly higher magnetization than the surrounding dacite rocks, our result may support the idea of Iizasa et al. (2004) that the knoll chain continues under the seafloor through the Bayonnaise knoll; the magnetization highs found in the caldera may represent intrusive basaltic rocks produced by the volcanic activity of the knoll chain, that could not come up to eruption blocked by the thick crust of the Bayonnaise knoll.

The magnetization high in the southeastern wall is found adjacent to the Hakurei site, that we consider infers the basaltic magma intrusion may have induced the hydrothermal activity of the Hakurei site. Another possible heat source of the Hakurei site is the volcanic activity which had formed the Bayonnaise knoll, however, though the age of the Bayonnaise knoll has not yet known, the caldera is considered to have been formed prior to or during the initiation of the back-arc rifting in the region at ~2.8 Ma (Iizasa et al., 2004; Ishizuka et al., 2003). Considering the fact that the Hakurei field is still active, it is rather questionable that the volcanism of the Bayonnaise knoll could keep supplying heat for such a long time. It has been found that some hydrothermal sites are associated with low crustal magnetization, which is considered resulting from the alteration of magnetic minerals and reduction in magnetization of crustal rocks due to the hydrothermal circulation. Tivey and Johnson (2002) show the strong correlation between regions of low magnetization and hydrothermal vent sites on the northern Juan de Fuca Ridge, and Seama et al. (2005) show the same relationship on the Suiyo seamount in the southern Izu-Ogasawara arc. In our study area, no clear magnetization low is apparently associated with the Hakuei hydrothermal site. The reason is that because the Bayonnaise knoll almost consists of dacite lava and fragments which have weak magnetization, altered and demagnetized basaltic rocks would be indistinguishable from nearby dacite rocks. We suppose that the lateral extent of the intrusion might be larger than the apparent area of high magnetization: the Hakurei deposit may be underlain by the altered part of the intrusive body and only the unaltered part appears as the area of high magnetization. But further surveys that encompass whole the Bayonnaise caldera and the knoll

Fig. 9. Comparison of magnetic anomaly profiles (a) that observed at sea-surface by ship and (b) that at deep-sea by AUV. Track lines of each profile are shown by a bold dashed line (ship track) or a bold solid line (AUV track). (c) Deep-sea anomalies upward continued on a level plane of 730 m water depth (see text in section 4 for details). The profile is extracted from the gridded data (Fig. 5b) along the same track line as (b).

chain are needed to make more convincing discussion on the relationship among the magnetization distribution, the knoll chain and the Hakurei deposit.

The minute results of this study are achieved by the high-resolution, deep-sea measurements by using AUV. The magnetic anomaly profiles obtained by the AUV and by the ship are compared in Fig. 9. The water depth is 820–890 m and the altitude of the AUV is ~100 m. The remarkable peak ~500 m wide observed by using the AUV, which is produced by the high magnetization in the northern caldera floor, is considerably attenuated in the ship observation. From a simple numerical experiment it can be also shown that the signal of such short wavelength becomes too weak to be observed if the altitude is more than 300 m. Deep-sea measurement close to the magnetic source is indispensable for such detailed investigation. However, we have not yet taken

the most advantage of the high-resolution data, because the data are considerably filtered in the analysis processes to obtain the magnetization distribution: short-wavelength components less than 400 m (for dive #36) or 500 m (for dive #51) are cut off to ensure the convergence of the calculation. Fig. 9c shows a profile of the upward continued magnetic anomalies, for the comparison with the observed one (Fig. 9b). In the analysis methods used in this study (Guspi, 1987; Parker and Huestis, 1974), the filtering to longer wavelength is required as the topography becomes more rugged or the depth of observation path varies in a wider range; that is the typical case of surveys in calderas or rifting zones. To avoid a loss of resolution in the reduction procedure of Guspi (1987) method, other methods have been designed where a substitute geometry of a level observation plane and a topography that maintains flying height is considered (Hussenöeder et al., 1995; Honsho et al., 2009). Concerning our data, however, these methods could not reach an enough solution to explain observed data, probably because the correction of error caused by switching geometry does not work sufficiently due to the extremely variable topography of our survey area. It is a crucial issue to develop analysis method without a large loss of spatial resolution.

6. Conclusions

The AUV r2D4 developed by Institute of Industrial Science, The University of Tokyo, successfully collected high-resolution, deep-sea magnetic data on the northern and southeastern parts of the Bayonnaise knoll caldera. The magnetic inversion result imaged two areas of high magnetization within the caldera, lying on an inferred line of the basaltic knoll chain running to the north and south of the Bayonnaise knoll. The magnetization highs found in the caldera may represent intrusive basaltic rocks produced by the volcanic activity of the knoll chain, that could not come up to eruption blocked by the thick crust of the Bayonnaise knoll. One of the high magnetization areas is located adjacent to the Hakurei deposit, indicating that the basaltic magma intrusion may have induced the hydrothermal activity of the Hakurei site. The Hakurei site is apparently not associated with obvious low magnetization, that is probably because the Bayonnaise knoll almost consists of dacite lava and fragments which have weak magnetization and altered and demagnetized basaltic rocks would be indistinguishable from nearby dacite rocks. We suggest it is nevertheless likely that the Hakurei deposit is underlain by the altered, demagnetized part of the intrusive basalt and only the unaltered part appears as the area of high magnetization.

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ベヨネーズ海丘カルデラにおける 自律型海中ロボット r2D4 を用いた深海地磁気観測

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要 旨

2008年3月および10月に、伊豆・小笠原弧の背弧リフト東縁部に位置するベヨネーズ海丘カルデラにおいて東京大学生産技術研究所が開発したAUV (Autonomous Underwater Vehicle: 自律型海中ロボット) r2D4による潜航調査が行われた。本研究では、カルデラ北部と南東部における2潜航で得られた地磁気データを用い、磁気インバージョンにより海底の磁化強度分布を明らかにした。その結果、カルデラ底北縁部とカルデラ壁南東部にそれぞれ磁化の強い箇所があることが判った。これらの高磁化域は、ベヨネーズ海丘の南北に延びる玄武岩質の海丘列とほぼ同じ線上にあることから、この海丘列の火山活動による玄武岩質の貫入岩であり、ベヨネーズ海丘の厚い地殻に阻まれて海底噴出には至らなかったものであることが推察される。また、この高磁化域のひとつはカルデラ床南東縁辺部にある白嶺鉱床に隣接しており、白嶺鉱床を形成した熱水活動の原動力がこの玄武岩質マグマの貫入であった可能性を示唆する。磁化強度分布と熱水鉱床との関係については、熱水循環に伴う変成作用で岩石が磁化を失い、鉱床周辺が低磁化域となることが指摘されているが、本研究域内にある白嶺鉱床は特に明らかな低磁化域を伴っているようには見えない。これは、ベヨネーズ海丘がそもそも強い磁化を持たないデイサイト質の溶岩と碎屑物から成るため、磁化を失った玄武岩などが存在しても周囲の岩石と見分けが付きにくいためであろう。熱水活動による消磁という効果を考慮すると、高磁化域として見えているのは、鉱床からある程度距離があり変成作用を受けなかった部分だけで、実際の貫入岩体の広がりには白嶺鉱床下まで及んでいることも考えられる。本研究で得られた磁化強度分布の解像度は、データ自体の解像度ではなく、解析過程で施される短波長成分を除くフィルターに規定されている。海上観測から深海観測へと重点が移りつつある海洋地磁気研究において、高解像度のデータを最大限に生かせる解析方法の確立こそが緊急の課題である。

キーワード: 深海地磁気・自律型海中ロボット・ベヨネーズ海丘カルデラ・白嶺熱水鉱床

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