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Magnetic anomalies over the Izu-Ogasawara (Bonin) Arc, Mariana Arc and Mariana Trough

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Abstract: We performed magnetic anomaly measurement over the Izu-Ogasawara (Bonin) Arc, the Mariana Arc and Trough, and the Ogasawara Plateau and its neighboring seamounts along dense ship tracks, the intervals of which are 2 to 4 miles in general.

Most submarine volcanoes on the Shichito Ridge and the Mariana Ridge (the volcanic front of the Izu-Ogasawara and Mariana Arcs) accompany large magnetic anomalies. Some volcanoes have fairly simple dipole-type anomalies (e.g. the Nishinoshima Volcano and Fukujin Seamount), and others have complicated anomaly distributions (e.g. the Iwojima Volcano) and/or anomalies poorly correspond to the shape of volcanoes (e.g. the Torishima Volcano and Nikko Seamount). The differences in the magnetic inhomogeneity of these volcanoes may reflect differences in the length of the volcanic activity. For volcanoes in the northern part of the Shichito Ridge, the magnetic inhomogeneity may reflect the bimodal volcanism. The back-arc rifts in the northern part of the Izu-Ogasawara Arc show no remarkable anomalies, which suggests that the seafloor spreading has not started yet.

Magnetic anomalies are useful for estimating the origin of seamounts. Seamounts distributed between the Sofugan and Nishinoshima Islands in the middle Izu-Ogasawara Arc (the Shichiyo Seamount Chain, the Omachi, Sawa and Tenpo Seamounts, etc.) are classified into four groups from magnetic anomaly patterns. The first group is Quaternary volcanoes having strong dipole-type anomalies. The second is faulted blocks of old island-arc crusts, accompanying little anomalies. The third is old volcanoes of possibly Oligocene age, which have the magnetization of eastward declination and shallow inclination. The fourth is broad positive anomalies over the Omachi and Tenpo Seamounts. These seamounts are inferred to be old basement highs because the similar anomalies are observed on forearc basement highs in the northern Izu-Ogasawara Arc (the Shinkurose Ridge) having Paleogene or Miocene age.

We have found for the first time clear magnetic lineations in the Mariana Trough between 20° and 22°N. A forward modeling showed that the seafloor spreading at 21° 30'N has started at 3 Ma or a little earlier at a half spreading rate of 2.5 cm/year. The rate has decreased to about 1 cm/year at present. Spreading axes probably overlap from 20° 30' to 21° N. Their offset is about 30 km. The occurrence of the large-offset overlapping spreading centers is unusual for ridges of slow spreading rates, which suggests that the crust here would be weaker (hotter and/or thinner) than that of major-ocean spreading centers.

Four peaks on the Ogasawara Plateau and three other seamounts in the east of it, which are thought to have been formed in the Cretaceous, can be divided into two groups from

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magnetic anomalies. The first group having negative anomalies over the seamount bodies was magnetized in an equatorial region in the Cretaceous. The second group has the magnetization close to the present geomagnetic field direction, suggesting induced and/or viscous magnetization or remagnetization by rejuvenated volcanism.

1. Introduction

We conducted magnetic survey over the Izu-Ogasawara (Bonin) Arc and the Mariana Trough from 1984 to 1989 as a part of the research program "Submarine Hydrothermal Activity in the Izu-Ogasawara Arc" to understand better the geological structure in this region. Survey areas include the whole Izu-Ogasawara Arc from Hachijojima Is. to Minami-Iwojima Is., the Ogasawara Trough, the Ogasawara Plateau and neighboring seamounts, the Mariana Ridge and the Mariana Trough north of 20°N, and along the spreading center of the Mariana Trough around 18°N. The spacings of the survey lines were 2 to 4 nautical miles (3.7 to 7.4 km) in general, and they were as close as 1 mile in several detailed survey areas. Such high density of ship tracks made us possible to draw magnetic anomaly contour maps of high accuracy.

The purpose of this report is to present magnetic anomaly distributions of above mentioned areas, and discuss the geological structure deduced from the magnetic anomalies.

2. Background

2.1 Izu-Ogasawara Arc

The Izu-Ogasawara (Bonin) Arc lies on the eastern rim of the Philippine Sea plate subducted by the Pacific plate (Fig. 1). It is about 1200 km long extending from the Izu Peninsula to Minami-Iwojima Is. It continues southward to the Mariana Arc.

The Shichito Ridge is occupied by a line of Quaternary arc volcanoes, which forms a recent volcanic front of the Izu-Ogasawara Arc. Volcanic rocks from the Shichito Ridge are known to be compositionally bimodal (Tsuya, 1937; Kuno, 1962). Occurrence of acidic rocks are abundant in the northern part of the Shichito Ridge, but little in the southern part (Yuasa, in prep.).

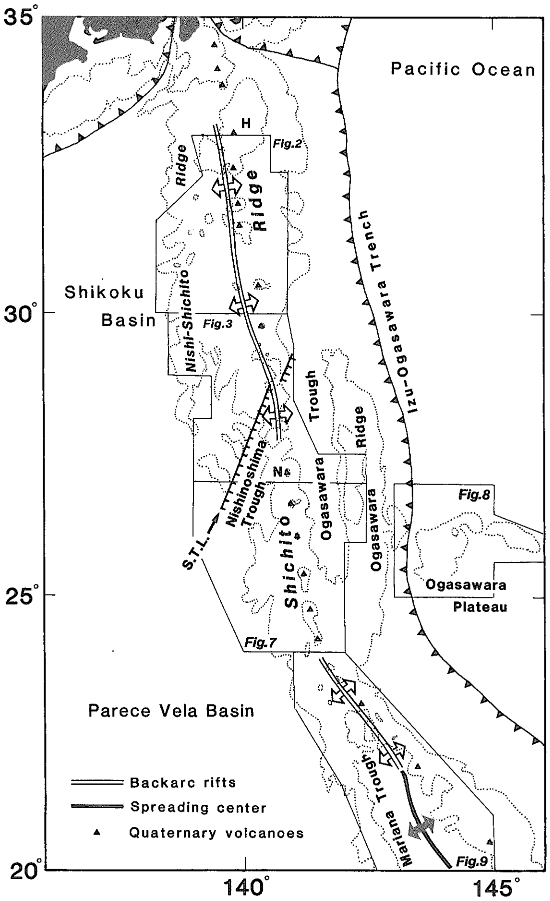


Fig. 1 Structural framework of the Izu-Ogasawara-Mariana Arc. Dotted lines represent 1000m and 3000m iso-depths. S.T.L.: Sofugan Tectonic Line (modified from Yuasa (1985)). H: Hachijojima Island, N: Nishinoshima Island.

A row of small grabens occurs just behind the volcanic front in the northern part of the Izu-Ogasawara Arc, from Hachijojima Is. to Nishinoshima Is. The Aogashima and

Sumisu Rifts in Fig. 2(a) are examples of such grabens. They have been considered to be young back-arc rifts, or incipient back-arc basins (Karig and Moore, 1975; Honza and Tamaki, 1985). Recent ODP (Ocean Drilling Program) drillings in the Sumisu Rift, one of these back-arc rifts, proved the young age of the rift. The age of the sediments in the Sumisu Rift is not older than 1.1 Ma (Leg 126 Scientific Drilling Party, 1989). Signs of hydrothermal activity were reported from the Sumisu Rift (Taylor *et al.*, 1990; Urabe and Kusakabe, 1990) and the Aogashima Rift (Yamazaki *et al.*, 1991). In the southern part of the Izu-Ogasawara Arc between Nishinoshima Is. and Minami-Iwojima Is., on the other hand, no backarc rifts are recognized.

In the back-arc of the Izu-Ogasawara Arc, geological structures being oblique to the trend of the arc are remarkable (Karig and Moore, 1975; Honza and Tamaki, 1985). In the north of about 30°N, several rows of basement highs, on which relatively large seamounts are located in line, run in NE-SW or ENE-WSW direction (so-called Nishi-Shichito Ridge or Izu Ridge). Examples are the Enpo and Genroku Seamount Chains in Fig. 2(a). In the south of 30°N, on the other hand, troughs of NNE-SSW strike are conspicuous. The most prominent among them is the Sofugan Tectonic Line (Fig. 1), a steep cliff of probably normal fault origin running linearly south-southwestward from the south of Sofugan Island. Yuasa (1985) considered that the Izu-Ogasawara Arc can be structurally divided into the southern and northern part by this fault. The Nishinoshima Trough lies on the east of the Sofugan Tectonic Line. It is bordered on the east by the Shichito Ridge. Yuasa (1991a) proposed that the Nishinoshima Trough was formed as a northern tip of the incipient opening of the Parece Vela Basin in Oligocene time (Mrozowski and Hayes, 1979). The Sofugan Tectonic Line would consist a western wall of the paleo-rift. The "Nishinoshima Trough" of Honza and Tamaki (1985) and Yuasa (1985) includes other topographic lows lying between the Shichito Ridge and the Nishi-Shichito Ridge (Izu Ridge), but in this report does not.

The Ogasawara Ridge is a forearc basement high of Eocene age (Tsunakawa, 1983). The Ogasawara Trough lies between the Ogasawara Ridge and the Shichito Ridge. A multi-channel seismic profile revealed that the Ogasawara Trough was formed by rifting (Abe *et al.*, 1989). The rifting of the Ogasawara Trough may be simultaneous with the rifting of the Nishinoshima Trough in the Oligocene (Yamazaki *et al.*, 1988a). The two troughs may have been a part of one paleo-rift, and later growth of the present Shichito Ridge may have separated them.

In the Izu-Ogasawara Arc, magnetic surveys have been conducted by several institutions for two decades but rather sporadically. Here we present a magnetic anomaly map of the whole area for the first time, which is based on systematic survey with dense ship's tracks. Previously the Geological Survey of Japan conducted a reconnaissance magnetic survey along lines at intervals of 15 miles (28 km) in 1979, and the results were presented as magnetic anomaly profiles (Miyazaki *et al.*, 1981). The Hydrographic Department, Maritime Safety Agency Japan has published a series of bathymetric maps of 1/200,000 scale over the northern part of the Izu-Ogasawara Arc, a part of which includes a magnetic total-force map of the same scale.

2.2 Mariana Trough

The Mariana Trough is known as one of active back-arc basins in the world (Karig, 1971). Recently active hydrothermal vents were discovered by submersible ALVIN at 18° N (Craig *et al.*, 1987; Moore and Stakes, 1990). Based on the results of DSDP (Deep Sea Drilling Project) drillings, Hussong and Uyeda (1982) considered that the rifting of the Mariana Trough at 18°N would have begun in the latest Miocene, about 6 Ma, with a half spreading rate of 2.15 cm/year. Bibee *et al.* (1980) correlated several magnetic anomaly

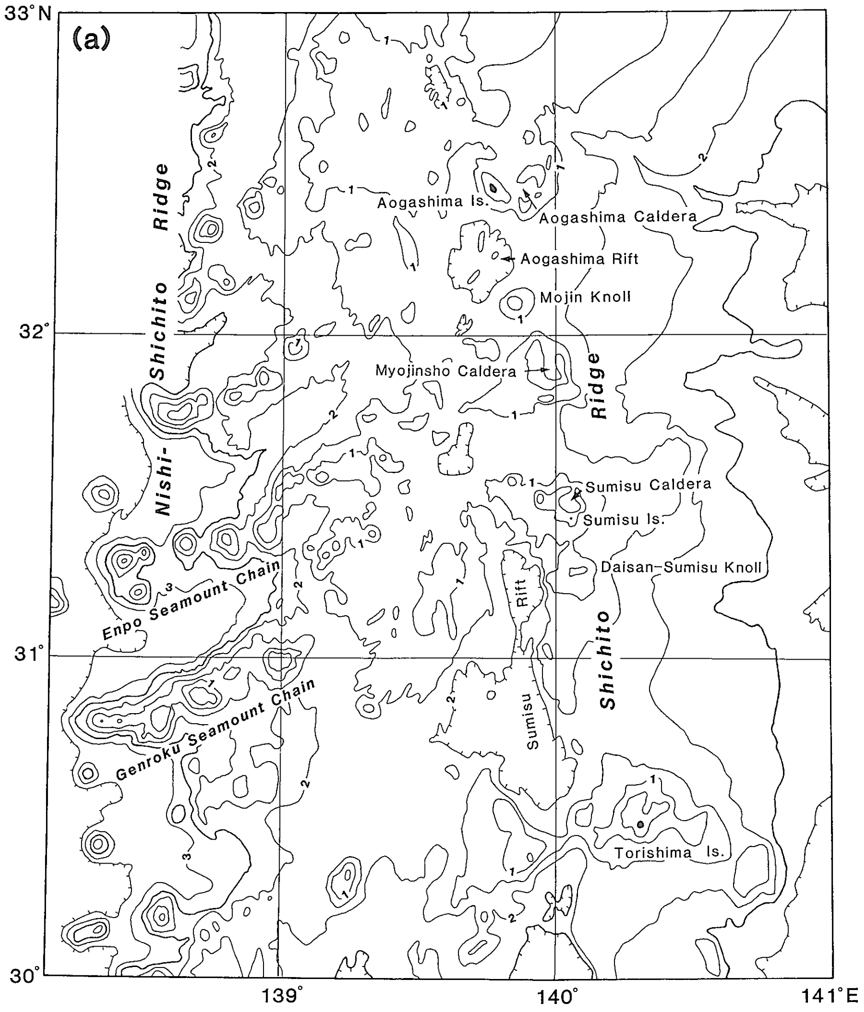


Fig. 2 (a) Outline of topography in the northern Izu-Ogasawara Arc from 30° to 33°N. Contours are at 500m intervals. Unit of the figures is 1000m. (b) Magnetic anomalies in the same area. Contours are at 100 nT intervals. Positive anomalies are shaded. (c) Survey lines of the magnetic anomalies.

profiles between 17° 30' to 18°N and estimated a half spreading rate of approximately 1.65 cm/year within 50 km of the spreading axis.

The manner of spreading in the Mariana Trough, however, has not been understood well. Survey lines of magnetic anomalies are still scarce except for the area near the spreading axis between 17° 30' to 18°N. It is very difficult to correlate magnetic anomaly profiles in the Mariana Trough unless these lines are closely spaced (Karig, 1971; Anderson, 1975; Karig *et al.*, 1978; Fryer and Hussong, 1982). One reason is that amplitudes of the magnetic anomalies are generally very low because the trough is close to the magnetic equator and the strike of the spreading axis is close to north-south. Another reason would be that the spreading manner of the Mariana Trough is not simple and many discontinuities such as fracture zones, propagating rifts (Hey,

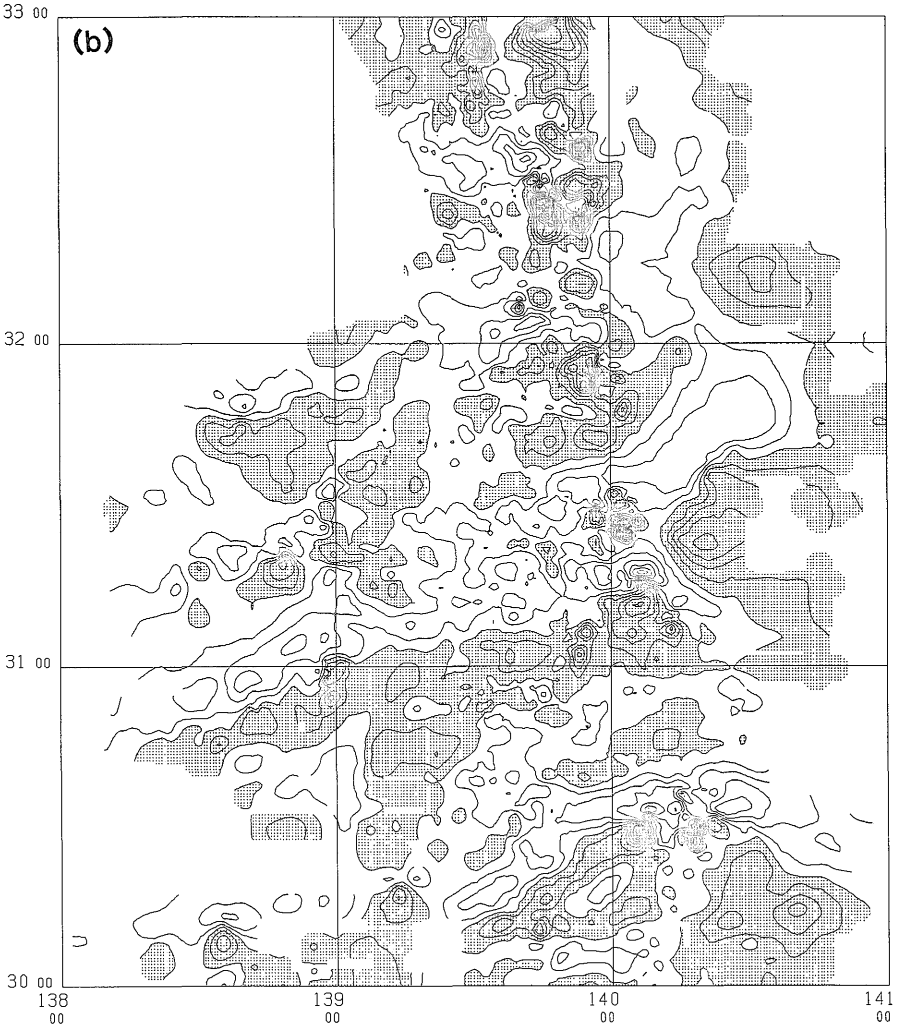


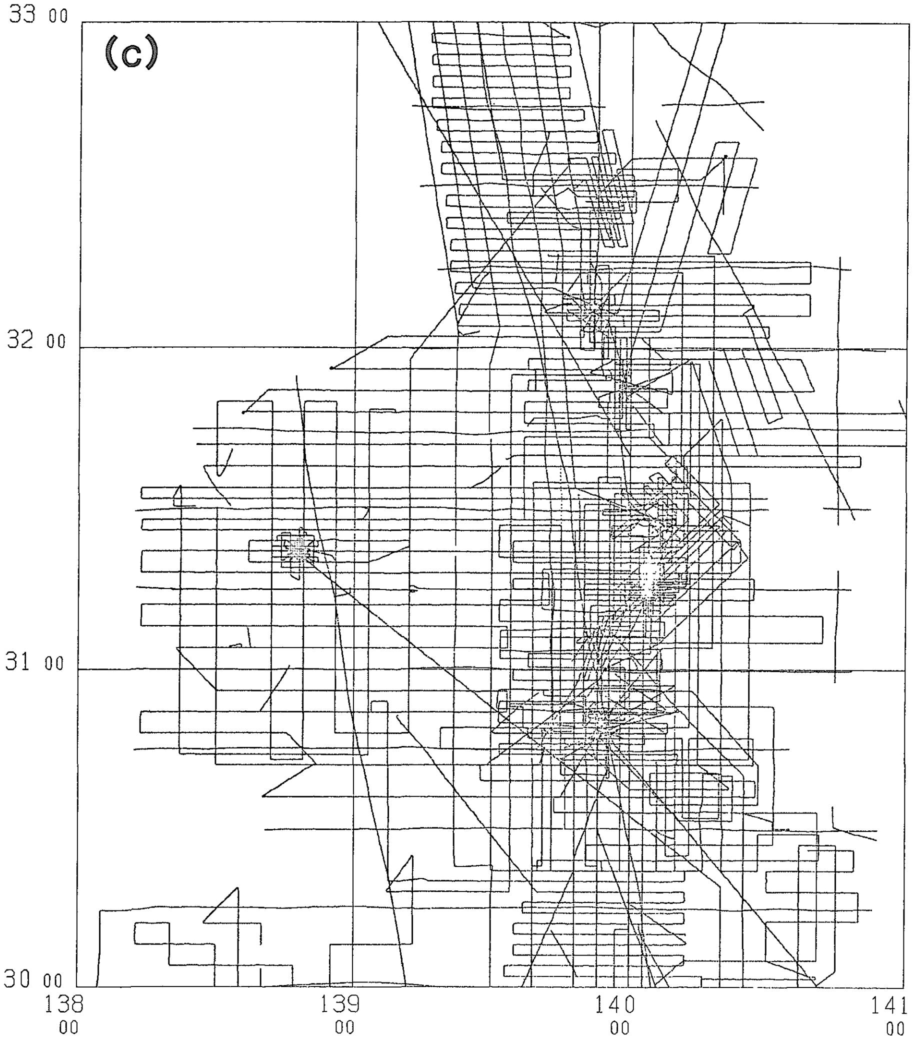
Fig. 2 continued

1977) and overlapping spreading centers (Lonsdale, 1983;Macdonald and Fox, 1983) may exist.

We have identified for the first time magnetic lineations in the northern Mariana Trough between 20° to 22°N based on dense magnetic profiles, and discuss the manner of seafloor spreading there.

3. Data acquisition and reduction

Magnetic total force was measured using a proton precession magnetometer (GeoMetrics G801) towed about 250m behind the R/V Hakurei-maru. Data were logged on a magnetic tape every 10 seconds, and finally edited as a series of records on every minute, which contain ship's position, speed and geophysical data (magnetics, gravity and depth). Residual total magnetic intensity field, that is, magnetic anomaly, was obtained by subtracting the 1985 version of the IGRF (International Geomagnetic Reference Field) (IAGA Division I Working Group 1, 1985) from the



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observed data. Diurnal correction was not applied. Ship's positions were determined by a satellite-Loran C integrated navigation system (Magnavox model 200). This system generally has an accuracy of about 0.1 nautical mile (180m). After 1988, the GPS (Global Positioning System) was also used for navigation.

After editing out anomalous data such as spiky noise, the data were interpolated onto a grid of 1 km spacing. The gridding was done by a weighted averaging method using a commercially available program package UNIRAS. The data collected during the previous cruises of the Geological Survey of Japan in 1979 (Miyazaki *et al.*, 1981) were also included.

4. Interpretation

4.1 Northern Izu-Ogasawara Arc: Hachijojima Is. to Torishima Is.

Quaternary volcanoes stand in line along the Shichito Ridge, the volcanic front of the Izu-Ogasawara Arc (Fig. 2(a)). They are the Aogashima, Myojinsho, Sumisu and Torishima Volcanoes, and the Daisan-Sumisu and Myojin Knolls. All but the Myojin Knoll show strong and short wave-length magnetic anomalies (Fig. 2(b)). The complicated anomaly patterns of these volcanoes suggest that strongly and weakly magnetized parts are mixed, which may reflect the bimodal volcanism of this area. The islands emerged from the sea are known to be composed of basalts (Kuno, 1962), but dacites are dredged from submarine calderas (Yuasa, in prep.).

A typical example is the magnetic anomaly distribution over the Torishima volcano. Strong dipole-type anomalies were observed in the close vicinity of Torishima Island. The area of shallow water depth extending north of the island, however, shows little anomalies (Fig. 2(b)). The island is composed of basalts (Kuno, 1962), which would have strong remanent magnetization. The shallow area north of it would be comprised by weakly magnetized rocks such as dacites. This implies bimodal volcanism of the Torishima volcano. This suggestion is consistent with Okamura and others' (1991) consideration that thick volcaniclastic sediments in the Sumisu Rift, which are composed mainly of dacitic pumice (Nishimura *et al.*, 1991), were derived from the Torishima volcano or its vicinity.

The Myojin knoll accompanies little magnetic anomalies although the volume of the volcano is not much smaller than that of others. It is suggested that the Myojin Knoll is composed of weakly magnetized rocks such as dacites. This inference has recently been confirmed by the observation using the submersible Shinkai 2000 (Yuasa, 1991b).

Back-arc rifts, which lie just behind the volcanic front, show no remarkable magnetic anomalies except for a chain of volcanoes crossing obliquely the Sumisu Rift (Fig. 2). The basalts taken from the intra-rift volcanoes in the Sumisu Rift have chemical composition of back-arc basin basalts (Ikeda and Yuasa, 1989; Fryer *et al.*, 1990). However, the fact that no strong magnetic signals like the magnetic lineations of mid-oceanic ridges were observed suggests that these basalts would be volumetrically small. It is thus considered that seafloor spreading has not started yet and the basement of the back-arc rifts would consists dominantly of island-arc crust.

The Nishi-Shichito Ridge lies to the west of the back-arc rifts, which consists of topographic highs trending obliquely to the Izu-Ogasawara Arc. The ridges (the Enpo Seamount Chain and the Genroku Seamount Chain) show relatively simple magnetic anomaly distribution: negative anomalies occur north of topographic highs, and positive south (Fig. 2). This pattern indicates the magnetization of normal polarity. The ages of the ridges are not clear. A K-Ar age of 2.2±1.1 Ma was reported from the Enpo Seamount (Yuasa, 1985). On the other hand, historical volcanic activity around the Genroku Seamount was documented (Kuno, 1962). The normal polarity of the magnetization might indicate young age of the ridges (younger than the Brunhes-Matuyama boundary at 0.73 Ma), but there is a possibility that induced magnetization or viscous magnetization of the present geomagnetic field direction have overcome the primary remanent magnetization. Magnetic properties of the rocks which comprise these ridges have not yet been known.

4.2 Middle Izu-Ogasawara Arc: Sofugan Is. to Nishinoshima Is.

The Sofugan and Nishinoshima volcanoes, the crests of which are emerged from the sea, are Quaternary arc volcanoes located on the

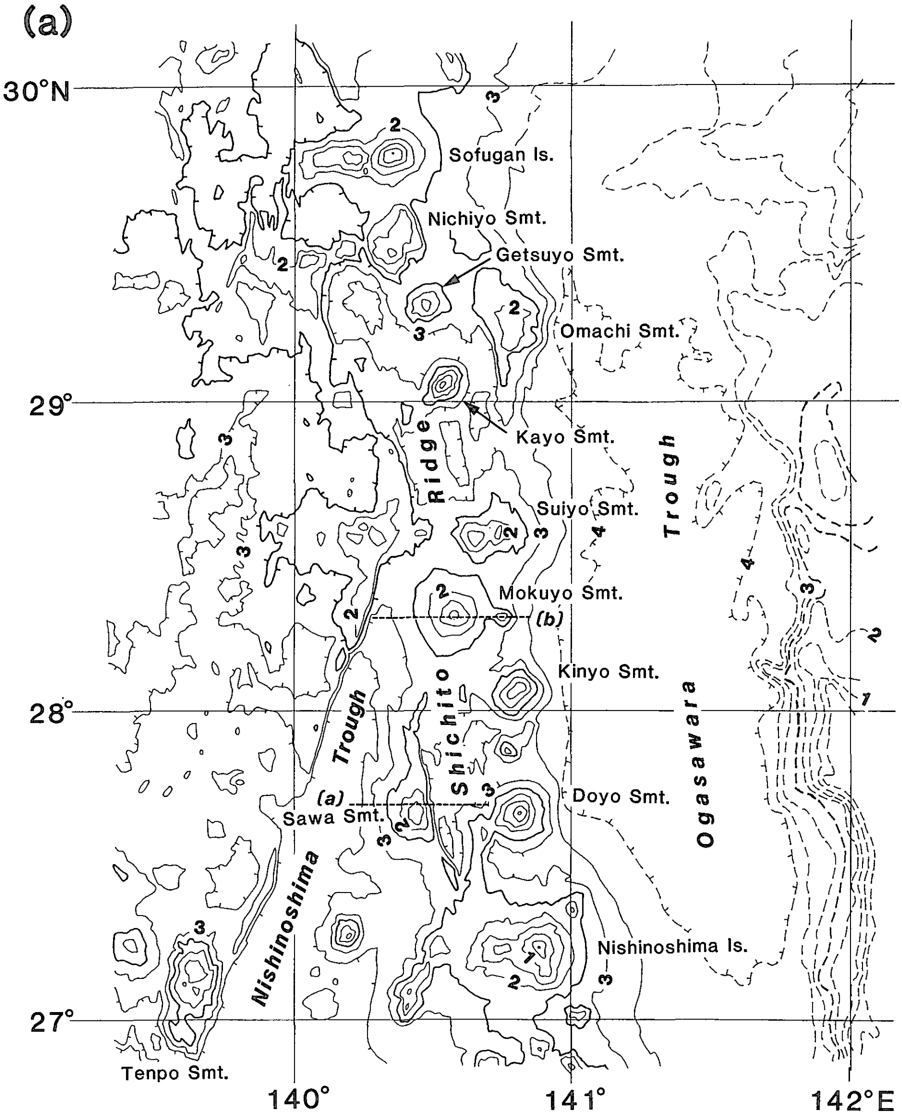


Fig. 3 (a) Outline of topography in the middle Izu-Ogasawara Arc from 27° to 30°N. Contours are at 500m intervals. Unit of the figures is 1000m. Broken lines indicate the location of seismic profiles shown in Fig. 5. (b) Magnetic anomalies in the same area. Contours are at 100 nT intervals. Positive anomalies are shaded. (c) Survey lines of the magnetic anomalies. Bold lines indicate the location of seismic profiles shown in Fig. 5.

volcanic front. They have dipole-type magnetic anomalies of normal polarity (Fig. 3(b)). There is no subaerial volcano between the two, but seven seamounts, recently named as the Shichiyo Seamount Chain, are located on the Shichito Ridge in a row (from the Nichiyo Seamount to the Doyo Seamount) (Fig. 3(a)).

The Shichiyo Seamount Chain and neighboring seamounts can be divided into four groups based on their magnetic anomalies (Fig. 4). The first group (group 1) has strong dipole-type anomalies of normal polarity (Fig. 3(b)). The Kayo Seamount, the Kinyo Seamount and the Doyo Seamount are includ-

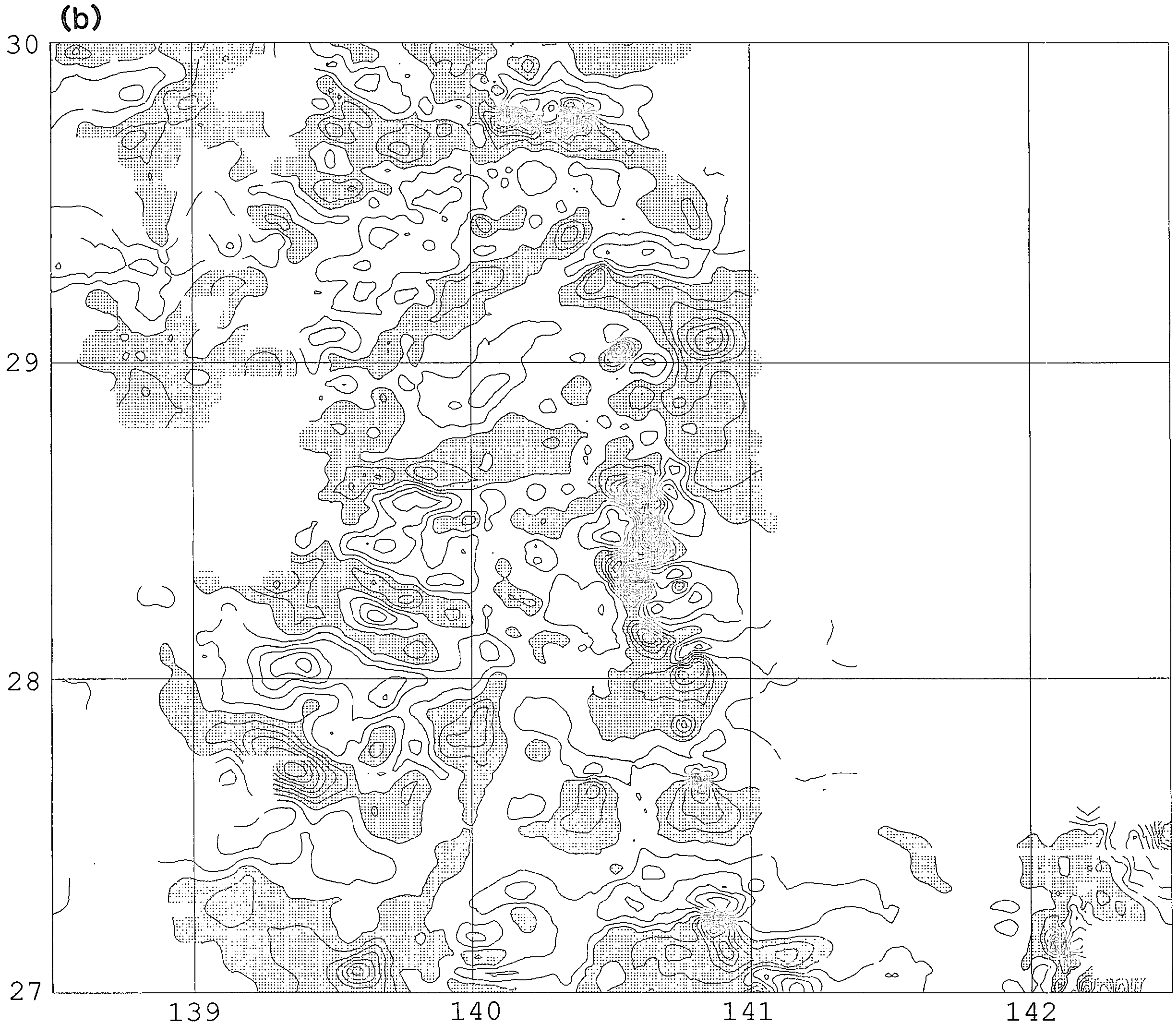
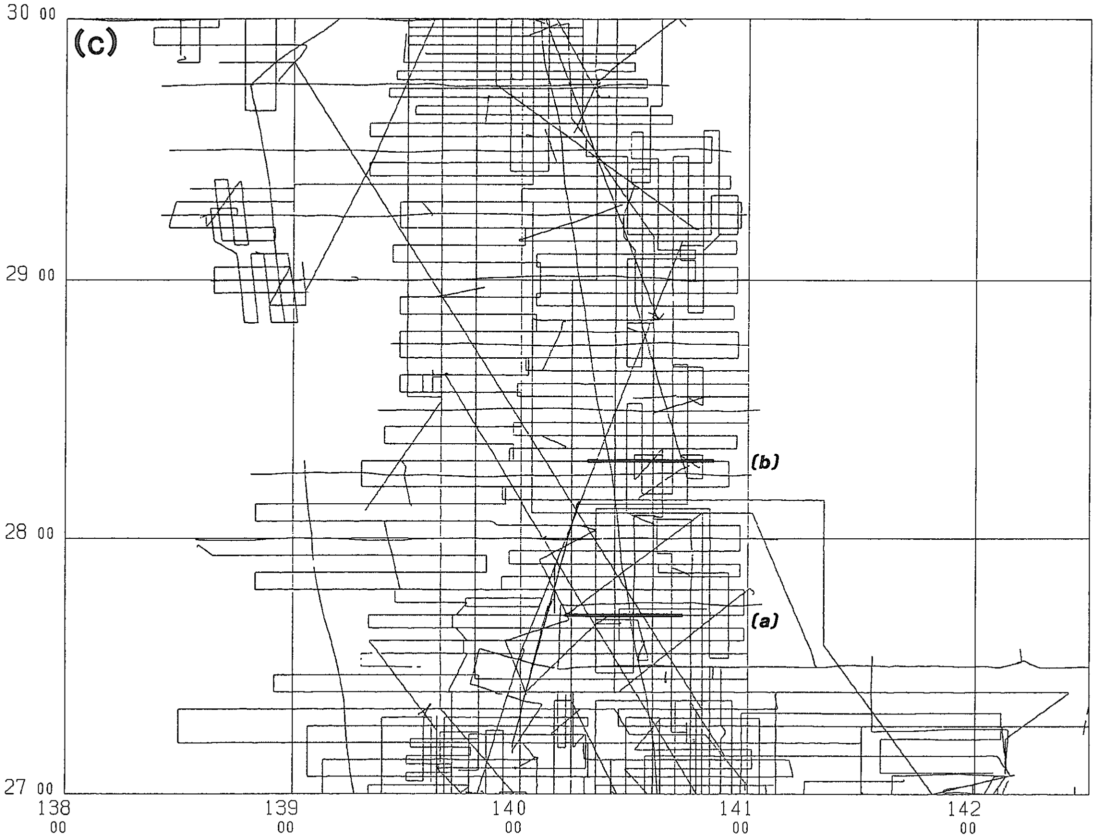


Fig. 3 continued

ed in this group. These seamounts are considered to be Quaternary arc volcanoes like the Sofugan and Nishinoshima volcanoes.

The second group (group 2 in Fig. 4) accompanies weak anomalies compared with the volumes of their edifices (Fig. 3(b)). The examples are the Nichiyo Seamount, the Sawa Seamount and an unnamed seamount at 28° 30'N, 140°15'E. It is considered that these seamounts are not young volcanoes but blocks of old island-arc crust. Seismic reflection profiles revealed that these seamounts are tilted blocks cut by faults and covered with sedimentary layers (Fig. 5(a)). The deformation would have been taken place under the extensional regime which formed the Nishinoshima Trough.

The third group (group 3 in Fig. 4) which includes the Suiyo Seamount and the Mokuyo Seamount is characterized by an unique anomaly distribution which cannot be explained by the magnetization of the present geomagnetic field direction (Fig. 3(b)). The Suiyo Seamount has a positive, stronger anomalies above its western flank and a negative, weaker anomalies above the eastern flank (Fig. 3(b)). This anomaly pattern can be interpreted as the magnetization of east-



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ward declination and shallow inclination (Fig. 6). The direction of the magnetization is fairly close to the paleomagnetic direction of Ogasawara (Bonin) Islands on the Ogasawara Ridge (Kodama *et al.*, 1983). The east deflected declinations have been reported not only from the Ogasawara Islands but also from the Mariana Islands (McCabe and Uyeda, 1983), the Palau Islands (Haston *et al.*, 1988), and Guam and Saipan (Haston and Fuller, 1991), and they can be explained by the clockwise rotation of the Philippine Sea plate since the Oligocene (Louden, 1977; Seno and Maruyama, 1984; Haston *et al.*, 1988, Haston and Fuller, 1991). The magnetization direction thus suggests that the Suiyo Seamount would have emplaced soon after the formation of the Nishinoshima Trough in the Oligocene, and after that it was rotated with the Philippine Sea plate.

The anomaly distribution of the Mokuyo Seamount is even more complicated (Fig. 3 (b)). A pair of positive and negative anomalies of north-south direction occurs on the seamount, but its spread is restricted just above its crest. Its vicinity, on the other hand, shows the anomaly pattern of eastward magnetization similar to that of the Suiyo Seamount. It is thus estimated that the edifice of the Mokuyo Seamount would have formed mainly at about the same time as the Suiyo Seamount, but recently rejuvenated volcanic activity has taken place at the crest. There are some other observations which support this inference. Seismic reflection profiles across the Mokuyo Seamount (Fig. 5

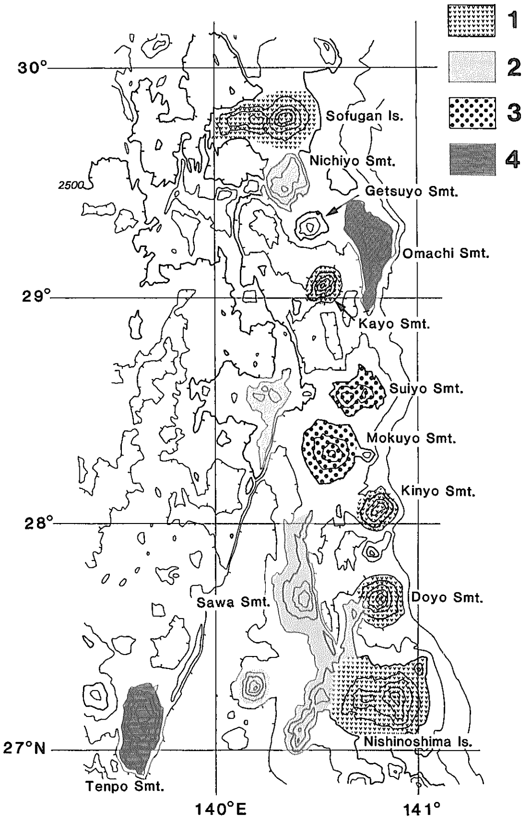


Fig. 4 Classification of the Shichiyo Seamount Chain and neighboring seamounts from their magnetic anomaly patterns. (1) Quaternary volcanoes having strong dipole-type anomalies of the normal polarity. (2) Faulted blocks of old island-arc crust accompanying weak magnetic anomalies. (3) Old volcanoes having east-deflected magnetization direction. (4) Old basement highs characterized by broad positive magnetic anomalies.

(b)) show that except for the crest the seamount has well stratified reflectors, which suggests that the seamount is covered with fine sediments rather than volcaniclastic debris. It is thus inferred that the seamount would not be young except for the top. Recent SeaBeam mapping revealed that the crest has caldera structure (Nagaoka *et al.*, 1991). In the caldera, hydrothermal activity was discovered by dives of the submersible Shinkai 2000 (Nagaoka, 1990), indicating a recent volcanic activity there.

Around the Tenpo Seamount and the Omachi Seamount (group 4 in Fig. 4), broad positive magnetic anomalies are conspicuous (Fig. 3(b)). The intensities of these anomalies are fairly large, more than 500 nT. The broadness of the anomalies and their rather poor correspondence to the topography suggest that the major cause of these anomalies would not be the magnetization of the edifices of the seamounts but somewhat deeper magnetized bodies. On the Omachi Seamount, K-Ar ages of 32 to 34 Ma and occurrence of late Eocene microfossils were reported (Yuasa *et al.*, 1988). A sedimentary rock having microfossil age of the early to middle Miocene was taken from the top of the Tenpo Seamount (Ikari and Nishimura, 1991). It is thus considered that these seamounts are not young volcanoes, but are composed of old island-arc crusts which formed before the Izu-

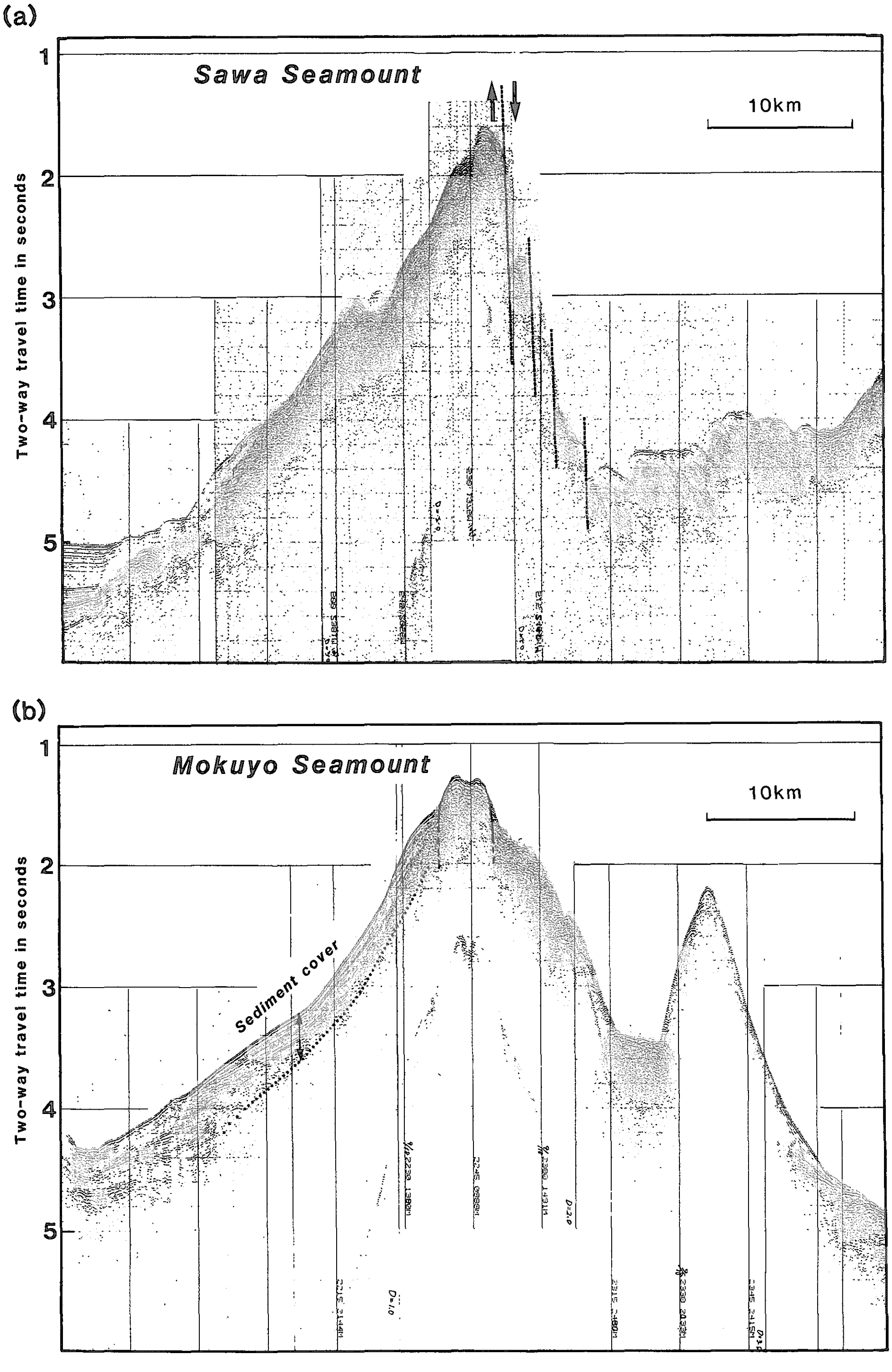


Fig. 5 Single-channel seismic reflection profiles across the Sawa Seamount (a) and the Mokuyo Seamount (b). The locations of these profiles are shown in Figs. 3(a) and (c).

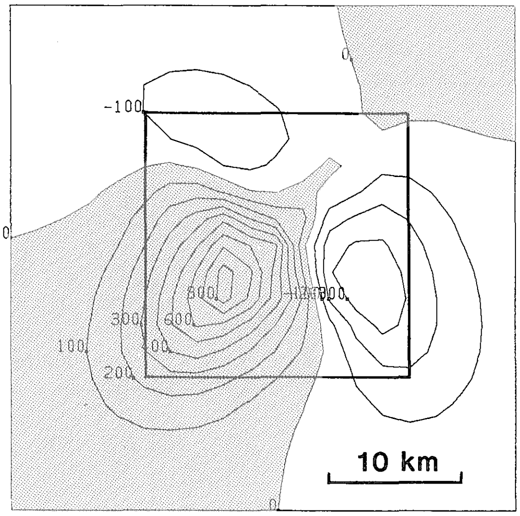


Fig. 6 Magnetic anomalies produced by a pyramid-shaped magnetized body. The declination of the remanent magnetization of the pyramid is 90° E, inclination 20° and intensity 7 A/m. The declination and inclination of the ambient field are -4° and 38°, respectively (value of the 1985 version of the IGRF at 28°N, 140°E). Depth of the top of the pyramid is 1 km, and the bottom 4 km. Contours are at 100 nT intervals. Positive anomalies are shaded.

Ogasawara Ridge and the Kyushu-Palau Ridge were separated by the creation of the Shikoku and Parece Vela Basin.

The broad positive anomalies similar to those observed over the Omachi and Tenpo Seamounts occur sporadically in the fore-arc region in the northern part of the Izu-Ogasawara Arc. They are at southeast of Torishima Is. and east of Sumisu Is. shown in Fig. 2(b), and the Shinkurose Bank (northeast of Hachijojima Is.), presented in Ishihara *et al.* (1981). These regions correspond to the uplifted portions of acoustic basement on seismic profiles, called the Shinkurose Ridge (Honza and Tamaki, 1985). The basement highs are interpreted to be composed of Paleogene and Miocene sedimentary rocks on the geological map of Honza *et al.* (1982). It is thus considered that the broad positive magnetic anomalies would characterize basement highs of the old Izu-Ogasawara Arc.

In the west of the Nishinoshima Trough, magnetic anomalies having relatively long wave-length are distributed (Fig. 3(b)). Topography of this region is fairly smooth (Fig. 3(a)). These anomalies are probably attributable to deeper magnetized bodies such as intrusives. The elongating direction of the anomalies, WNW-ESE, is perpendicular to the structural trend of this area , represented by the Sofugan Tectonic Line.

4.3 Southern Izu-Ogasawara Arc: the Kaikata Seamount to Minami-Iwojima Is.

Volcanoes on the Shichito Ridge (Fig. 7(a)) show strong, short wave-length magnetic anomalies (Fig. 7(b)) reflecting their large volume and shallow water depths. The basic pattern of magnetic anomaly distribution over the Kaikata Seamount, the Kaitoku Seamount and Kita-Iwojima Is. is of normal-polarity magnetization: the anomalies over the northern flank of the volcanoes are dominantly negative, and those over the southern flank are positive. Being superimposed on this pattern, dipole-type anomalies of shorter wave-length are distributed. Some of them correspond to topographic highs, but others do not. The latter would be due to highly variable magnetization, reflecting thermal and compositional inhomogeneity of the volcanoes.

The Iwojima and the Minami-Iwojima Vol-

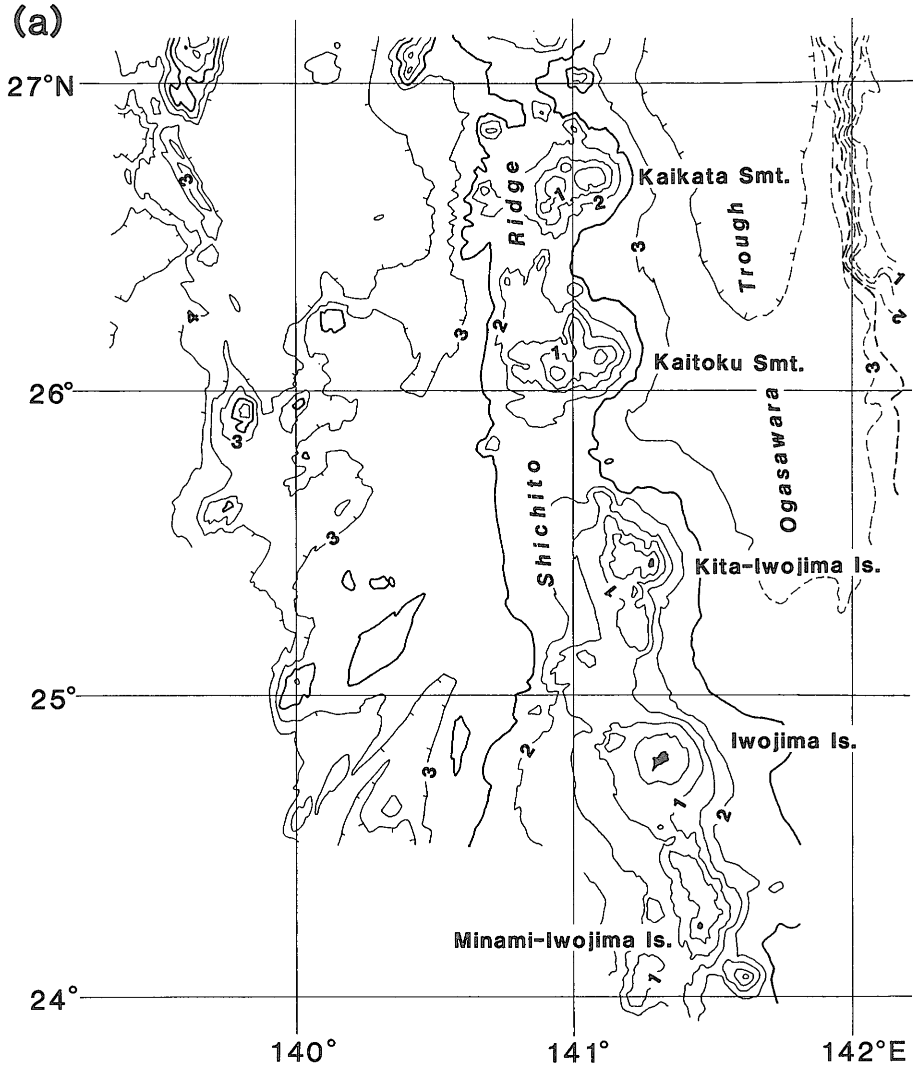
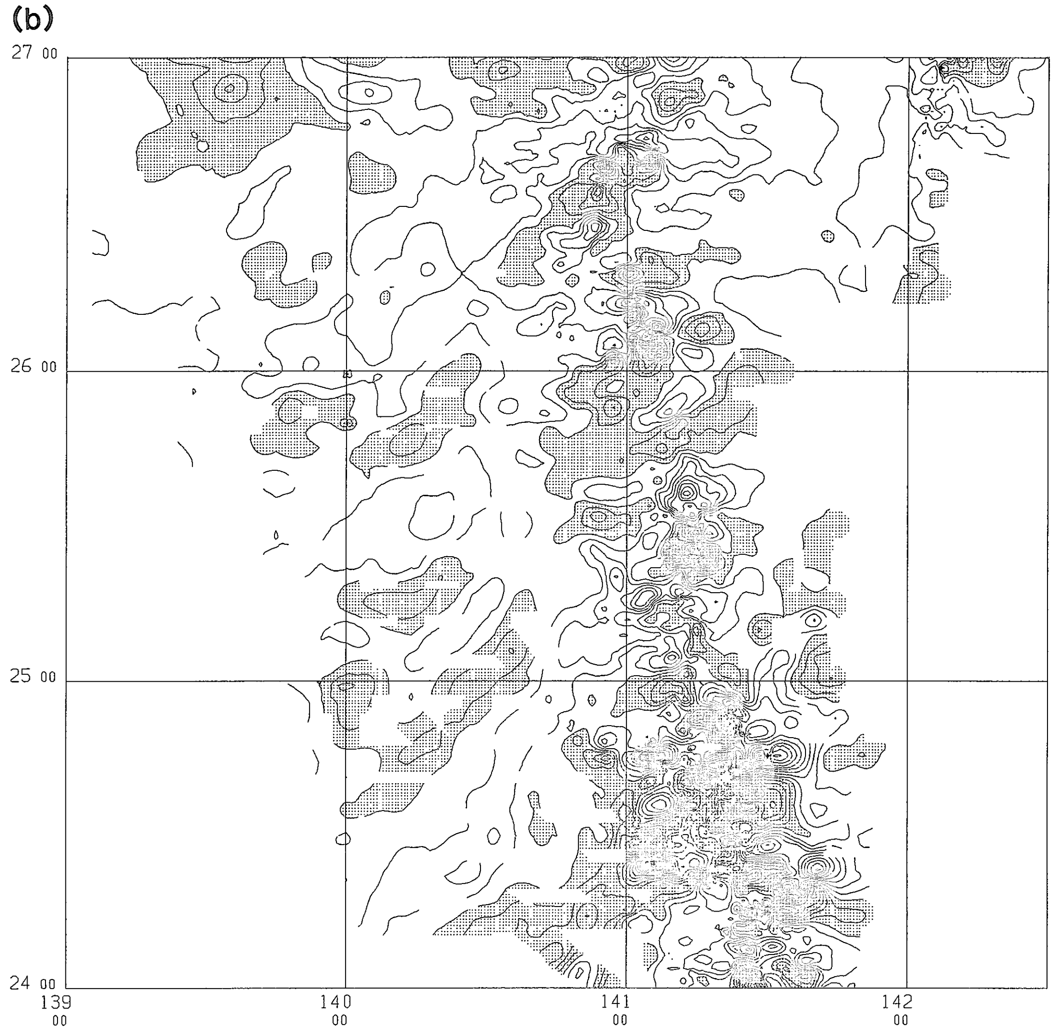


Fig. 7 (a) Outline of topography in the southern Izu-Ogasawara Arc from 24° to 27°N. Contours are at 500m intervals. Unit of the figures is 1000m. (b) Magnetic anomalies in the same area. Contours are at 100 nT intervals. Positive anomalies are shaded. (c) Survey lines of the magnetic anomalies.

canoes are characterized by extremely complicated magnetic anomaly distribution (Fig. 7 (b)). The anomalies have very high amplitude (up to 3000 nT) and short wave-length. Their complexity is more than that of the three volcanoes mentioned above. This would reflects higher inhomogeneity of these volcanoes, suggesting longer history of the volcanic activity. The magnetic anomaly contour map of these two volcanoes, however, has some room for further revision because the spacings of survey lines are still too large compared with the observed short wave-length of the anomalies (Fig. 7(c)), and the accuracy of positioning is low around Iwojima Is., sometimes worse than 500m, because of too short distance from a Loran-C station being located on the island. In the vicinity of the Iwojima Is., the Hydrographic Department, Maritime Safety Agency Japan has already conducted not only total-intensity measurement by a ship but also three-component



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measurement by an airplane (Oshima *et al.*, 1982;1985). They estimated using some modeling technique that the center of the Iwojima Volcano from surface to 2 km in depth is nonmagnetic because of high temperature. This explains why dipole-type anomalies of reversed direction (north side is positive and vice versa) occur on the center of the volcano (Fig. 7(b)).

In the back-arc area west of the Shichito Ridge, northwest trending belts of positive and negative anomalies alternate like the magnetic lineations of mid-oceanic ridges (Fig. 7(b)). The origin of these anomaly belts is not clear, but they cannot be explained by the effect of surface topography because the topography of this area is rather smooth (Fig. 7(a)). The anomalies may reflect a relief of the basement covered with thick sedimentary layers derived from the arc volcanoes. Another possibility is that the basement of this area may be northeastern extension of the oceanic crust in the Parece Vela Basin having magnetic lineations. This hypothesis implies that the present Izu-Ogasawara Arc of this region has grown on the oceanic crust.

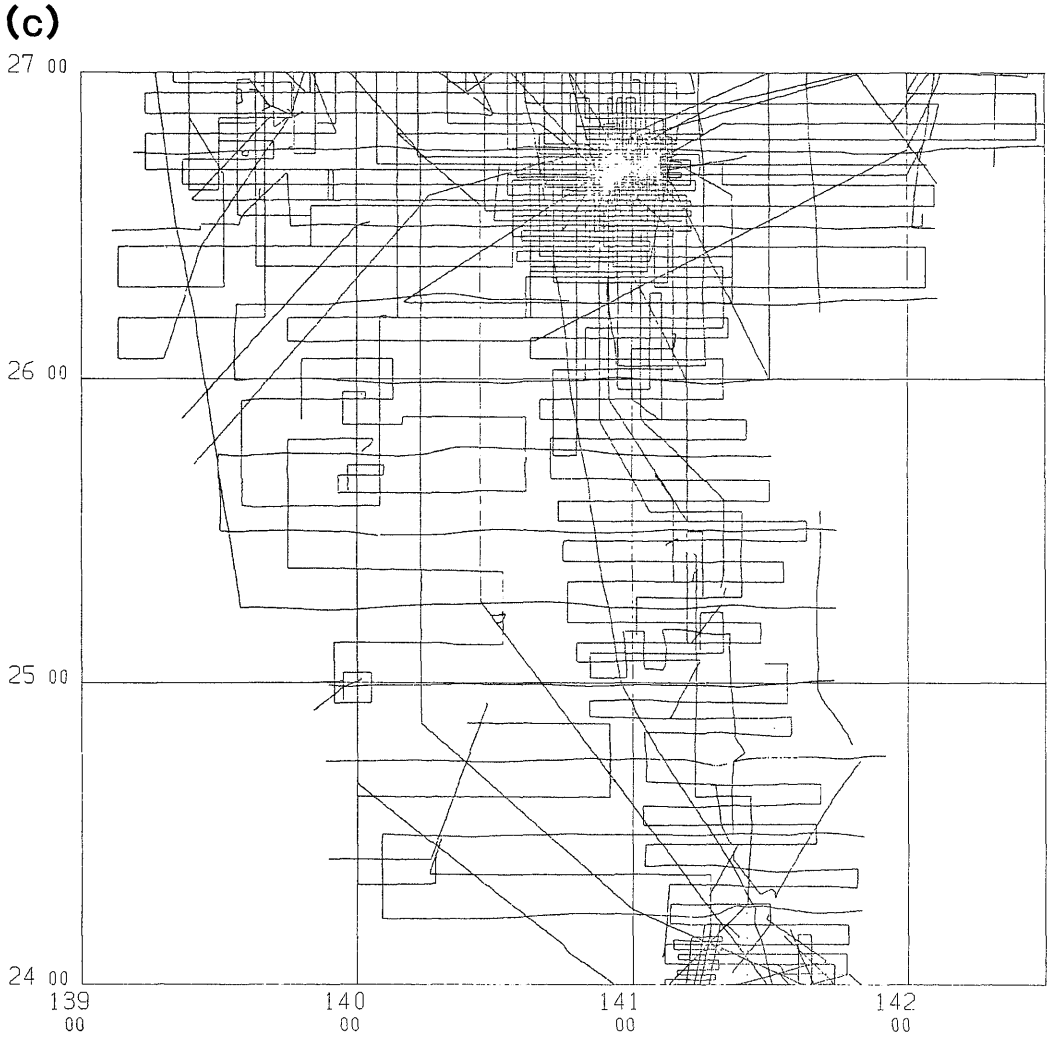

Fig. 7 continued

The Ogasawara Trough (Figs. 3(a) and 7(a)) shows slight negative magnetic anomalies, and no lineations can be recognized (Figs. 3(b) and 7(b)). This is consistent with the consideration that the basement of the Ogasawara Trough is rifted island-arc crust (Abe *et al.*, 1989). On the other hand, Isezaki *et al.* (1989) carried out three-component measurements of the geomagnetic field, and found lineations of north-south strike on the east and vertical components in the Ogasawara Trough. But the origin of the lineations is not clear.

4.4 Ogasawara Plateau and neighboring seamounts

The Ogasawara Plateau and three other seamounts east of it (the Yabe Seamount, the Hanzawa Seamount and the Katayama Seamount) which we studied (Fig. 8(a)) occupy the western end of the Marcus-Wake seamount chain (the Michelson Ridge of Smoot (1983)). The Ogasawara Plateau has collided against the Izu-Ogasawara Arc at the junction between the Izu-Ogasawara and Mariana Trenches.

A belt of negative magnetic anomalies was observed over the three seamounts east of the Ogasawara Plateau (Fig. 8(b)). The amplitude of the anomalies of the Yabe Seamount was about -700 nT, and that of the Hanzawa Seamount and the Katayama Seamount exceeded -1000 nT. The fact that negative magnetic anomalies occur above the bodies of the seamounts indicate that their magnetizations are normal polarity and have shallow inclinations, while too scarce survey lines in the northern and southern vicinity of those seamounts (Fig. 8(c)) prevent from calculating their magnetization more quantitatively by an inversion method. The ages of these seamounts are estimated to be the Cretaceous from the microfossil age of limestone covering the top of the Yabe Seamount (Shiba, 1979). It is thus considered that these seamounts were emplaced in an equatorial region in the Cretaceous, and have been moved to the present position by the northward shift of the Pacific plate since then (e.g. Clague and Jarrard, 1973). In the vicinity of these seamounts, Vacquier and Uyeda (1967) reported another seamount (No. Z-4-3 at 27° N, 148° 40'E) having the magnetization of shallow inclination.

The Ogasawara Plateau has several peaks on it (Fig. 8(a)). The Kita Seamount on the Ogasawara Plateau has dominantly negative anomalies (Fig. 8(b)), which is similar to the seamounts mentioned above. The Higashi Seamount (the Broken-Top Guyot of Smoot (1983)), the Nishi Seamount and the Minami Seamount have, on the other hand, a pair of positive and negative anomalies (positive anomalies are on the southern flanks of the bodies, and vice versa) (Fig. 8(b)). This type of anomaly distribution suggests that the magnetization directions of the seamounts are close to that of the present geomagnetic field there. This implies that these seamounts were magnetized at a place near the present latitude. However, fossil evidence shows that the Higashi Seamount was formed in the Cretaceous in an equatorial region like the Yabe Seamount (Konishi, 1985). One possible explanation for this discrepancy is that induced magnetization and/or viscous magnetization of the present field direction have overcome the primary remanent magnetization of the seamounts which would have been acquired in low latitudes. Another possibility is that these seamounts were remagnetized by rejuvenated volcanic activities of relatively young age, that is, after the directional change of the movement of the Pacific plate from NNW to WNW, which is known to have occurred at about 43 Ma (Clague and Jarrard, 1973). Nemoto *et al.* (1986) suggested the existence of Eocene volcanic activities at the Higashi Seamount.

The stripes of the positive and negative anomalies over the Ogasawara Plateau seems to continue landward across the trench although their amplitudes decrease. This observation suggests that the western flank of the Ogasawara Plateau has been already subducting underneath the forearc wedge of the Izu-Ogasawara Arc.

4.5 Northern Mariana Trough

The Mariana Trough is initiated at about 24°N, just south of Minami-Iwojima Is. (Fig. 9 (a)). It develops from a rifting stage to a spreading stage at about 22°N (Yamazaki *et al.*, 1988b; Murakami *et al.*, 1989). The trough widens southward from 80 to 120 km at this boundary at 22°N, and deepens more than 500m. Small ridges and grabens trending NNW-SSE become conspicuous in the south of the boundary.

The characteristics of magnetic anomaly distribution also vary significantly at this boundary (Fig. 9(b)). In the north of 22°N, dipole-type anomalies or short wave-length anomalies are remarkable, which are of seamount or intrusive origin. No magnetic lineations are observed. The seafloor of this region would consist of stretched and sundered island-arc crust. In the south of 22°N, on the other hand, NNW trending magnetic lineations can be recognized, which would be caused by magnetization of oceanic crust.

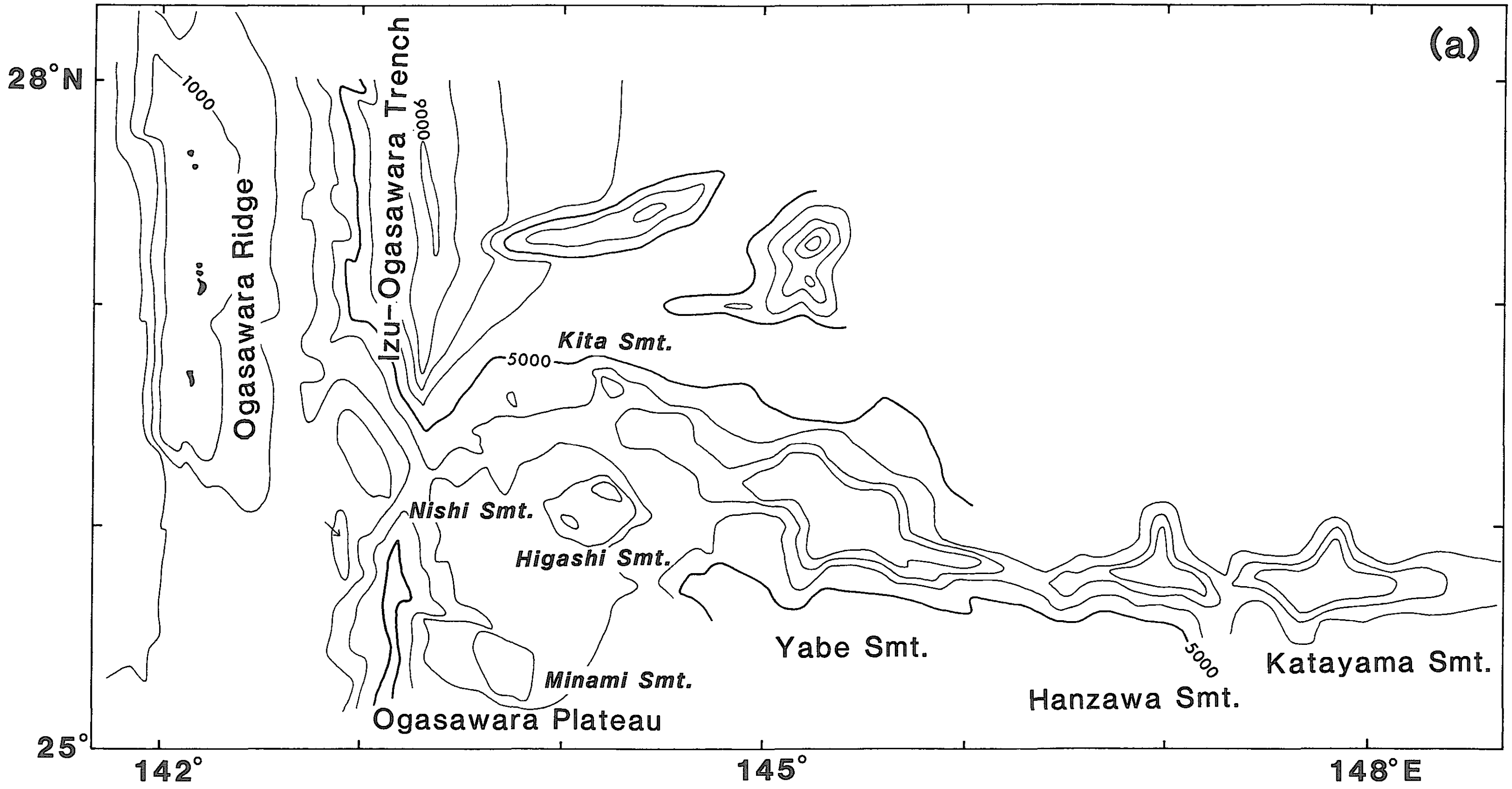

Fig. 8 (a) Outline of topography of the Ogasawara Plateau and neighboring seamounts. Contours are at 1000 m intervals. (b) Magnetic anomalies in the same area. Contours are at 100 nT intervals. Positive anomalies are shaded. (c) Survey lines of the magnetic anomalies.

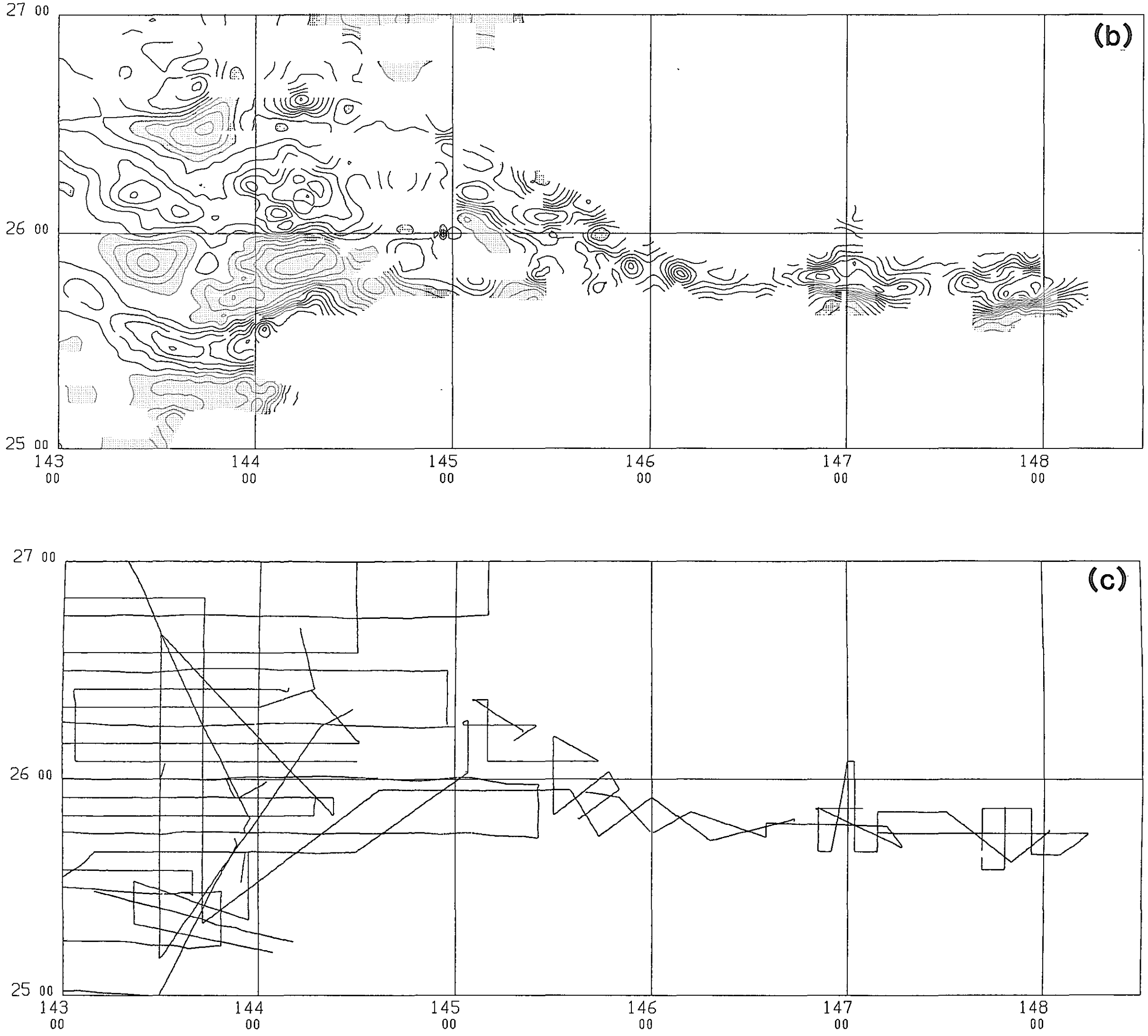

Fig. 8 continued

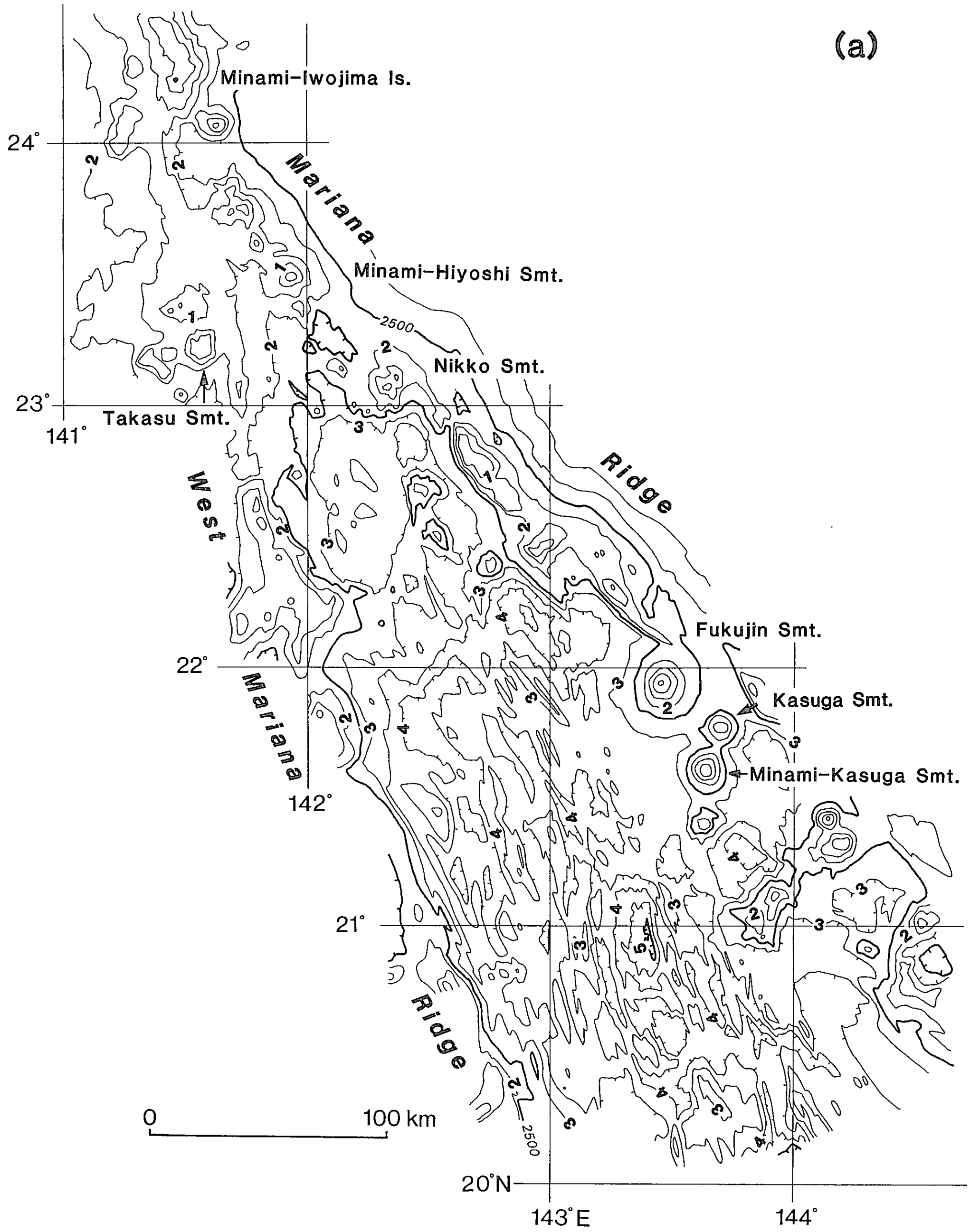

Fig. 9 (a) Outline of topography in the northern Mariana Trough from 20° to 24°N. Contours are at 500m intervals. Unit of the figures is 1000m. (b) Magnetic anomalies in the same area. Contours are at 100 nT intervals. Positive anomalies are shaded. (c) Survey lines of the magnetic anomalies.

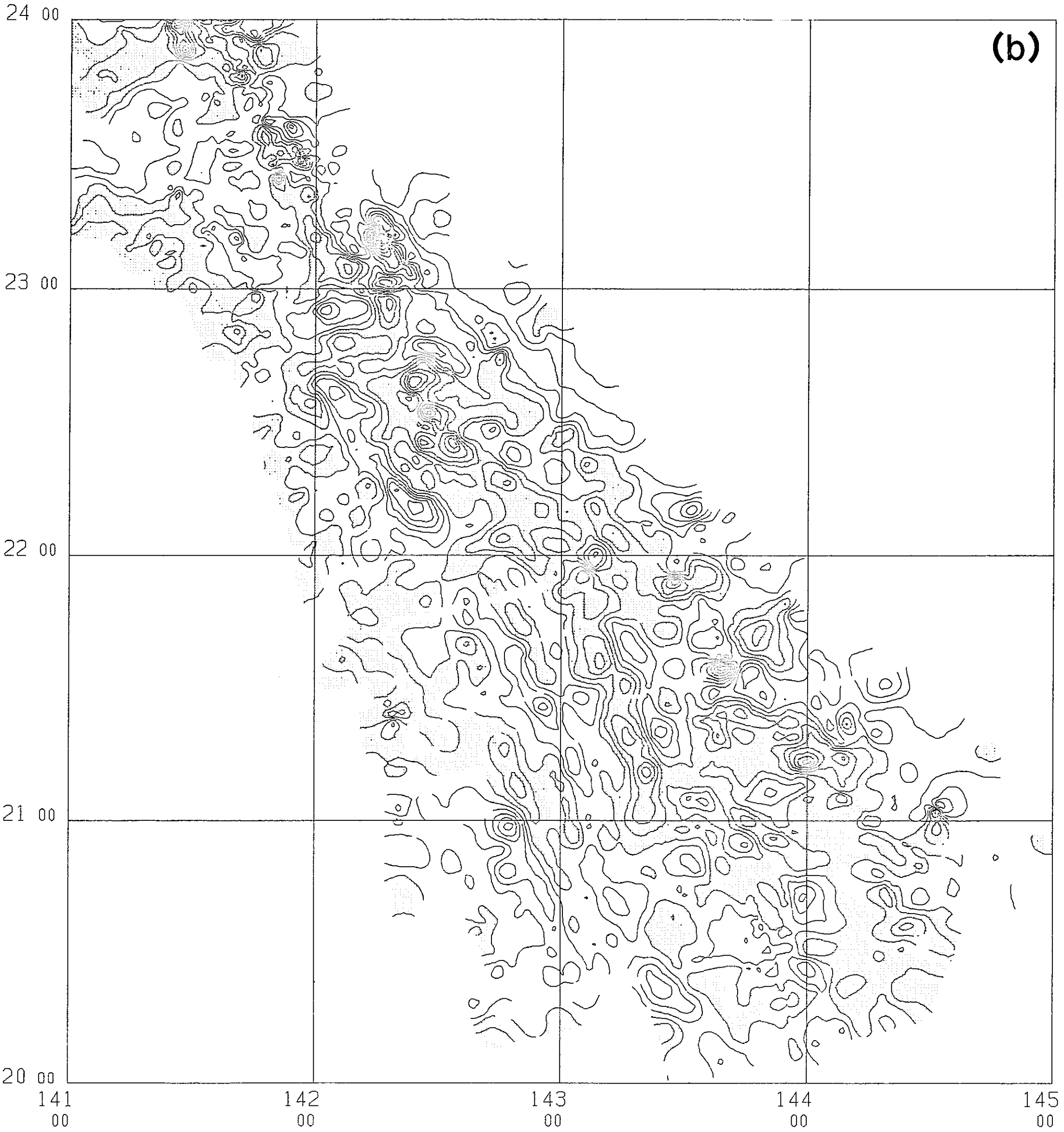

Fig. 9 continued

Correlation is obvious on the magnetic anomaly profiles along the survey lines (Fig. 10(a)), particularly between 21° and 22°N.

4.5.1 *Identification of magnetic lineations*

To assign ages to the magnetic lineations, we performed forward modeling by a two-dimensional block model. The model shown in Fig. 11 fits well the anomaly profiles between 21° and 22°N. We adopted the skewness parameter of -58°, which is derived on the assumption that two-dimensional blocks having N20°W strike were magnetized at the present latitude. We thus considered that the formation of oceanic crust between 22° and 21°N would have started at 3 Ma or a little earlier with a half-spreading rate of about 2.5

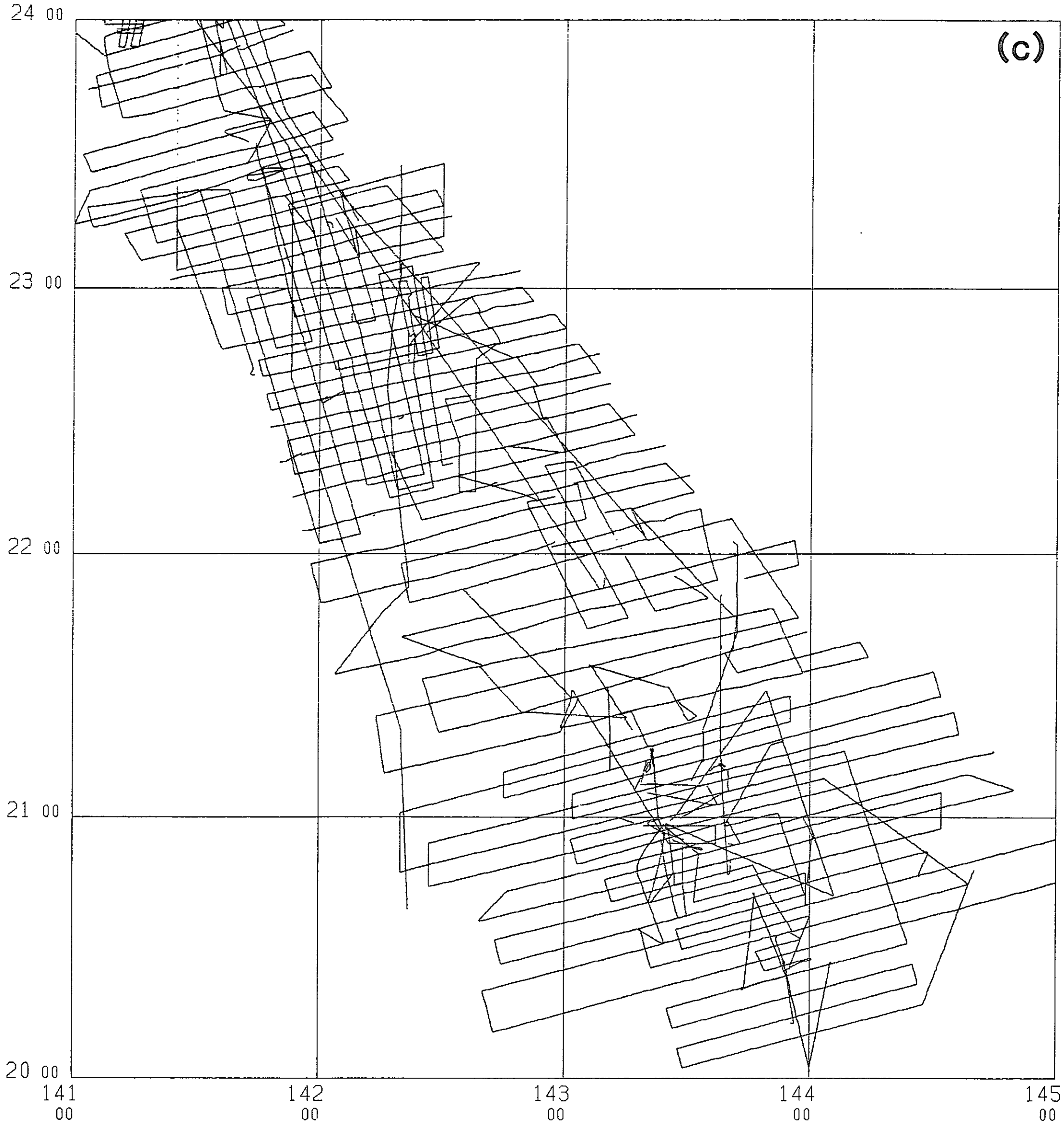

Fig. 9 continued

cm/year. The rate would have decreased to about 1 cm/year at present. The present spreading rate at the northern end of the spreading axis close to 22°N is estimated to be a little faster, about 2 cm/year. The topography of the spreading axis supports this interpretation. The rift valley on the spreading axis becomes less remarkable northward on the topographic profiles shown in Fig. 10(b), which suggests that spreading rate becomes higher northward (Macdonald, 1986).

The correlation between the model and the observation on the eastern flank of the spreading center is not good because the magnetic lineations are disturbed by the anomalies accompanied by seamounts (Figs. 9 (b) and 10 (a)). They are the Fukujin Seamount and a chain of submarine volcanoes

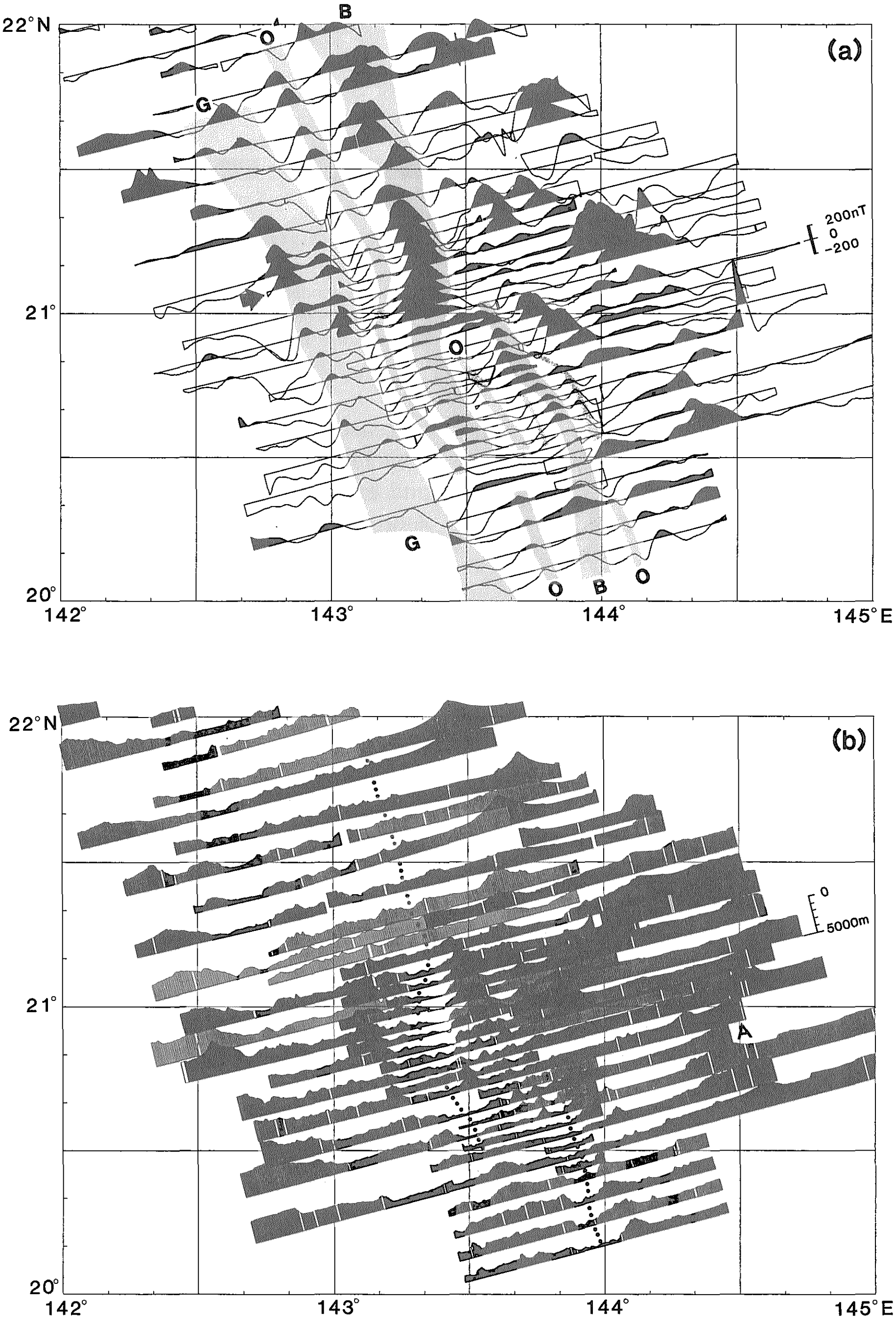

Fig. 10 (a) Magnetic anomaly profiles along the survey lines of ENE-SWS direction in the Mariana Trough from 20° to 22°N. Solids are positive anomalies and opens are negative. Interpretation is superimposed: shaded belts represent the magnetization of the normal polarity. B: the Brunhes Epoch (0 - 0.73 Ma; Harland *et al.* (1982)), O: the Olduvai Event (1.67 - 1.87 Ma), G: the Gauss Epoch (2.48 - 3.40 Ma). (b) Topographic profiles along the same lines. Dots indicate the location of spreading centers estimated from the magnetic lineations. Line A is the location of the seismic reflection profile shown in Fig. 13.

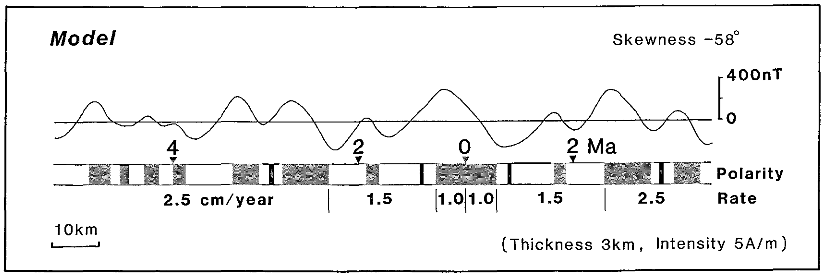

Fig. 11 Magnetic anomalies produced by a two-dimensional block model. Spreading rates were adjusted so that the theoretical anomaly profile fits the observed ones around 21° 30'N in the Mariana Trough. Solid blocks represent the normal polarity and open ones are reversed. The magnetic polarity time scale of Harland *et al.* (1982) was used.

lineated southwestward from the Kasuga Seamount (Cross-chain seamounts; Hussong and Fryer, 1983) (Fig. 9(a)), which were emplaced after the formation of oceanic crust.

4.5.2 *Overlapping spreading centers at 21°N*

Our interpretation of magnetic anomaly profiles leads to the conclusion that two spreading centers overlap from 20° 30' to 21°N (Fig. 10(a)). The characteristic anomaly pattern which has been recognized on the profiles north of 22°N continues southward to about 20° 30'N, although the amplitudes of the anomalies become small, an order of about 100 nT. To the east of it, on the other hand, another identical anomaly pattern runs parallels to the former from 20° 30° to 21°N. The latter continues southward to 20°N, where axial valleys of the Mid-Atlantic Ridge (MAR) type can be seen on topographic profiles (Fig. 10(b)). Between the two spreading axes, an anomalously deep graben occurs (Figs. 9(a) and 10(b)). The depth reaches 5300m at maximum. This situation, that is, two spreading axes and an intervening graben, is similar to the Overlapping Spreading Centers (OSCs) which has been observed commonly on the East Pacific Rise (EPR) as a form of non-transform offsets of mid-oceanic ridges (Macdonald and Fox, 1983; Lonsdale, 1983). The graben at 21°N would correspond to the Overlap Basin, which is a basic constituent of OSCs (Macdonald *et al.*, 1988). The depth of the spreading centers in the Mariana Trough increases toward the OSCs at 21° N (Fig. 12). This feature is similar to the OSCs on the EPR, and explained by that the amount of magma supply is small at OSCs (Macdonald *et al.*, 1988).

We estimate from seismic reflection profiles that the spreading at the western axis would have been subsiding now, and in the east of it, a new spreading system is instead under developing with destroying older oceanic crusts. A seismic reflection profile shown in Fig. 13 shows that the western spreading axis accompanies a typical rift valley. The eastern axis is, on the other hand, more complicated in geological structure. Many faulted blocks exist there, but no clear rift valley.

The OSCs found at 21°N in the Mariana Trough is anomalous in the following points compared with already documented OSCs. First, the size is large. The OSCs at 21°N offset about 30 km and overlap each other by about 50 km. It is known, however, the lateral offsets of the OSCs on the EPR are less than 15 km (Macdonald and Fox, 1983, Macdonald *et al.*, 1988). Second, OSCs were commonly observed on fast-spreading ridges such as the EPR, but never on slow-spreading ridges like the MAR (Macdonald and Fox, 1983). The spreading rate of the Mariana Trough is nearly as small as that of the MAR. A spreading center-transform fault pattern prevails in the case that an offset of ridges is large or a spreading rate is small. This is because spreading axes are in contact with

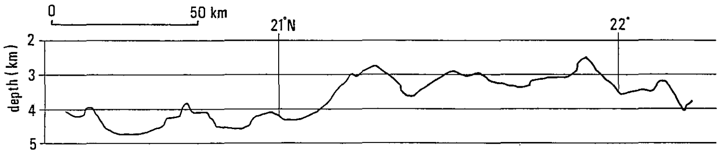

Fig. 12 Axial depth profile along spreading centers in the northern Mariana Trough.

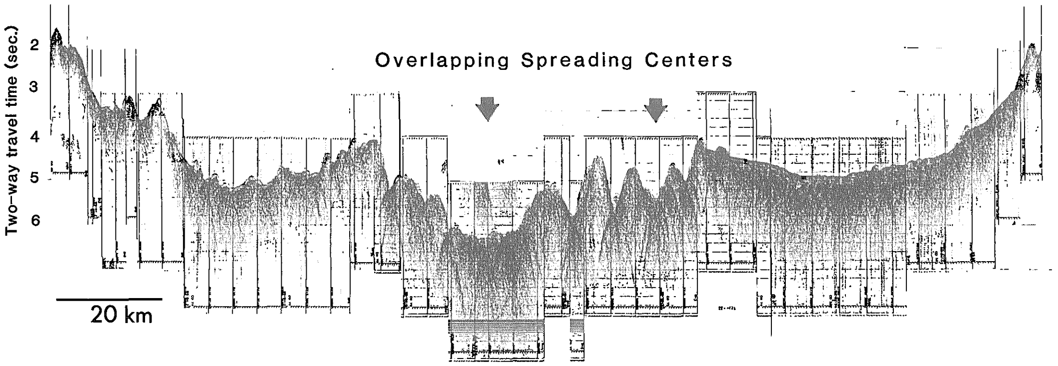

Fig. 13 Single-channel seismic profile across the overlapping spreading centers in the Mariana Trough. Positions of the spreading centers indicated by arrows were estimated from magnetic lineations. Location of this profile is shown in Fig. 10.

cooler and thicker crusts than in the case of a small offset or a fast spreading rate, and thus the crusts would not be weak enough to allow non-rigid deformation like the OSCs. It is hence suggested that the crust of the Mariana Trough spreading center may be weaker (thinner and/or hotter) than those of major-ocean spreading centers. The third point is that the magnetic anomalies of the Mariana Trough at 21°N are smaller than those of neighboring areas while the OSCs in the EPR have stronger magnetic anomalies (Lonsdale, 1983; Sempere *et al.*, 1984). It is considered that high magnetization intensity which is carried by highly fractionated basalts enriched in iron is responsible for the strong magnetic anomalies of the OSCs on the EPR (Sempere *et al.*, 1984;1988). The weak anomalies at 21° N in the Mariana Trough suggests that the iron enrichment may not have occurred there.

4.5.3 *Mariana Ridge and West Mariana Ridge*

Next we discuss the magnetic anomalies accompanied by a row of Quaternary arc volcanoes on the Mariana Ridge. Some of them have simple dipole-type anomalies, but others have complicated anomaly distributions which do not correspond well to the topography of the seamounts (Fig. 9(b)). The former examples are the Fukujin Seamount and the Minami-Kasuga Seamount, and the latter the Nikko Seamount and the Minami-Hiyoshi Seamount. This difference would reflect difference in the ages of these seamounts. The latter would have had longer volcanic activity than the former, resulting in highly inhomogeneous magnetization. Magnetization of normal and reversed polarities may be mixed. Topography of these seamount supports this inference;the former has a simple conical shape, but the latter shows complex topography having two or more peaks. On the Fukujin Seamount, the spread of the anomalies is narrow compared with the size of the seamount body. It is thus suggested that the seamount would be covered with thick volcaniclastic debris, and highly magnetized part is relatively small in volume.

The West Mariana Ridge, the remnant arc, does not have strong magnetic anomalies in general (Fig. 9(a)). The Takasu Seamount, in particular, accompanies little anomalies although it has a flat top of very shallow depth, about 50m. This suggests that the Takasu Seamount would not be a volcano. An unnamed small peak at about 21°20'N showed the anomaly pattern which indicates reversed magnetization.

4.6 Spreading axis at 18°N in the Mariana Trough

The Mariana Trough is widest at about 18° N, and the occurrence of active spreading ridges is well documented (e.g. Fryer and Hussong, 1981). Thus the existence of the magnetic anomalies of seafloor-spreading origin is expected. While magnetic lineations are vague on an anomaly contour map (Fig. 14 (b)) due to the low amplitude of the anomalies (200 nT or less), anomaly profiles along main survey lines can be correlated each other (Fig. 15). Spreading rate estimated from comparing the profiles with the model in Fig. 11 varies somewhat from place to place, but it is an order of 2 cm/year. This agrees with the previous estimations by Bibee *et al.* (1980) and Hussong and Uyeda (1982). Discontinuities in magnetic lineations can be recognized at 17° 40'N, 18°N and 18° 20'N (Fig. 15). They roughly coincide with topographic and structural discontinuities, that is, the Pagan fracture zone between 17°30' and 17° 40'N, the 17.9° N offset and the 18.5°N offset of Volpe *et al.* (1990), respectively. The trend of the magnetic lineation between 18° and 18°20'N is close to north-south (Fig. 15) although the strike of

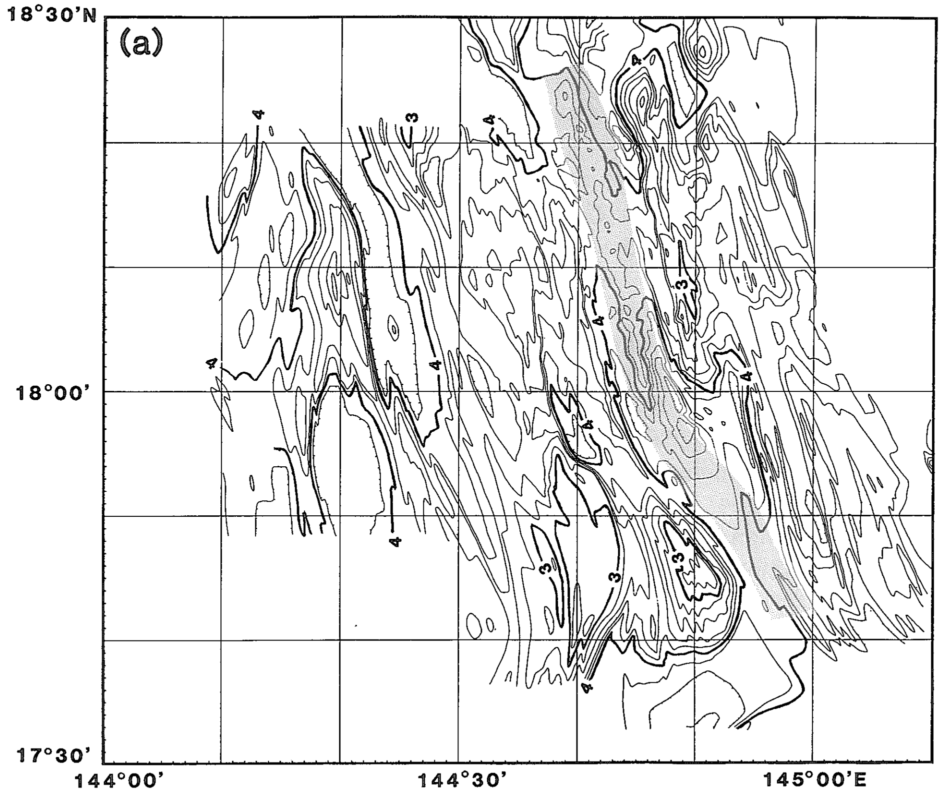

Fig. 14 (a) Bathymetric contour map around a spreading axis (shaded) at 18°N in the Mariana Trough. Contours are at 200m intervals. (b) Magnetic anomalies in the same area. Contours are at 100 nT intervals. Positive anomalies are shaded. (c) Survey lines of the magnetic anomalies.

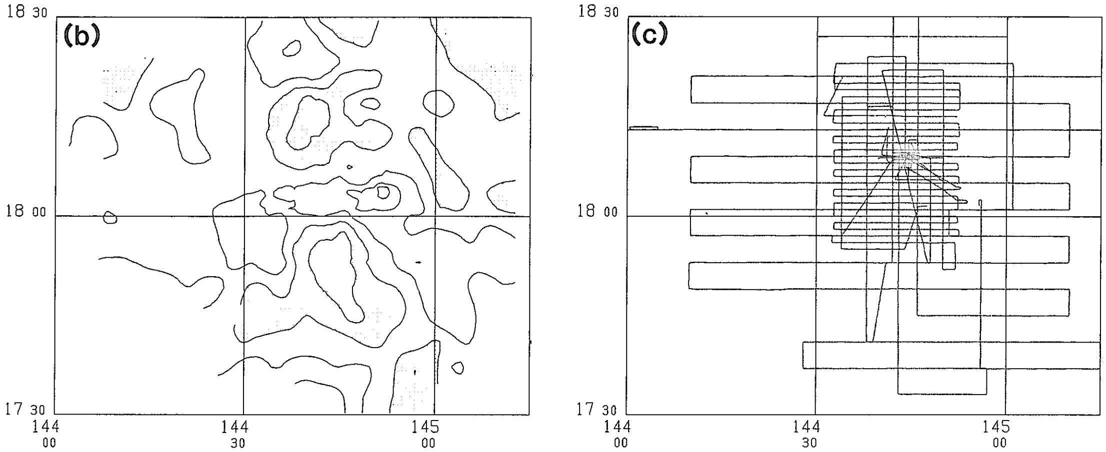

Fig. 14 continued

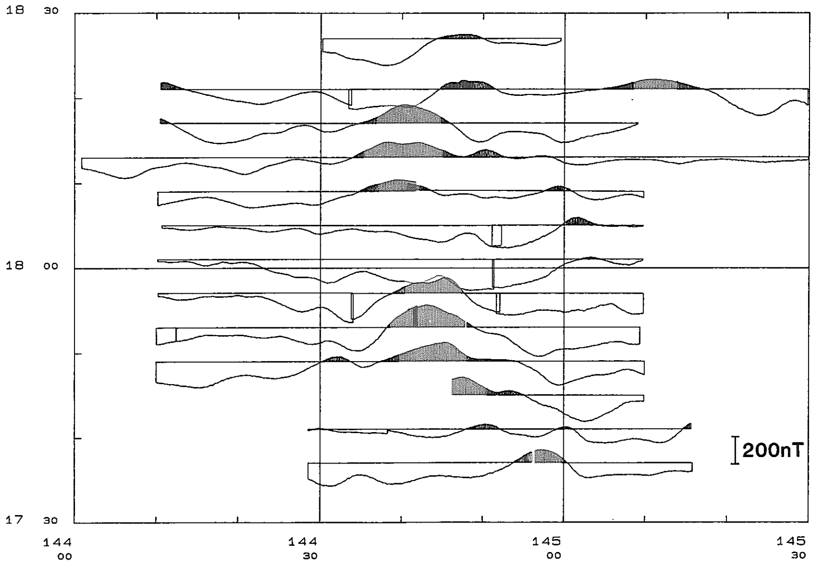

Fig. 15 Magnetic anomaly profiles along main survey lines around a spreading axis at 18°N in the Mariana Trough. Solids are positive anomalies and opens are negative.

the rift valley is NNW (Fig. 14(a)). This suggests that a small change in spreading direction and accompanying reorganization of normal faults would have occurred recently, say an order of 100 k.y. before.

5. Conclusions

We conducted magnetic survey on the Izu-Ogasawara Arc and the northern Mariana Trough along dense ship tracks. Geological interpretation of the resulting magnetic anomaly distribution are summarized as follows.

(1) Volcanoes on the Shichito Ridge, the volcanic front of the Izu-Ogasawara Arc, have usually strong magnetization probably owned by basaltic rocks. Some volcanoes (e.g. the

Nishinoshima Volcano) has rather simple dipole-type anomalies, but others have very complicated anomaly distribution (e.g. the Iwojima Volcano), which may reflect the difference in the length of the volcanic activity.

(2) On the northern part of the Shichito Ridge, some volcanoes accompanies only weak magnetic anomalies (e.g. the Myojin Knoll), which suggests their composition being acidic rocks such as dacite. This reflects the bimodal volcanism in this region.

(3) Back-arc rifts in the northern Izu-Ogasawara Arc show no remarkable magnetic anomalies except for cross-chain seamounts in the Sumisu Rift. Seafloor spreading has not started yet.

(4) The Shichiyo Seamount Chain and neighboring seamounts in the middle Izu-Ogasawara Arc can be divided into three groups based on their magnetic anomalies. The first group is Quaternary volcanoes, which have strong dipole-type anomalies of the normal polarity. The second is faulted blocks of old island-arc crusts, accompanying little anomalies. The third is old volcanoes of possibly Oligocene age, which have the magnetization of eastward declination and shallow inclination.

(5) Fore-arc basement highs of Paleogene or Miocene age (the Shinkurose Ridge) are characterized by broad positive magnetic anomalies. Similar anomalies are observed on the Tenpo Seamount, an old basement high lying in the back-arc region west of the Sofugan Tectonic Line.

(6) In the back-arc region north of 30°N, topographic highs striking obliquely to the arc (the Nishi-Shichito Ridge) have relatively simple magnetic anomalies of normal polarity. Topographically smooth area around 28°N has relatively large anomalies caused by deeper source. In the back-arc between 24° to 27°N, alternating belts of positive and negative anomalies run in NNE-SSW direction. This may reflect a relief of the basement, or suggest the possible existence of oceanic crust underneath thick sedimentary cover.

(7) Four peaks on the Ogasawara Plateau and three other seamounts in the east of it can be divided into two groups from magnetic anomalies. The first group having dominantly negative anomalies was magnetized in an equatorial region probably in the Cretaceous. The second group shows the magnetization close to the present geomagnetic field direction, suggesting induced and/or viscous magnetization or remagnetization by rejuvenated volcanism.

(8) We show for the first time that magnetic anomaly profiles in the Mariana Trough south of 22°N can be correlated clearly. A forward modeling indicates that the seafloor spreading around 21° 30'N started at 3 Ma or a little earlier at a half spreading rate of 2.5 cm/year. The rate has decreased to about 1 cm/year.

(9) Spreading axes overlap about 50 km in the Mariana Trough between 20° 30' and 21°N. Previously the existence of OSCs was not known on slowly spreading ridges. Furthermore, the offset of the two axes, about 30 km, is much larger than that of the already documented OSCs on the East Pacific Rise. The crust at the OSCs in the Mariana Trough may be hotter and/or thinner than that of the major ocean.

(10) Some seamounts on the northern Mariana Ridge have simple dipole-type anomalies (e.g. the Fukujin Seamount), but others show complicated anomaly patterns which poorly correspond to their topography (e.g. the Nikko Seamount). This would reflect difference in the length of the volcanic activity. The northern part of the West Mariana Ridge, the remnant arc, accompanies no strong anomalies in general (e.g. the Takasu Seamount).

(11) The spreading rate at the ridges at 18°N in the Mariana Trough is about 2 cm/year at present. A small change in spreading direction from E-W to ENE-WSW would have occurred recently.

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伊豆・小笠原弧，マリアナ弧及びマリアナトラフの磁気異常

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要　旨

伊豆・小笠原弧，マリアナ弧，マリアナトラフ及び小笠原海台とその付近の海山について，磁気異常の測定を行った．測線間隔は一般に2－4マイルと密である．

七島海嶺及びマリアナ海嶺(伊豆・小笠原弧，マリアナ弧の火山フロント)上の海底火山の大部分は強い磁気異常を示す．このうちいくつかの火山は比較的単純なダイポール型の異常を示すが(例えば，西之島火山や福神海山)，他方では，非常に複雑な異常分布を示すもの(例，硫黄島火山)や，火山体の地形と異常との対応の悪いもの(例，日光海山，鳥島火山)が見られる．このような磁気的な均質性の差は，火山活動の長さの差を反映していると推定される．さらに，七島海嶺北部の火山に見られる不均質な磁化は，バイモーダルな火山活動が影響していると考えられる．

磁気異常は海山の起源を推定するのに役立つ．伊豆・小笠原弧中部の孀婦岩と西之島の間に分布する海山(七曜海山列，大町海山，沢海山，天保海山など)は，磁気異常から次の4つのグループに分類できる．第一は，強いダイポール型の異常を持つ第四紀火山，第二は，ほとんど磁気異常を伴わない，断層で切られた島弧地殻の断片，第三は，東向きの偏角と浅い伏角の帯磁を持つ，漸新世の年代と推定される古い火山である．第四のタイプは大町海山と天保海山で見られる，やや長波長の正異常であり，同様の異常が，伊豆小笠原弧北部の前弧に発達する，古第三紀あるいは中新世の年代と考えられる基盤の高まり(いわゆる新黒瀬海嶺)に対応して分布することから，これらの海山は古い基盤の高まりと推定される．

マリアナトラフの北緯20度から22度にかけて，海洋底拡大に伴う明瞭な磁気縞模様が存在することを初めて明らかにした．北緯21度30分付近では，海洋底拡大は3Maあるいはそれより少し早い時期に，片側拡大速度約2.5cm/年で開始した．現在では拡大速度は1cm/年に減少している．北緯20度30分から21度にかけて，拡大軸が約30kmの間隔をもって重複している．このような大規模な重複拡大軸の存在は拡大速度の遅い海底拡大系では異例であり，ここの地殻の強度が通常の海底拡大系のそれより小さい，すなわち厚さが薄い，または高温であることを示唆している．

白亜紀に形成されたと考えられている小笠原海台上の4つのピーク及びその東の3つの海山は，磁気異常より2つに区分できる．第一のグループは山体上に負の異常を伴い，白亜紀に赤道域で磁化したと推定される．第二のグループは現在の地球磁場の方向に近い帯磁を持ち，誘導磁化あるいは粘性磁化が卓越している，又は比較的新しい時期に再び起こった火山活動により再磁化したと推定される．

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