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Submarine topography of seamounts on the volcanic front of the Izu-Ogasawara (Bonin) Arc

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Abstract : Geomorphology of submarine volcanoes along the volcanic front (Shichito-Iwojima Ridge) of the Izu-Ogasawara Arc was studied based on the results obtained during marine geologic researches by Geological Survey of Japan.

Morphology of the volcanic edifices on the Shichito-Iwojima Ridge shows regularity for the height, basal diameter and spacing of them between the northern and southern parts of the Shichito-Iwojima Ridge, respectively. They are summarized as follows:

	Northern part	Southern part
Height	low	high
Elevation	decrease to south	decrease to north
Spacing	narrow (irregular)	wide (constant)
Height of basement	decrease to south	decrease to north
Basal diameter	small	large
Submarine caldera	abundant	few

The different regularity of each part is resulted originally from the different crustal thickness between them and their independency of each other in their development history. The irregularity of spacing found in the northern part seems to be caused by the structural discontinuity in the arc. The seamounts in the Nishinoshima Trough make an independent group and are subdivided into three types based on the topographic and seismic profiling features.

Existence of submarine calderas producing acidic volcanics is a special feature in the northern part of the Shichito-Iwojima Ridge. These calderas are presumed to be submarine pumice cones based on their morphologic and geophysical features. Pumice cone is difficult to be formed under the subaerial condition but easy under the subaqueous situation.

1. Introduction

Izu-Ogasawara (Bonin) Arc is one of the arc-trench systems in the western Pacific and is situated along the eastern edge of the Philippine Sea Plate. The size of the whole arc including submarine parts is about 1200 km long from Oshima to Minami-Iwojima islands and 400 km wide, being comparable with the Honshu Arc of Japan. From west to east, the arc consists of the Nishi-shichito,

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Keywords : submarine topography, seamount, submarine volcano, height, basal diameter, spacing, submarine caldera, pumice cone, Nishinoshima Trough, Shichiyo Seamount Group, Sofugan Tectonic Line, Izu-Ogasawara (Bonin) Arc, Shichi-to-Iwojima Ridge, along arc variation

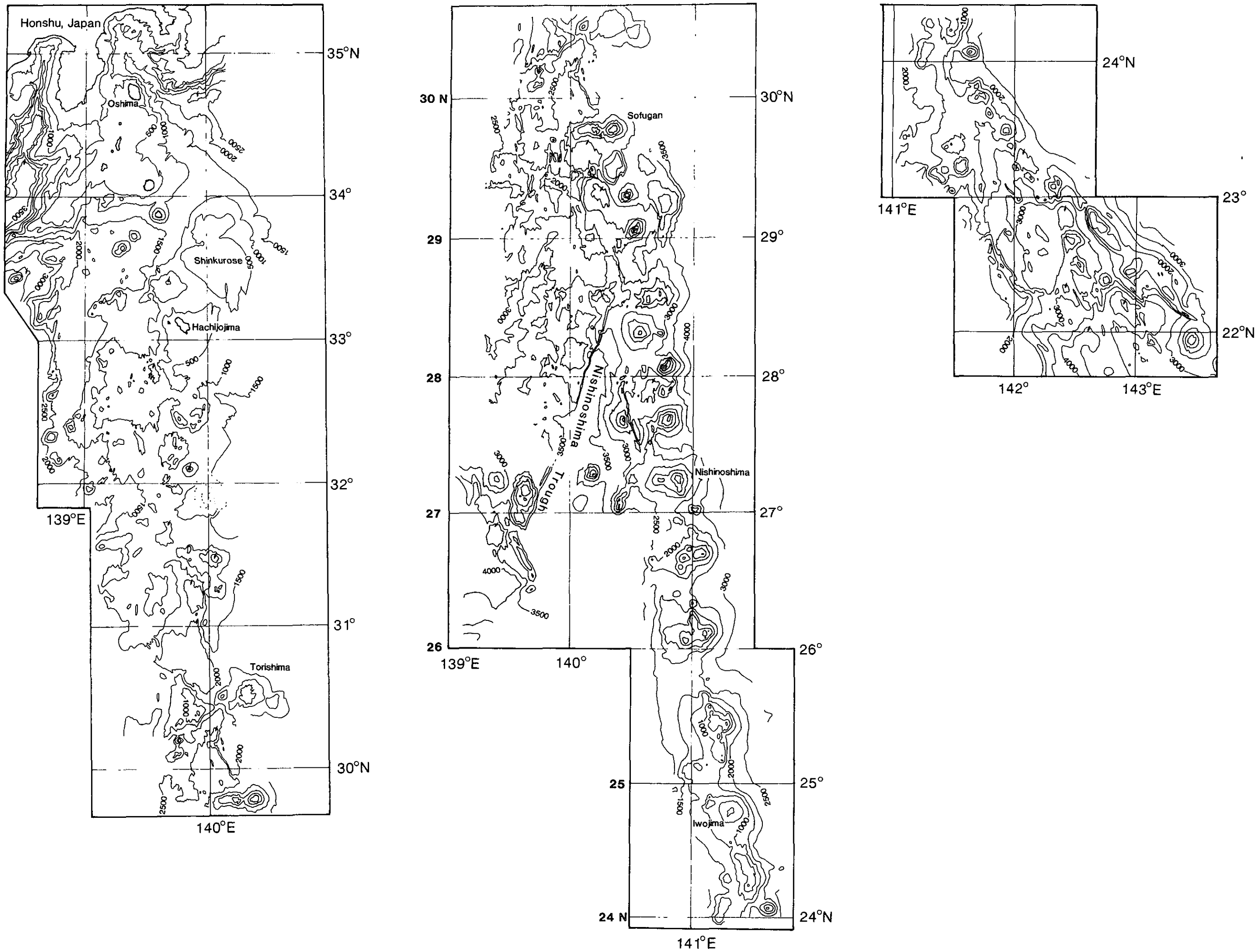


Fig. 1 Submarine topography of the Shichito-Iwojima Ridge. The depth contours (500 m) reproduced from submarine topographic maps of the Hydrographic Department of the Maritime Safety Agency of Japan (the area north of Hachijojima Island) and Geological Survey of Japan (the area south of the island).

Table 1 List of volcanoes along the Shichito-Iwojima Ridge.
Elevation shows height above or depth below the sea level. Height, N-S and E-W diameters are measured on the basis of transitional point on the slope of volcanic edifice. Volcano spacing is shown by the interval from center to center between a given volcano and its neighboring (lower) one.

Island / seamount	latitude	Elevation	Height	Basal diameter		Spacing	Canyon / Trough
		m	m	(N-S)km	(E-W)km	km	
Hakone*		1438				76	Sagami Trough
Oshima*	34.44	755	1955	28	26	25	
Omurodashi	34.33	-28	872	26	20	48	Niijima Canyon
Miyakejima*	34.05	814	2014	41	24	25	
Mikurajima	33.52	851	2051	22	18.5	53	Minami-mikura Canyon
Kurose*	33.24	-114	1286	31.5	28	35	
Hachijojima*	33.08	854	2052	41	33	74	Aogashima Canyon
Aogashima*	32.27	423	1723	35	33	39	
Myojin Knoll*	32.06	-451	950	22	18.5	22	
Bayonnaise Rocks*	31.53	10	1410	28	31.5	58	Myojinsho Canyon
Sumisujima*	31.26	136	935	22	22	20	
Daisan-Sumisu Knoll*	31.16	-350	850	16.5	18.5	90	
Torishima*	30.29	394	1794	31.5	31.5	74	Sofu Canyon
Sofugan	29.47	99	2350	30	28	33	
Nichiyo Seamount	29.30	-1150	1650	31.5	24	22	
Getsuyo Seamount	29.18	-625	2675	22	28	28	
Kayo Seamount	29.03	-820	2680	27	21	56	
Suiyo Seamount	28.34	-1418	1380	15	31.5	30	Nishinoshima Trough
Mokuyo Seamount*	28.18	-920	1780	35	39	33	
Kin'yo Seamount	28.03	-640	2660	26	28	39	
Doyo Seamount	27.40	-860	2340	28	26	48	
Nishinoshima	27.14	38	2538	54	44.5	65	
Kaikata Seamount*	26.42	-150	2350	52	44.5	67	
Kaitoku Seamount	26.06	-10	2485	55.5	52	78	Iwojima Trough
Kita-iwojima	25.25	792	3282	70	55.5	71	
Iwojima	24.48	161	2161	48	52	64	
Minami-iwojima	24.13	916	2916	55.5	30	24	
Fukutoku Seamount	24.04	-201	2100	20	20	37	
Kita-hiyoshi Seamount	23.44	-214	1986	31.5	28	42	
Minami-hiyoshi Smt	23.30	-30	2470	37	30	60	
Nikko Seamount	23.05	-391	2909	41	26	178	
Fukujin Seamount	21.56	-217	2833	41	48		
Ohmachi Seamount	29.13	-1700	1750	59	31.5		
Sawa Seamount	27.41	-690	2800	72	26		
*: accompaning with caldera							

Shichito-Iwojima and Ogasawara (or Bonin) ridges. Subaerial parts of the Shichito-Iwojima Ridge are recognized as a chain of many volcanic islands from Oshima to Minami-iwojima islands. The ridge corresponds to the volcanic front of the Izu-Ogasawara Arc and continues to the Mariana Ridge with a chain of active submarine volcanoes like Minami-hiyoshi, Nikko seamounts, etc. These volcanic islands and submarine volcanoes run parallel to the Ogasawara Trench. Geomorphologic outlines of these volcanoes are shown in Fig.1. Some quantitative topographic properties of volcanic islands including their subaqueous parts and seamounts on the Shichito-Iwojima Ridge are listed in Table1. Definition of terms used here are shown in Fig. 2. Several seamounts located between Sofugan and Nishinoshima islands are not regarded as Quaternary volcanoes on the basis of the characteristic features of seismic profiles and bathymetric map as mentioned later. In the table, however, these older seamounts are also listed for reference.

Seismic profiles by single channel air-gun and submarine topographic data compiled from 12 kHz PDR, which are used in this paper are all obtained during the 1980 and 1984 to 1987 R/V Hakurei-maru cruises on the marine geologic research for hydrothermal activity in the Izu-Ogasawara region by Geological Survey of Japan.

2. Description of seamounts

There are thirteen volcanic islands and fifteen major seamounts on the volcanic front (Shichito-Iwojima Ridge) of the Izu-Ogasawara Arc. Of these islands, Bayonnaise Rocks, Sumisujima, Torishima, Nishinoshima, Kita-iwojima, Iwojima and Minami-iwojima islands form a part of individual seamount, respectively. Such seamounts including each island as a peak on them are described here in addition to other usual seamounts. However, the islands corresponding to only one major peak of a volcanic edifice (e.g., Oshima, Miyakejima islands, etc.) are excluded in the description because they have been previously studied in detail. In the following descriptions are made for 1) submarine calderas which characterize most of the seamounts in the northern part, 2) seamounts in the Nishinoshima Trough, and 3) seamounts between Nishinoshima and Minami-iwojima islands.

2.1 Submarine calderas

Nine submarine calderas are recognized in the Shichito-Iwojima Ridge. Myojinsho and Sumisu calderas are accompanied with recent volcanic events (Morimoto and Ossaka, 1955, 1970; Kuno, 1962). Eight of the calderas are in the northern part of the ridge and they are all accompanied with acid volcanics. High appearance rate of caldera is characteristic of the area. On the other hand, in the southern part of the ridge there is only one caldera, Kaikata Caldera, which consists of andesitic volcanic rocks with basaltic central cone. No acid rocks are found in this caldera.

2.1.1 Kurose Hole

Kurose Hole is located at lat.33°24'N, long. 139°41'E on the Kurose Bank, 30 km north of Hachijojima Island (Figs. 3 and 4). The summit of Kurose Bank is 107 m below the sea level. This caldera was previously mapped by Hydrographic Department in 1979 (Oshima *et al.*, 1981). The Kurose Hole is a nearly circular caldera of about 5-7 km diameter. The caldera floor is 2 km across and 600-700 m depth. The floor inclines to north and the maximum depth of the floor is about 760 m. Relief of the caldera wall is about 500 m and inclination of the wall is 14-20°. The somma is flat-topped, shallower than 200 m depth. Northern part of the somma increases its depth to about 300 m and a canyon-like feature is developed here.

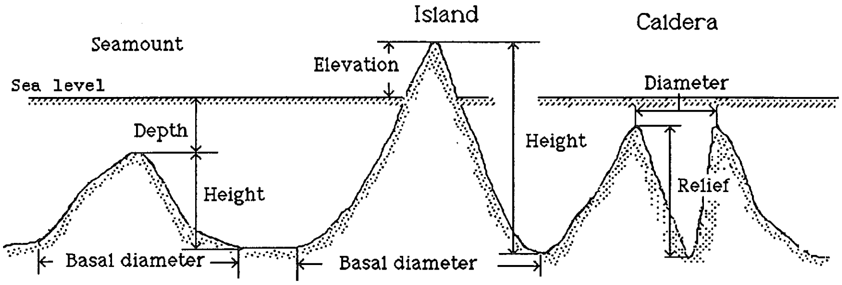


Fig. 2 Definition of topographic terms for volcanic edifice.

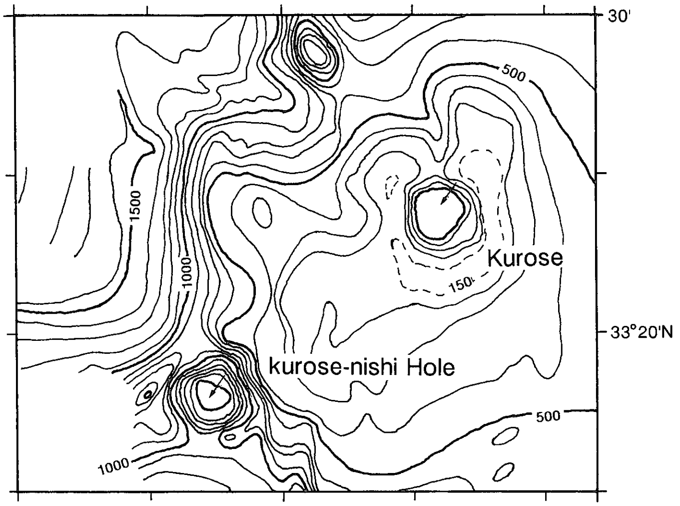


Fig. 3 Submarine topographic map of Kurose and Kurose-nishi Hole (after Saito *et al.*, 1988). Contour interval 100 m.

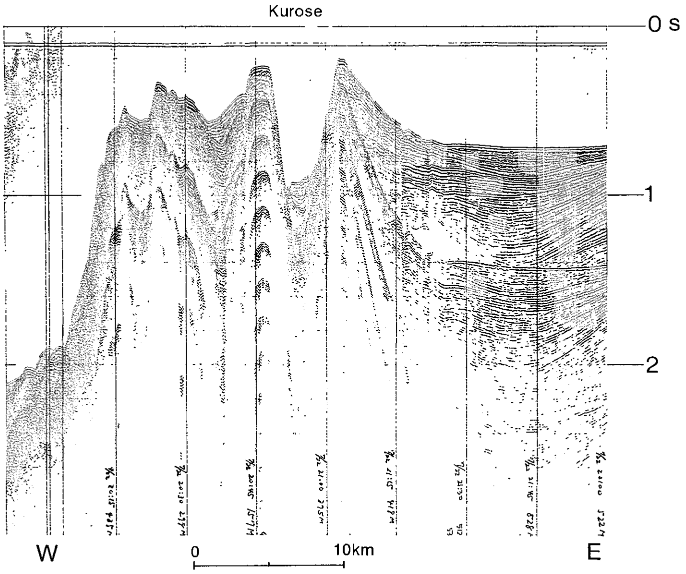


Fig. 4 Single channel air-gun reflection profile across the Kurose Caldera west to east obtained by GSJ, GH 80-4 Cruise.

High free-air gravity anomaly is observed on the caldera, though the central part is lower in anomaly than the surroundings. No remarkable magnetic anomaly is recognized in this caldera.

2.1.2 Kurose-nishi Hole

Kurose-nishi Hole is located at lat.33°18'N, long.139°33'E, 20 km southwest of Kurose Hole (Figs. 3 and 5). The diameter of caldera rim is about 5-6 km. The shallowest part of the rim is about 400 m depth. The floor is as deep as 1500 m, but its precise topographic feature

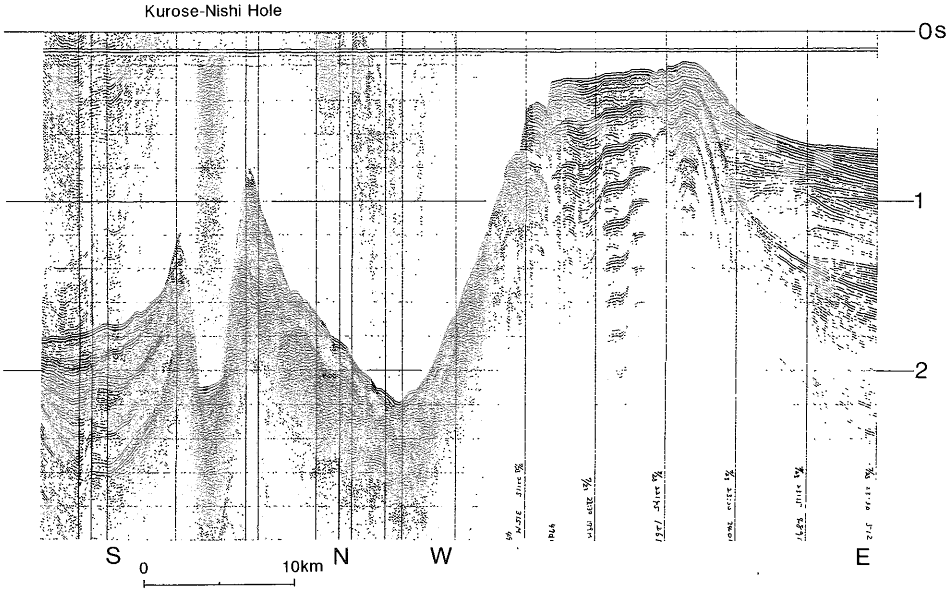


Fig. 5 Single channel air-gun reflection profile across the Kurose-nishi Hole and Kurose west to east obtained by GSJ, GH80-4 Cruise.

is not confirmed because of few sounding lines.

2.1.3 Higashi-aogashima Caldera

This caldera is located at lat. 32°27'N, long. 139°54'E, and 12 km east of Aogashima Island. It rests on a NNE-SSW trending seamount with two peaks, Daini-higashi-aogashima Knoll to the north and Daisan-higashi-aogashima Knoll to the south (Figs. 6 and 7). The shape of the caldera is ellipsoidal and the size is 5.4 (E-W) × 9.9 (N-S) km across. The caldera floor is 4-7 km across with 600-800 m depth. The maximum depth of the floor is 805 m at the southern part. The somma consists of the two knolls as above mentioned. The shallowest points of two knolls are 180 m depth on the north and 275 m depth on the south. West col of somma decreases its depth to 600-700 m. Relative height from col to floor becomes only 100-200 m and the height is lower than the other calderas. Inclination of the caldera wall is characteristically small (14-20°). There are recognized well stratified layers unconformably overlying the acoustic basement of the seamount on the acoustic profiles crossing this caldera (Fig. 7). This suggests that the age of this caldera is older than the others.

Bouguer gravity anomaly is highest at the central part of the caldera. Although the high gravity anomaly area is slightly biased to south, this caldera seems to be a high gravity anomaly type one (Ishihara, 1987). A remarkable dipole magnetic anomaly, negative to the north and positive to the south, is found on the southern part of the caldera.

2.1.4 Kita-Bayonnaise Caldera

This caldera is located at lat.32°06'N, long. 139°51'E, and NNW of Bayonnaise Rocks. The caldera rim is nearly circular and 5-7 km in diameter (Figs. 8 and 9). The caldera floor is about 1300 m depth and 5-6 km across. The floor is divided into two parts, northwest and southeast, by a central cone. The somma is flat-topped and generally 600-700 m in depth, although the west part of somma named

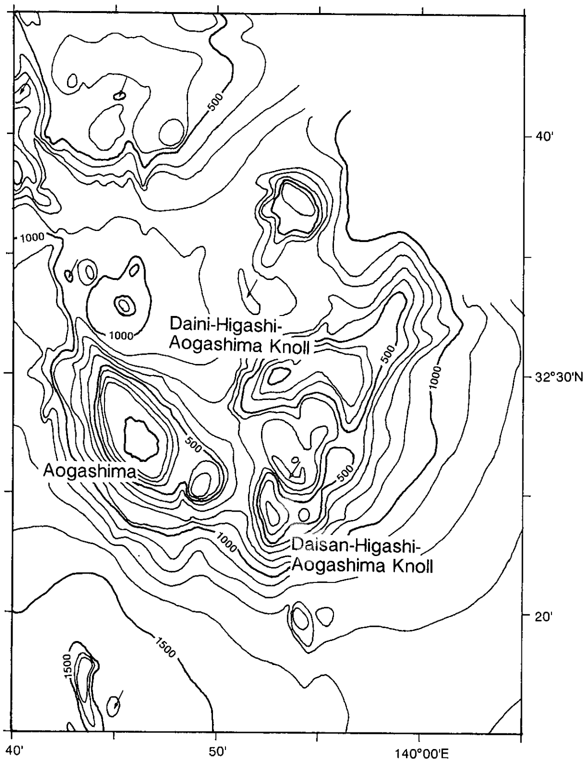


Fig. 6 Submarine topographic map of the Higashi-aogashima Caldera (after Saito *et al.*, 1988). Contour interval 100 m.

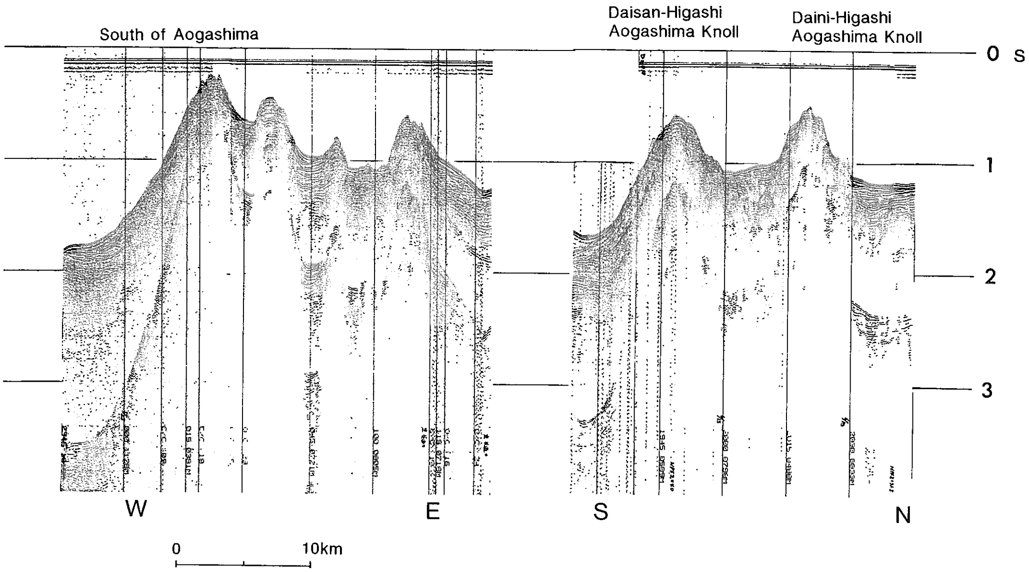


Fig. 7 Single channel air-gun reflection profiles across the Higashi-aogashima Caldera west to east (left) and south to north (right) obtained by GSJ, GH84-2 Cruise.

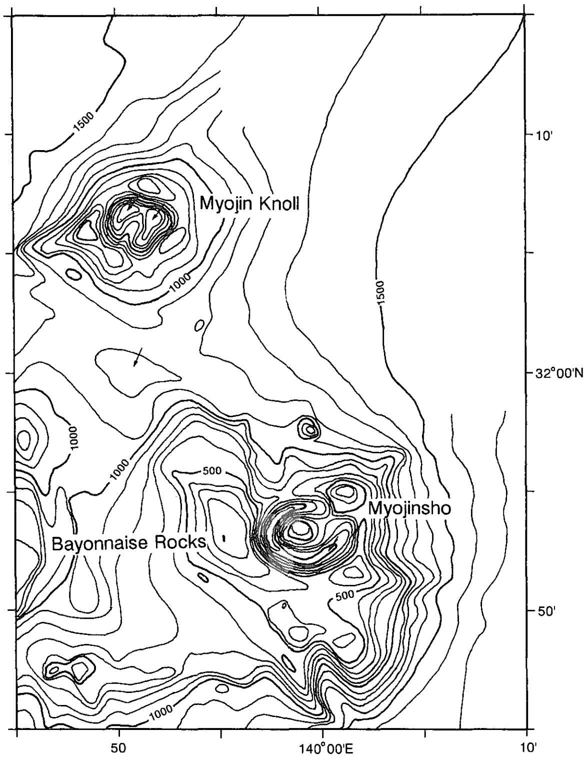


Fig. 8 Submarine topographic map of the Myojin Knoll (Kita-Bayonnaise Caldera) and Myojinsho Caldera (after Saito *et al.*, 1988). Contour interval 100 m.

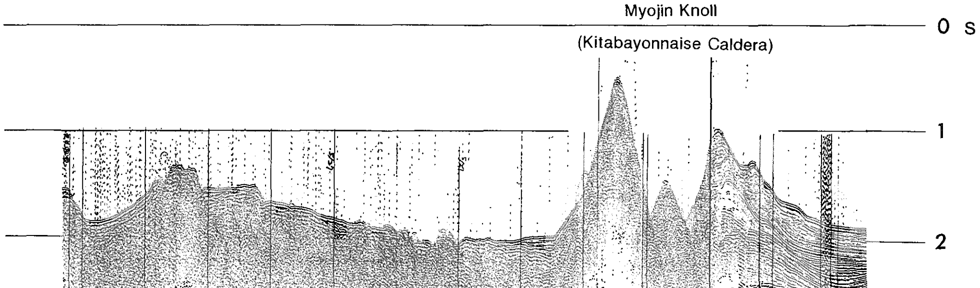


Fig. 9 Single channel air-gun reflection profile across the Myojin Knoll (Kita-Bayonnaise Caldera) west to east obtained by GSJ, GH84-2 Cruise.

Myojin Knoll has a shallow point of 364 m depth. Relief of the caldera wall is about 700-900 m and the inner slope is as steeper as 20-30°.

Low gravity anomaly is observed on the eastern outer slope, whereas the central part of the caldera is relatively high. Accordingly, the caldera seems to be of the high gravity anomaly type. No remarkable magnetic anomaly is recognized in this caldera.

2.1.5 Myojinsho Caldera

Myojinsho (Myojin Reef) is an active submarine volcano. It is enclosed by a circle with 10 mile diameter described ″ Dangerous area″ on the chart published by the Hydrographic Department, Maritime Safety Agency of Japan.

The caldera is located at lat.31°53'N, long. 139°59'E, about 4 km east of the Bayonnaise Rocks (10 m above sea level), which is a western peak on its somma (Figs. 8 and 10). It had been thought that Myojinsho is a central cone and the northeastern part of the caldera rim surrounding it has been lost by volcanic or tectonic movement (e.g., Morimoto and Ossaka, 1955). Recent submarine geologic survey, however, confirmed that Myojinsho is a northeast peak of the somma and the caldera rim is well preserved. The caldera rim is nearly circular and 7-9 km in diameter. The caldera floor is 5-6 km across and 900-1000 m depth. Relief of the caldera is 650 to 900 m. A large central cone with a depth of 330 m at the top was built on the central part of caldera floor, and the floor became a narrow and ring-shaped depression. The deepest point of the floor is 1102 m in the western part, whereas the northeast part becomes shallower to 600 m depth by development of the flank of Myojinsho. The northern part of the somma deepens to 700 m depth. The slope of the caldera wall is steep and inclines 30°.

2.1.6 Sumisu Caldera

Sumisu Caldera is located at lat.31°19'N, long.140°03'E, 6 km north of Sumisujima Island (136 m above sea level), which is a peak on its somma. The caldera forms part of a large seamount with a basal diameter of about 20

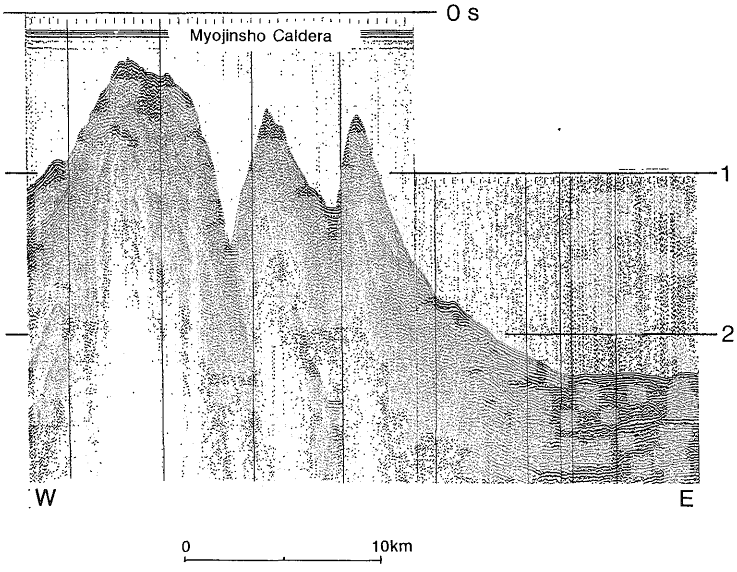


Fig. 10 Single channel air-gun reflection profile across the Myojinsho Caldera west to east, obtained by GSJ, GH87-3 Cruise.

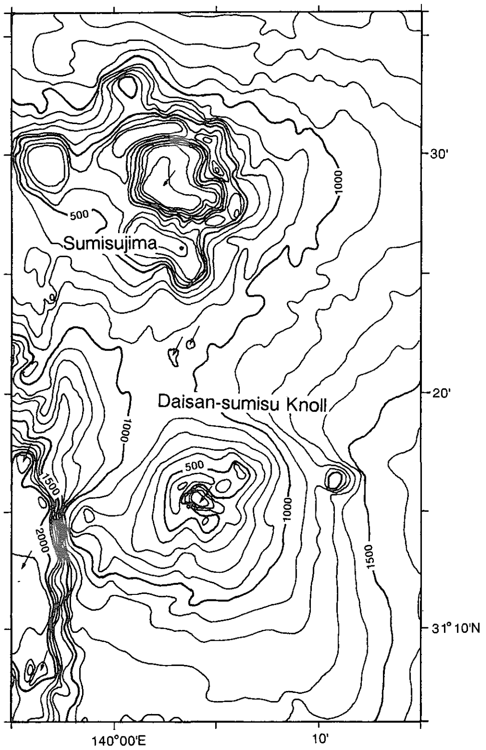


Fig. 11 Submarine topographic map of the Sumisu Caldera and Daisan-sumisu Knoll (Minami-sumisu Caldera) (after Saito *et al*., 1988). Contour interval 100 m.

km (Fig. 11). This caldera is also nearly circular and about 6-9 km in diameter. The caldera floor is 5-6 km across and 800-900 m in depth. Maximum depth of the floor is about 969 m. Relief of the caldera is 600 to 700 m. A central cone with relative height of 250 m and 2 km of diameter exists in the eastern part of the floor. Slope of the caldera wall is very steep, 32° in average (Fig. 12).

This caldera is of the high gravity anomaly type, about 25 mgal (Bouguer) higher than surroundings. A remarkable dipole magnetic anomaly, negative to the north and positive to the south, is observed in the caldera.

2.1.7 Minami-sumisu Caldera

A small caldera is found at 20 km south of Sumisujima Island (Taylor *et al*., 1990). It is located at lat.31°16'N, long.140°04'E. The size of caldera is small, 2-4 km in diameter (Fig. 11). The caldera floor is 1 km across with a maximum depth of 842 m. The summit of somma is 300-500 m in depth, although a peak rises up to 269 m in the northwest part. Inclination of the caldera wall is 20-40° (Fig. 13).

The caldera is accompanied with several satellite cones on the flank and the adjacent sea floor. Two larger cones are mapped on the east and west sides of the caldera (Fig. 11).

2.1.8 Torishima Submarine Caldera

This caldera is located at lat. 30°32'N, long. 140°20'E just north of Torishima Island (Fig. 14). The caldera is ellipsoidal and 6 (E-W) × 8 (N-S) km in diameter. The caldera floor is about 1 km across. The maximum depth of the floor is 660 m and relief of the caldera is 480 m. There is a small central cone on the eastern floor, and Torishima Island is on the south of the somma. The northern part of the somma

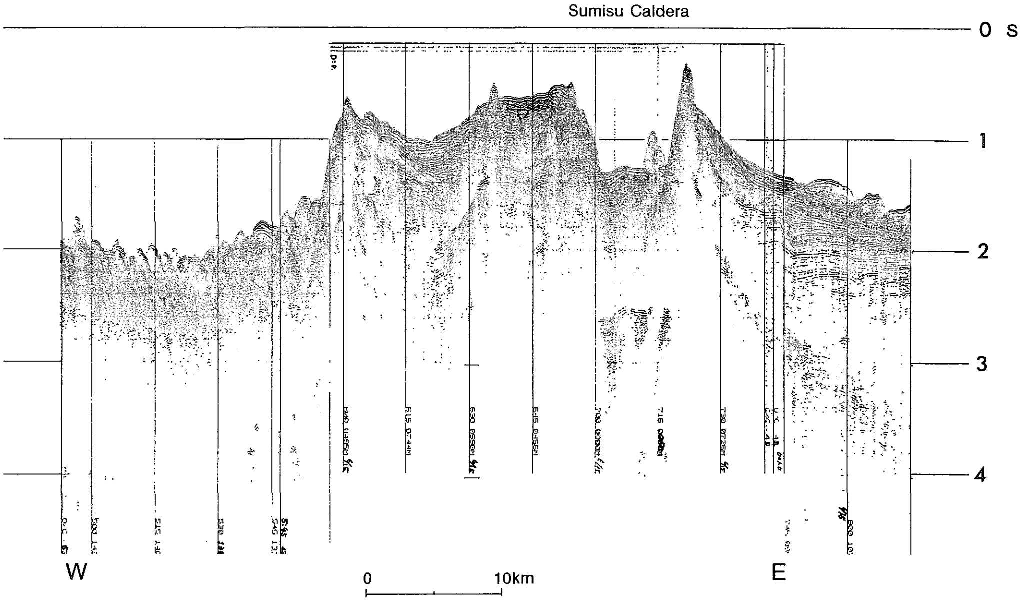


Fig. 12 Single channel air-gun reflection profile across the Sumisu Caldera west to east, obtained by GSJ, GH 84-2 Cruise.

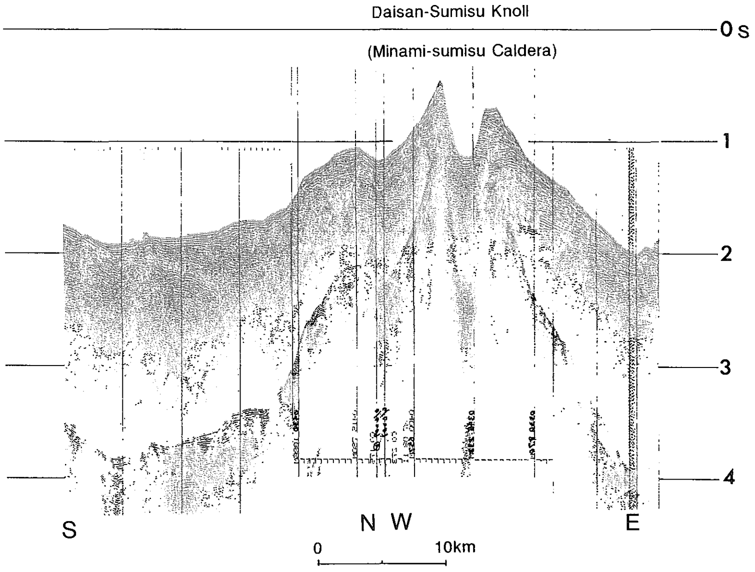


Fig. 13 Single channel air-gun reflection profile across the Daisan-sumisu Knoll (Minami-sumisu Caldera) west to east, obtained by GSJ, GH87-3 Cruise.

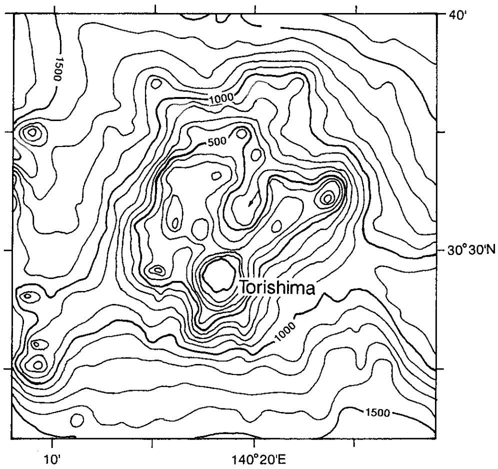


Fig. 14 Submarine topographic map of the Torishima Caldera (after Bathymetric chart No.6553, Torishima by Hydrographic Department of Maritime Softy Agency of Japan). Contour interval 100 m.

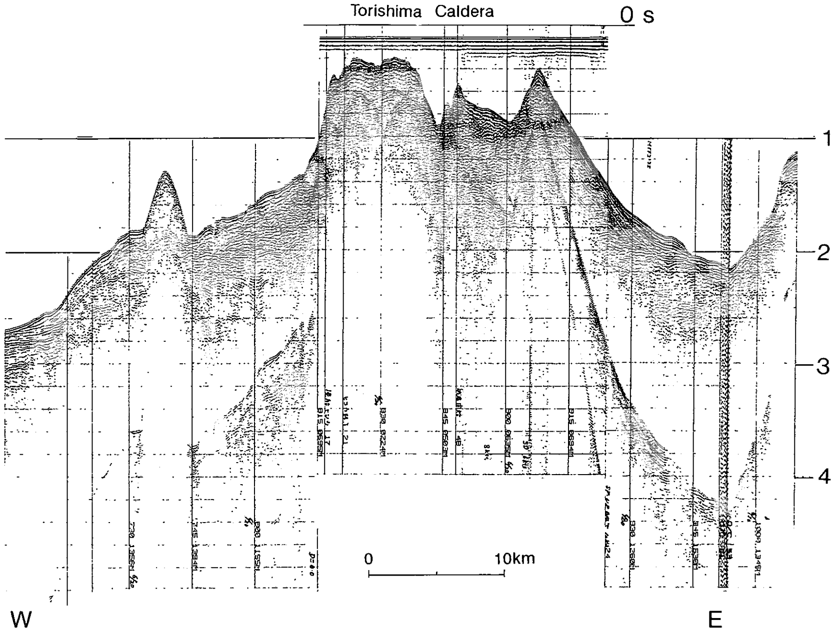


Fig. 15 Single channel air-gun reflection profile across the Torishima Caldera west to east, obtained by GSJ, GH84-2 Cruise.

decreases its depth to 700 m where the caldera wall is obscured. Inclination of the caldera wall is remarkably (20°) steeper than the outer slope (12°) (Fig. 15).

2.1.9 Kaikata Caldera

Above mentioned eight calderas all belong to the northern half of the arc, while Kaikata Caldera is only one caldera existing in the southern part.

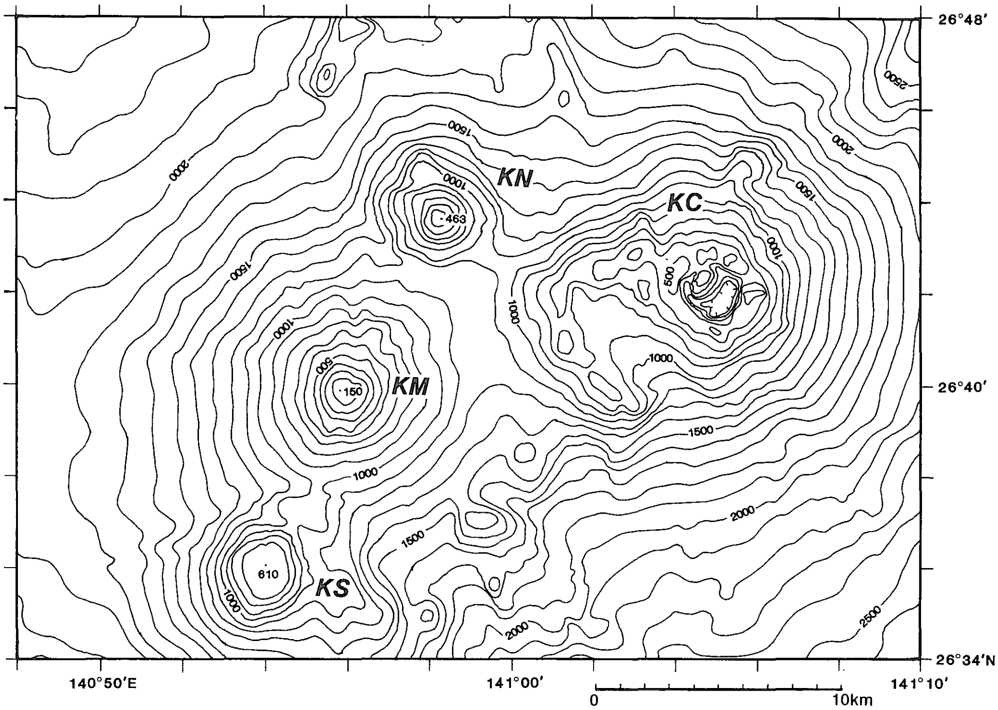


Fig. 16 Submarine topographic map of Kaikata Seamount (after Saito *et al.*, 1986, partly modified). Four peaks (called KC, KN, KM and KS) are recognized. Eastern peak KC accompanies the caldera. Contour interval 100 m.

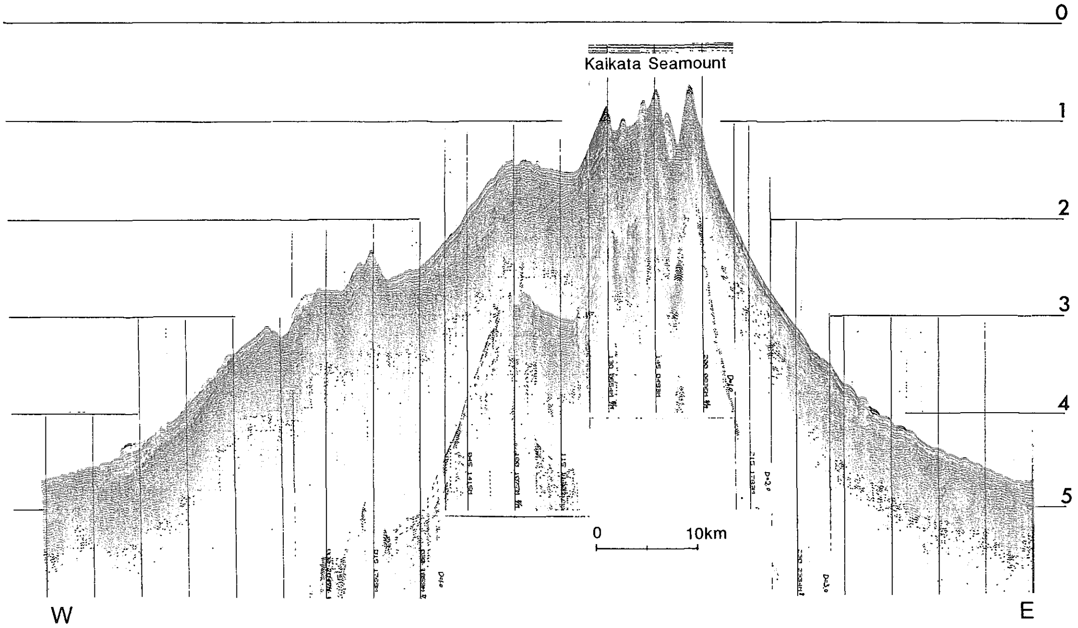


Fig. 17 Single channel air-gun reflection profile across the Kaikata Seamount west to east, obtained by GSJ, GH85-1 Cruise.

The caldera is located at lat. 26°42'N, long. 141°05'E on the Kaikata Seamount, 65 km south of Nishinoshima Island. This caldera is nearly circular and about 3 km in diameter (Fig. 16). A large central cone exists on the northwestern part, and the caldera floor is not circular but crescent, 1.6 km long and 0.8 km wide. The floor is rather flat and about 920 m depth. The caldera wall is very steep and inclines 27-30° (Fig. 17). Relief of the caldera is about 400 to 500 m.

Positive gravity anomaly over 120 mgal is recognized in this caldera. It is not clear whether the central gravity anomaly of the caldera is relatively higher or lower than the surroundings. A remarkable dipole magnetic anomaly, negative to the north and positive to the south, is found on the caldera.

2.2 Seamounts within the Nishinoshima Trough

Nishinoshima Trough shows a kind of rift morphology cutting across the Izu-Ogasawara Arc between Sofugan and Nishinoshima Islands. An interval distance between islands is widest here throughout the Shichito-Iwojima Ridge and no islands are observed over about 290 km. Here is also the deepest point of the ridge.

There are nine large seamounts, with parasitic highs in some cases between Sofugan and Nishinoshima islands. Of these seamounts, seven conical and sub-conical seamounts distribute linearly along the Shichito-Iwojima Ridge and other two large seamounts exist on the outer and inner sides of the ridge (Fig. 18). These seamounts have been named Nichiyo (Sunday), Getsuyo (Monday), Kayo (Tuesday), Suiyo (Wednesday), Mokuyo (Thursday), Kin'yo (Friday), Doyo (Saturday) seamounts for seven seamounts from north to south, and Ohmachi and Sawa seamounts for two larger elongated seamounts at the northeast and southwest parts. Nichiyo to Doyo seamounts are totally called Shichiyo (Seven Days) Seamounts Group. Table 1 lists the size of these seamounts, and Figs.19a-j show some available seismic profiles crossing each seamount.

Ohmachi Seamount (Fig.19a) was regarded as an old seamount (Paleogene to Early Miocene) on the basis of seismic profile analysis as shown in the marine geologic map of the area by Honza *et al.* (1982). Recently, Yuasa *et al.* (1988a) sampled volcanic and sedimentary rocks from the seamount and dated two samples of andesite with the results of about 32-33 Ma. The age of the Sawa Seamount is not known, but it may be regarded older since the seamount is covered by thick stratified sediment layers and cut by many faults as shown in the seismic profiles (Fig. 19j).

The rest seven seamounts are divided into two groups on the basis of bathymetric map and seismic profiles. One group of seamounts has a conical shape with a sharp slope, and no stratified layer is observed on the flank (Figs. 19c, d, h and g). These seamounts are regarded as younger volcanoes. Getsuyo, Kayo, Kin'yo and Doyo seamounts belong to this group. The height of these seamounts is higher than 2000 m. The other three seamounts are covered by thick stratified layers and some fault patterns are observed on the flank. Their summits are not sharp but rather flat. Many small valley-like patterns are incised on the flank. They are possibly older seamounts than the above four. Nichiyo, Suiyo and Mokuyo seamounts belong to this older group. Their height is lower than 2000 m.

According to the magnetic anomaly map by Yamazaki *et al.* (1991), the above relations are also well recognized except for a seamount. They distinguished four types of magnetic anomaly caused by the seamounts. The first type is characterized by a dipole with a negative to the north of the summit and a positive to the south. This pattern is normally magnetized one for the middle latitudinal seamounts on the Northern hemisphere of recent age (after 0.7 Ma). Kayo, Kin'yo and Doyo seamounts have this characteristic pat-

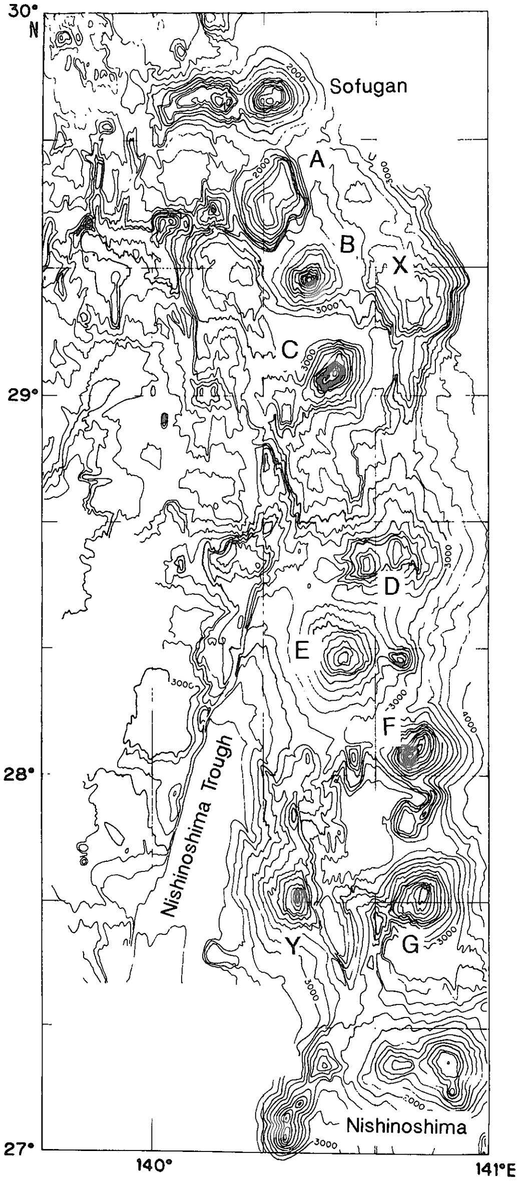


Fig. 18 Submarine topographic map of the seamounts in the Nishinoshima Trough (Geological Survey of Japan, unpublished data). West edge of the trough corresponds to the fault scarp of the Sofugan Tectonic Line (Yuasa, 1985a). Contour interval 100 m.
A: Nichiyo Seamount, B: Getsuyo seamount, C: Kayo Seamount, D: Suiyo Seamount, E: Mokuyo Seamount, F: Kin'yo Seamount, G: Doyo Seamount, X: Ohmachi Seamount, Y: Sawa Seamount.

tern. The second type has a weak anomaly compared with the volume of their edifices. Nichiyo and Sawa seamounts belong to this group. The height of the seamounts is lower than 2000 m. The third type is characterized by a unique anomaly distribution with a complicated pattern. In the case of Suiyo seamount, a large negative anomaly is recognized to the east of the summit and two large positives exist to the northwest and south of the summit. In another case, Mokuyo seamount is characterized by a large positive anomaly on the summit. Although the origin of these complicated anomaly patterns is not well known, it is suggested that both seamounts have been affected by the magnetic field of different age from the recent field at this latitudinal terrain. Getsuyo seamount also belongs to this type and shows a dipole pattern with slightly shifted to northeast. The fourth type is characterized by a broad monopole, or a flat pattern observed on the summit of Ohmachi Seamount.

The division based on the bathymetry and seismic profiles well corresponds to that by the magnetic anomaly data except for Getsuyo seamount. That is, the sharp, conical seamounts regarded as younger volcanoes are comprised in the first type of magnetic anomaly pattern that has been caused by the recent middle latitudinal magnetic field of the Northern hemisphere. The flat-topped or valley-incised seamounts regarded as older ones are complicatedly or weakly magnetized. Getsuyo seamount is regarded as a young one from the seismic profile (Fig. 19d) and morphologic data (see Fig. 32), but magnetic anomaly data show the characteristics slightly different from the other young seamounts (Yamazaki *et al.*, 1991).

Recently, the Hydrographic Department and the submersible ″ Shinkai 2000″ recognized a caldera morphology and hot water (about 40° C) seepage on the top of the Mokuyo Seamount (Nagaoka *et al.*, 1991). The hydrothermal activity has remained yet in the seamount.

2.3 Larger seamounts between Nishinoshima and Minami-iwojima islands

In the southern part of the Izu-Ogasawara Arc, a deep trough, Ogasawara Trough, develops on the east side of volcanic front. The eastern flank slope of each seamount or island continues deepening downward to the trough floor. In fact, the basal diameter of these seamounts is relatively larger in the Shichito-Iwojima Ridge. These six volcanoes are all large composite volcanoes with multi-peaks as shown in Fig. 1 (center). Since the islands form a part of the seamount edifice, such islands, including submarine part, are called here by the name of island attached with the word "Volcano."

2.3.1 Nishinoshima Volcano

Nishinoshima Volcano is an active volcano which erupted in 1973-1974 (Aoki and Ossaka 1974). This volcano consists of a main peak which appears as an island and other two subaqueous peaks which exist west and south of the island. There is a small cone on the northeast flank of the main peak, which may be a satellite cone. An elongated high trending in NNE to SSW is present on the west side of western peak. The high is covered by thick sedimentary layers (Fig. 20). Since thick manganese oxide crusts of hydrogenous origin were recovered from the high, it is not regarded as a part of recent Nishinoshima Volcano but an older high.

2.3.2 Kaikata Seamount

There are no records or observations of volcanic activity at this seamount, though it consists of andesitic and basaltic volcanic rocks and has a caldera on the east summit. A hydrothermal alteration zone was found in the caldera (Yuasa *et al.*, 1988b) and disseminated sulfides were dredged from the caldera wall (Urabe *et al.*, 1987). Reddish brown-colored precipitates drifting were also observed in the seawater within the caldera and deposited on the wall and floor, and weak simmering of the seawater on a wall, where thick precipitates cover the outcrop of altered rocks (Yuasa *et al.*, 1988b). These phenomena show the presence of hydrothermal activity in the caldera and there is a high possibility that the volcano is active.

Kaikata Seamount consists of major four peaks with several small satellite cones (Fig. 16). As already mentioned, a caldera topography exists on the eastern peak of the

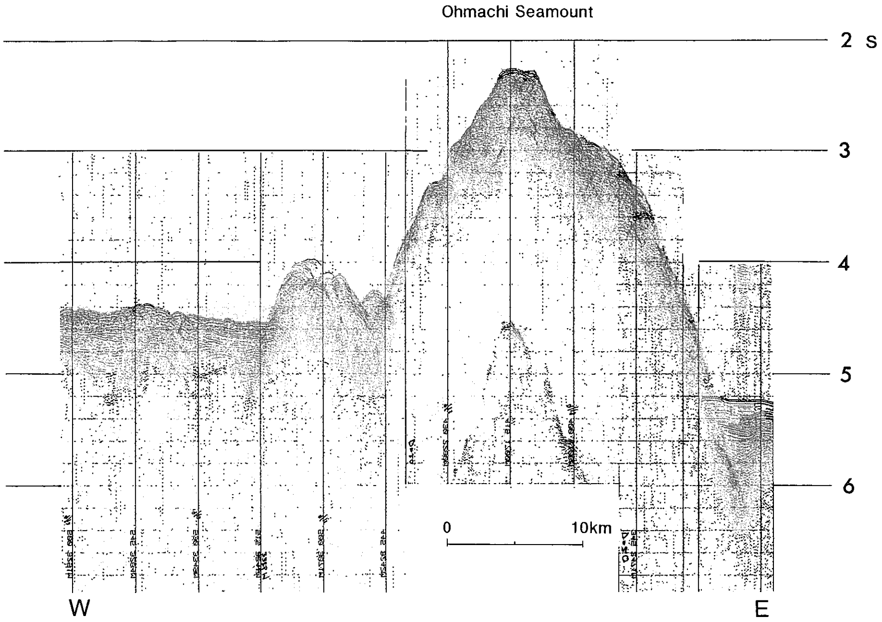


Fig. 19a Single channel air-gun reflection profile across the Ohmachi Seamount in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

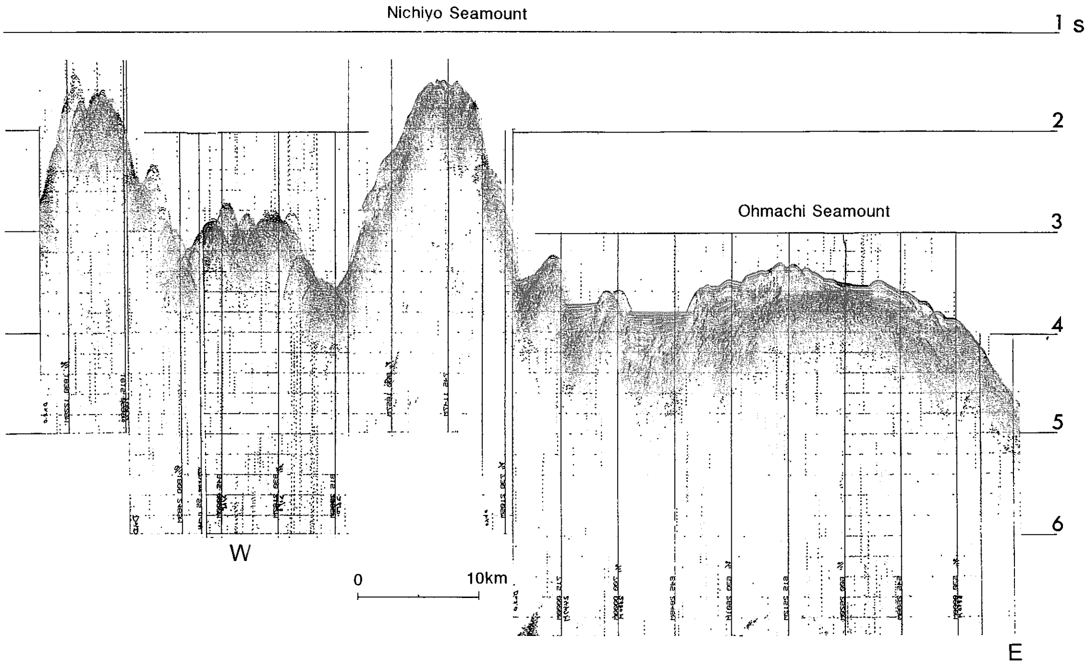


Fig. 19b Single channel air-gun reflection profile across the Nichiyo and Ohmachi seamounts in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

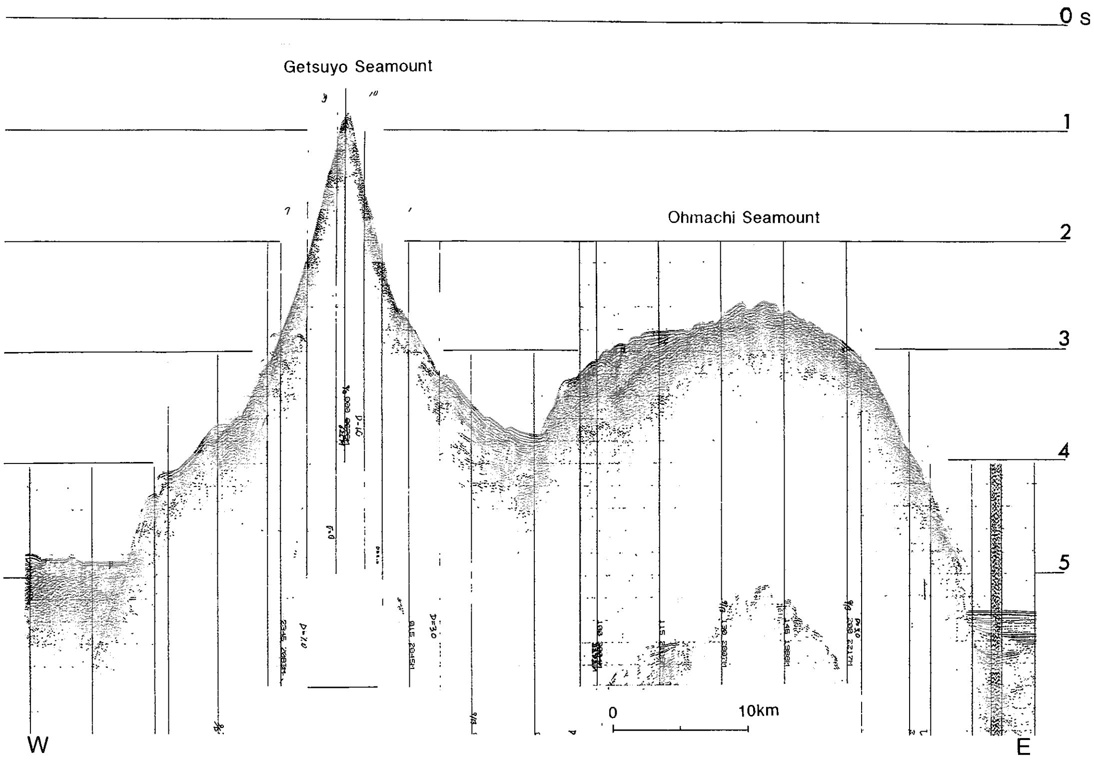


Fig. 19c Single channel air-gun reflection profile across the Getsuyo and Ohmachi seamounts in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

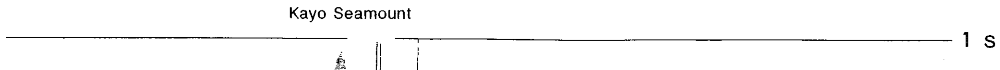


Fig. 19d Single channel air-gun reflection profile across the Kayo Seamount and southern extension of Ohmachi Seamount in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

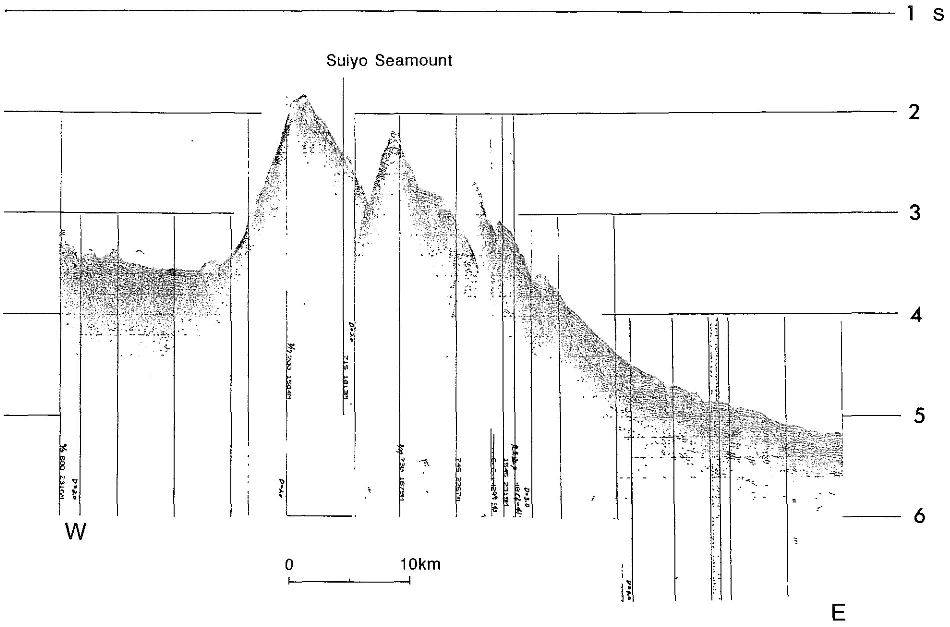


Fig. 19e Single channel air-gun reflection profile across the northern part of Suiyo Seamount in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

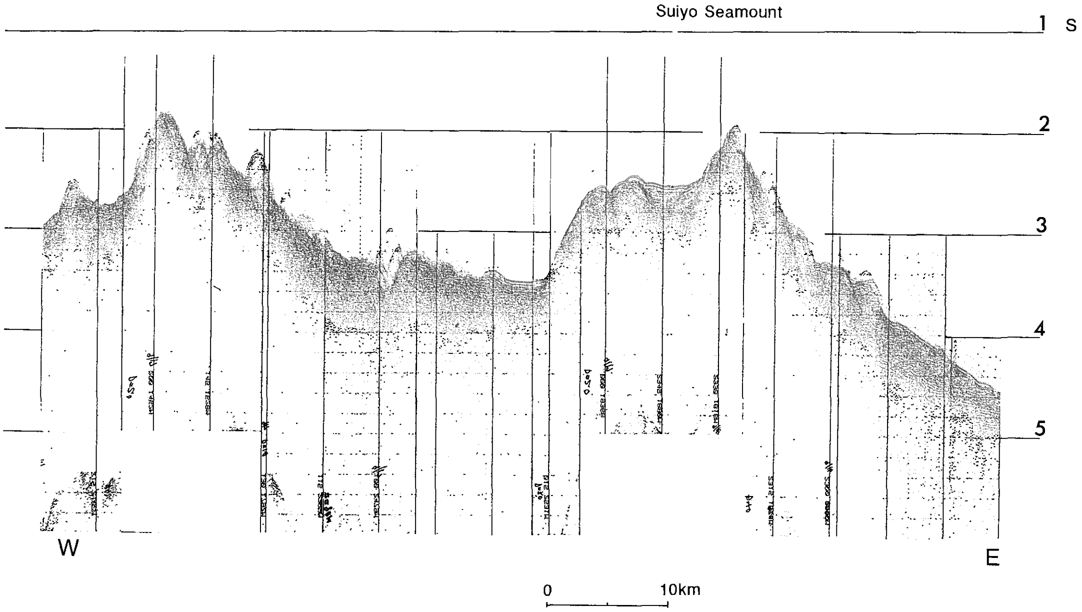


Fig. 19f Single channel air-gun reflection profile across the southern part of Suiyo Seamount in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

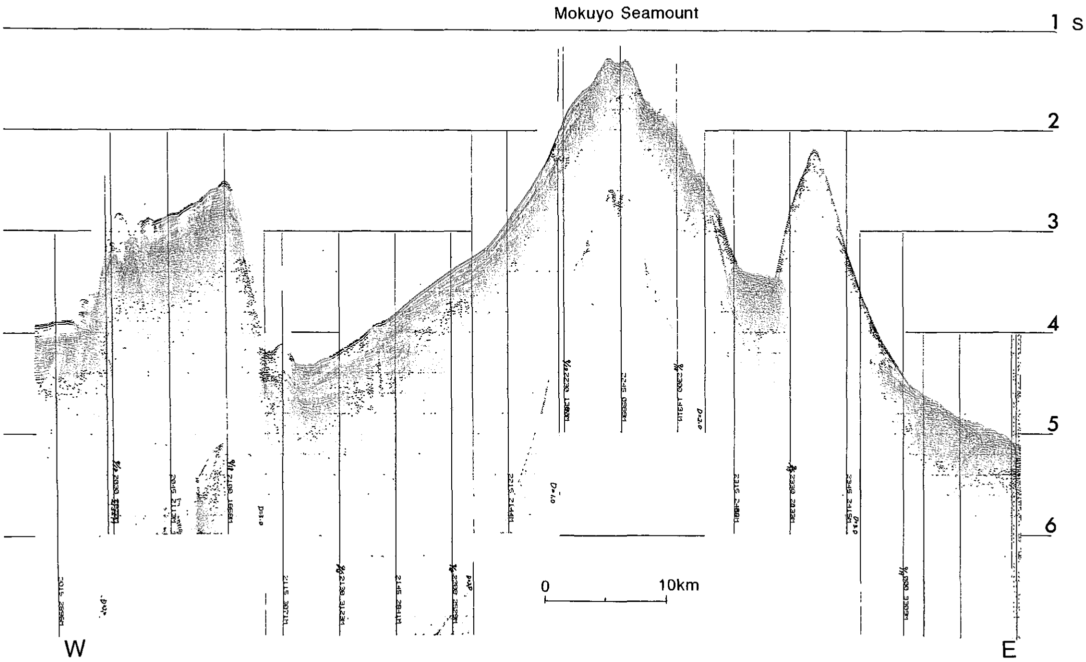


Fig. 19g Single channel air-gun reflection profile across the Mokuyo Seamount in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

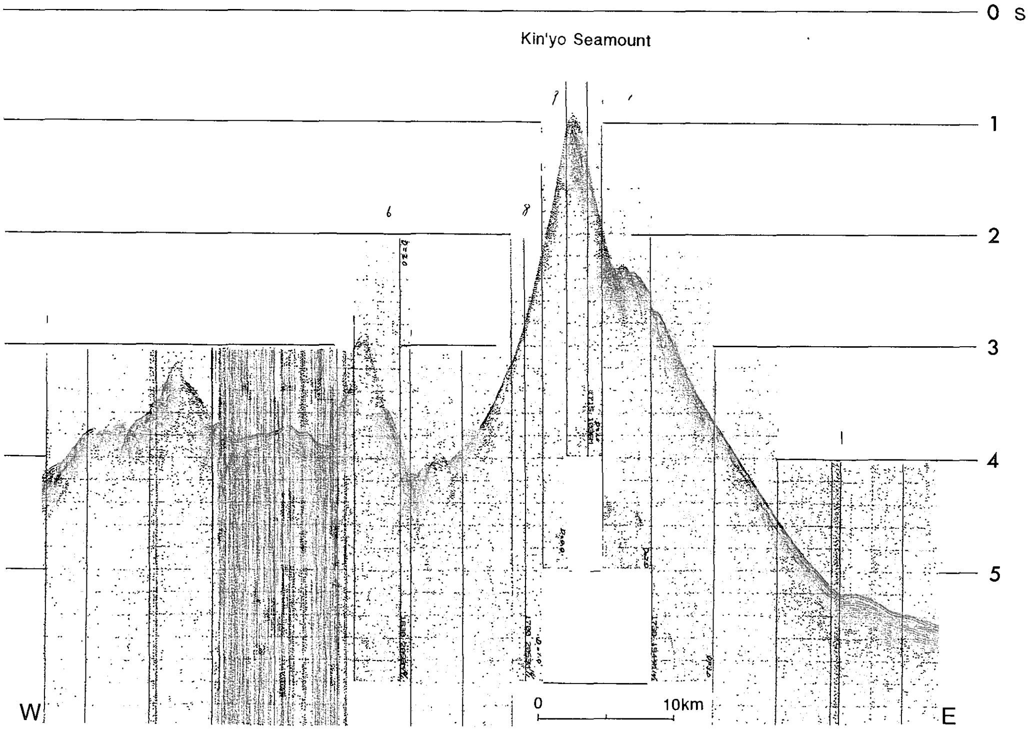


Fig. 19h Single channel air-gun reflection profile across the Kin'yo Seamount in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

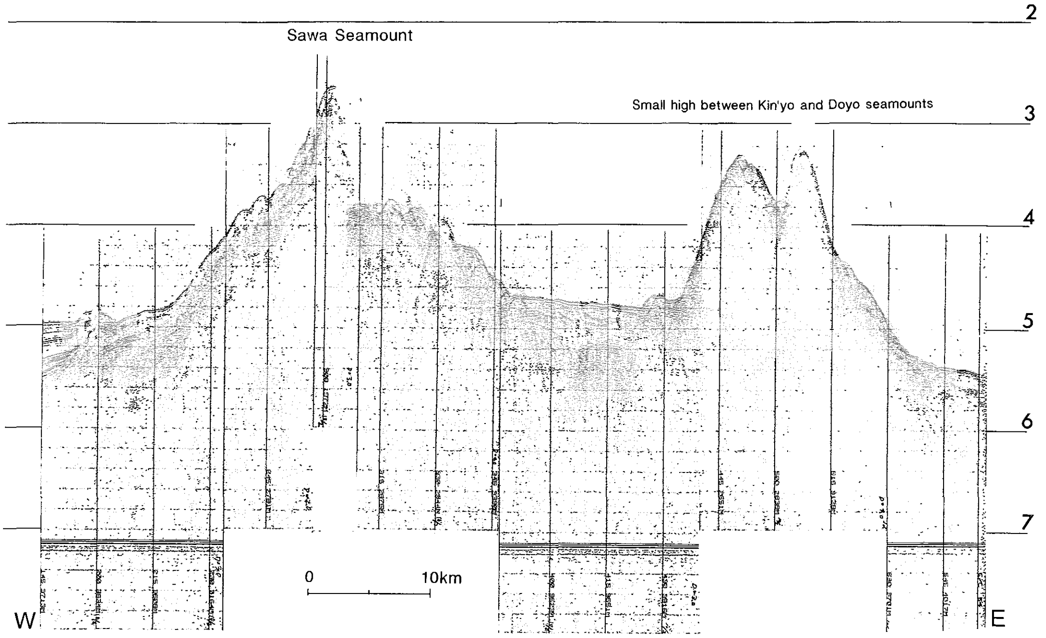


Fig. 19i Single channel air-gun reflection profile across the Sawa Seamount and a small knoll between Kin'yo and Doyo seamounts in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

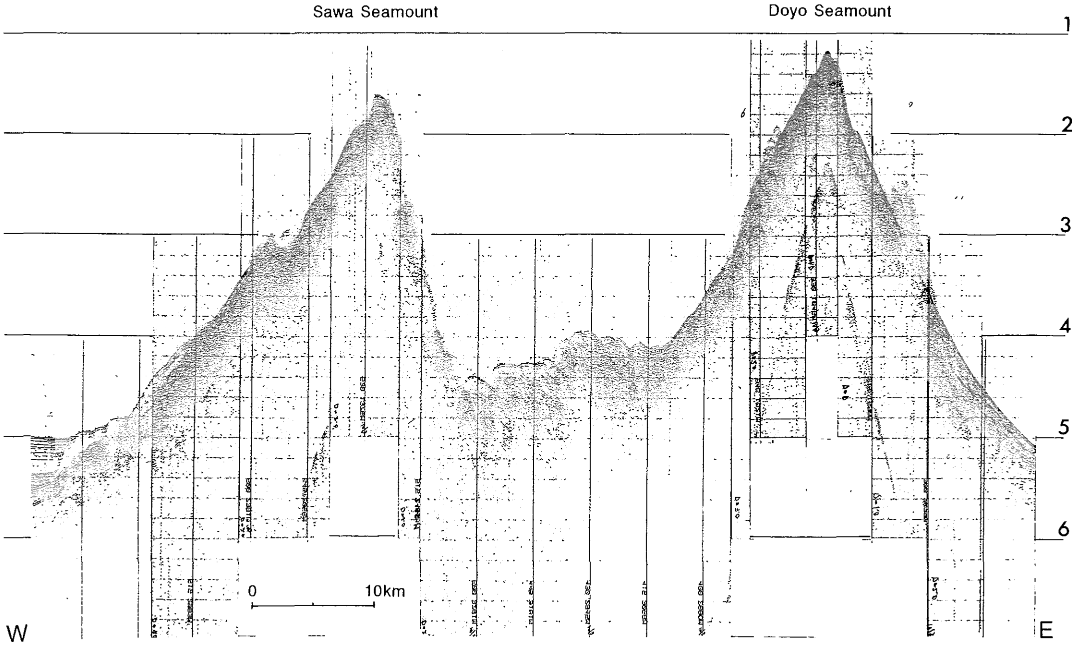


Fig. 19j Single channel air-gun reflection profile across the Sawa and Doyo seamounts in the Nishinoshima Trough west to east, obtained by GSJ, GH84-4 Cruise.

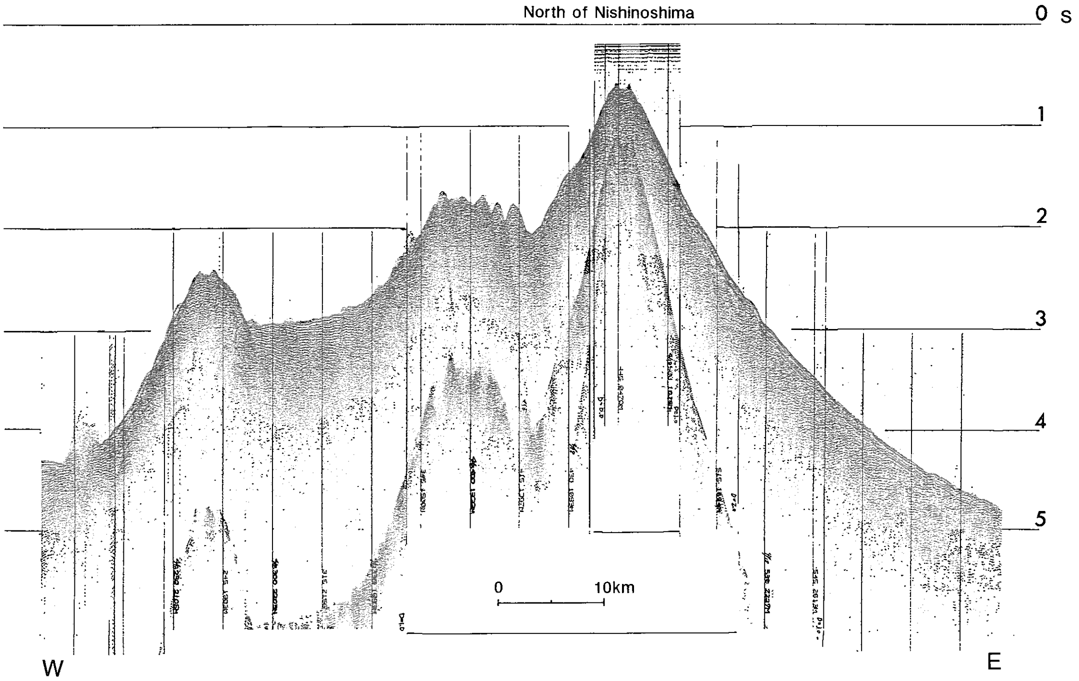


Fig. 20 Single channel air-gun reflection profile across the northern part of Nishinoshima Volcano west to east, obtained by GSJ, GH85-1 Cruise.

seamount. A minor ridge extends to the west from northwestern somma of the caldera and the ridge turns to southeast. This ridge forms a horseshoe shape together with the caldera (Fig. 16). This feature may indicate a part of larger somma of older caldera. Three peaks except for the caldera peak arrange in NNE to SSW trend. An isolated high exists on the west of the volcano. As thick sediment layers are observed in a seismic profile (Fig. 17), the high may be as old as the elongated high on the west of Nishinoshima Volcano.

2.3.3 Kaitoku Seamount

Kaitoku Seamount is an active volcano which erupted in 1984 (Tsuchide *et al.*, 1985). The volcano consists of three major peaks with some satellite cones (Fig. 21). East and west peaks which are separated by a deep of 1000 m depth have been called Higashi-kaitoku-ba and Nishi-kaitoku-ba, respectively, by Japanese fishermen. When the submarine eruption occurred at the Higashi-kaitoku-ba in 1984, the Hydrographic Department named Kaitoku Seamount for the whole seamounts.

Above three volcanoes are very similar in size, about 50 km in basal diameter and about 2400 m in height. All of them are composite volcanoes consisting of three or four large peaks. On the other hand, the following three volcanoes, Kita-iwojima, Iwojima and Minami-iwojima volcanoes, are also composite volcanoes but different from the above three in their topographic features.

2.3.4 Kita-iwojima Volcano

A remarkable double chain of small cones trending in NNW-SSE is recognized in the volcano (Fig. 22). Kita-iwojima Island is located at about 10 km east of the chain. There are ten or more small cones on the volcano and some of them have flat planes regarded as a wave-cut terrace. Submarine eruptions were observed at the Hunka-asane 5 km west of the island in 18th and 19th centuries. In recent years, discolored water has been often observed at the same point.

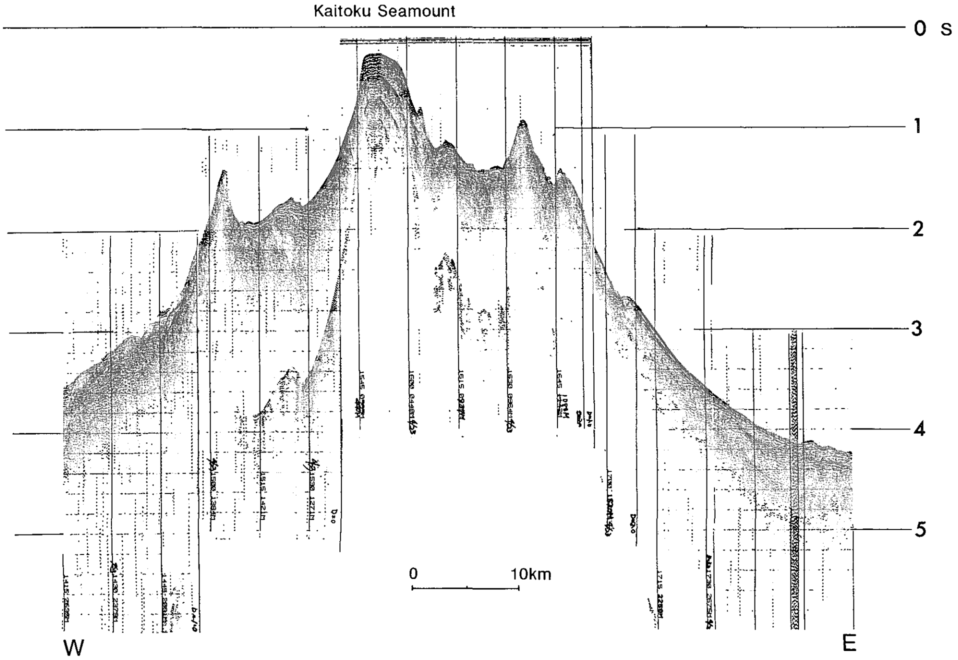


Fig. 21 Single channel air-gun reflection profile across the Kaitoku Seamount west to east, obtained by GSJ, GH85-1 Cruise.

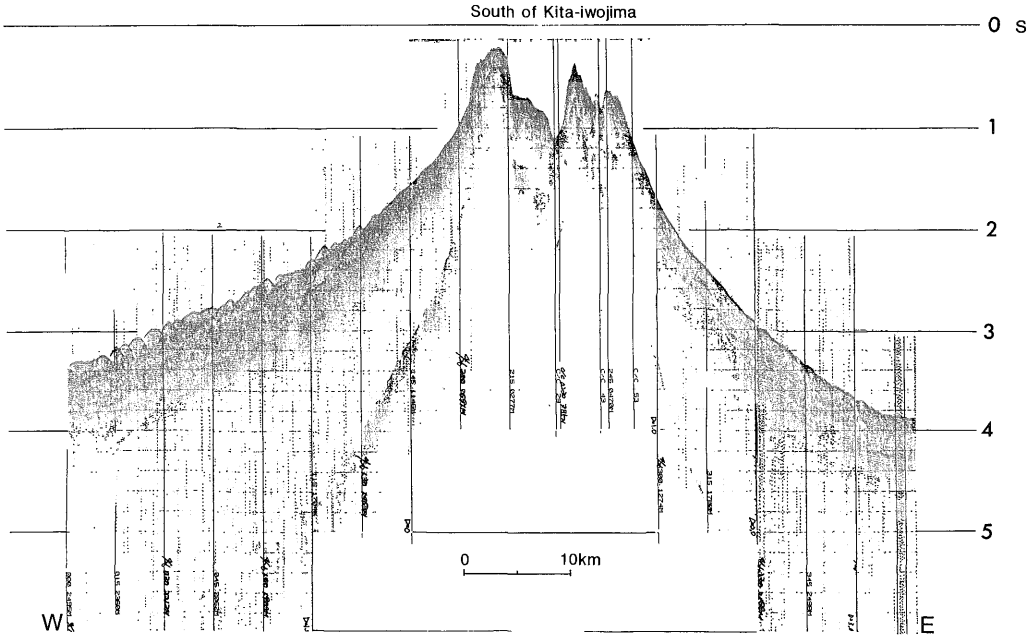


Fig. 22 Single channel air-gun reflection profile across the southern part of Kita-iwojima Volcano west to east, obtained by GSJ, GH85-1 Cruise.

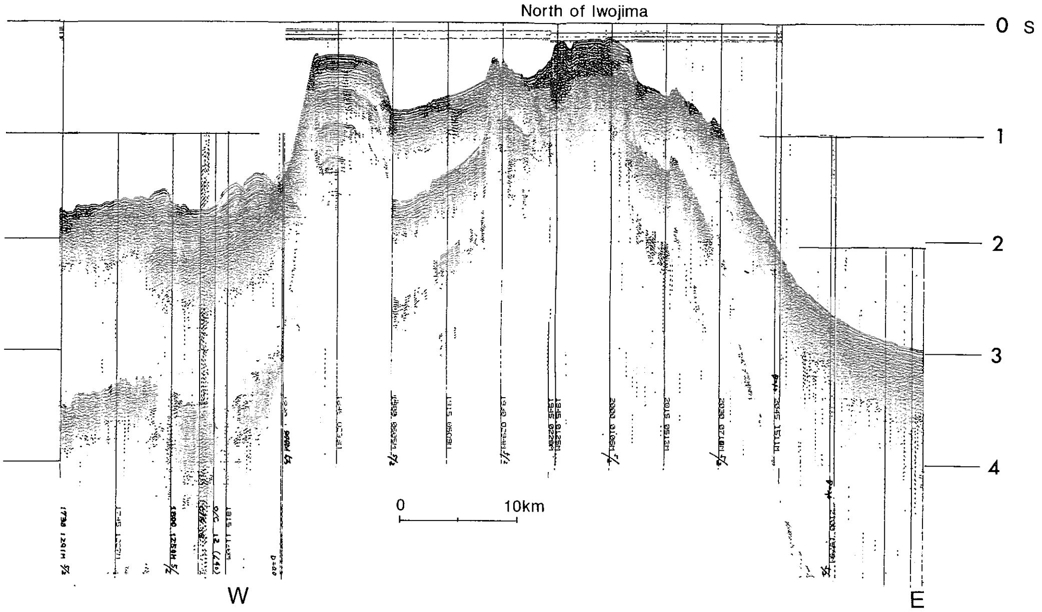


Fig. 23 Single channel air-gun reflection profile across the northern part of Iwojima Volcano west to east, obtained by GSJ, GH85-1 Cruise.

2.3.5 Iwojima Volcano

This volcano has a dome structure in central part of Iwojima Island. It contrasts markedly with the elongated feature of Kita-iwojima Volcano. A flat-topped high called Kaise-nishinoba exists on the WNW flank of Iwojima Island. The flat-top is about 200 m depth and considered to be a wave-cut terrace (Fig. 23). This may be an older high because the dredged rocks are coated by a thin ferromanganese oxide crust. Many satellite cones are present on the slope around Iwojima Island. Kato and Ikeda (1984) and Kaizuka *et al.* (1985) described a caldera around the Motoyama of Iwojima Island on the basis of bathymetric feature that several highs surround the Motoyama in a circle. Volcanic activity of Iwojima Volcano is characterized mainly by phreatic eruptions on land, and many fumaroles, hot springs, alteration zones and high temperature areas are present on Iwojima Island.

2.3.6 Minami-iwojima Volcano

This volcano shows an elongated topography similar to Kita-iwojima Volcano. Two major highs join with each other to form a large elongated volcano with a NNW-SSE trend. One is the Minami-iwojima Island above sea level. There are several small cones around the northern high (Fig. 24). Volcanic activity of this volcano has been often observed on a small bank called Fukutoku-okanoba northeast of the Minami-iwojima Island. The bank grew into an islet during the eruption in 1904 and 1914, and named "Shin-iwojima Island" (Ogura, 1915). This island disappeared several months later (1904 eruption) or within two years (1914 eruption). The latest eruption of the Fukutoku-okanoba occurred in 1986 and a new volcanic island appeared again within a short time. Recently discolored water is often observed. There are two isolated highs west and east of the volcano. It is not clear whether these highs belong to the member of the volcano or not. From the eastern high, benmoreitic trachyte lava was dredged. It is similar to the rocks recovered from Fukutoku-okanoba and Iwojima.

As described above, there is a remarkable difference between Kita-iwojima and Minami

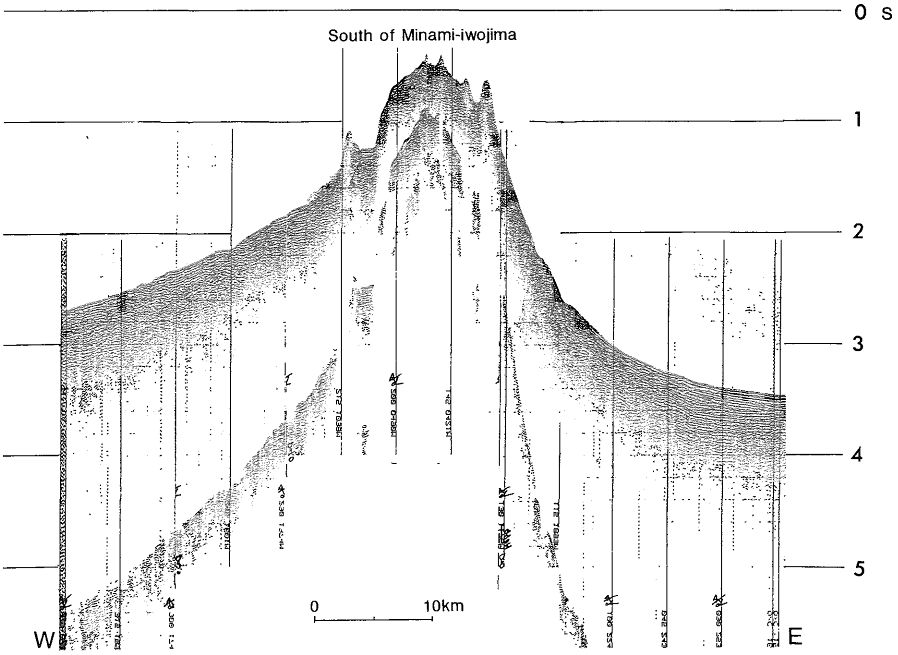


Fig. 24 Single channel air-gun reflection profile across the southern part of Minami-iwojima Volcano west to east, obtained by GSJ, GH85-1 Cruise.

-iwojima volcanoes and Iwojima Volcano in shape. The former two have large elongated features with 55-70 km in long axis and 30-55 km in short axis, while the latter has a dome-like feature with a basal diameter about 50 km. The height of Kita-iwojima and Minami-iwojima volcanoes is higher (2900-3300 m) than Iwojima Volcano.

3. Characteristics of distribution, height and spacing of volcanoes along the volcanic front of the Izu-Ogasawara Arc

It has been often pointed out that there may be some regularity regarding the dimensions (height, diameter and volume), spacing and distribution of arc volcanoes (e.g., Vogt, 1974 a, b; Ben-Avraham and Nur, 1980; Katsui, 1981; Bloomer *et al.*, 1989). Such regularity was discussed in connection with the nature of the underlying crust, continental or oceanic, (Ben-Avraham and Nur, 1980), the crustal thickness of arc (Vogt, 1974a), the depth of partial melting (Lingenfelter and Schubert, 1974), or magma supply rate or age of volcano (Bloomer *et al.*, 1989). Ben-Avraham and Nur (1980) indicated that the elevation of volcanoes is approximately constant within individual arc on the oceanic crust but varies on the continental crust, while edifice heights are greatly variable on the oceanic crust but rather constant on the continental crust. Basic relations among the elevation, height and crustal property may be generalized as above. Other aspects of the relations in the arc volcanoes may be also revealed by detailed examination within an arc. Here, we will present the regularity among the height, basal diameter and spacing of volcanoes on the Shichito-Iwojima Ridge, the volcanic front of the Izu-Ogasawara Arc, and discuss the origin of the regularity.

3.1 Distribution and spacing of volcanoes

The arrangement of volcanoes on the volcanic front shows an almost linear distribution pattern parallel to the trench. The linear distribution, however, is interrupted by some

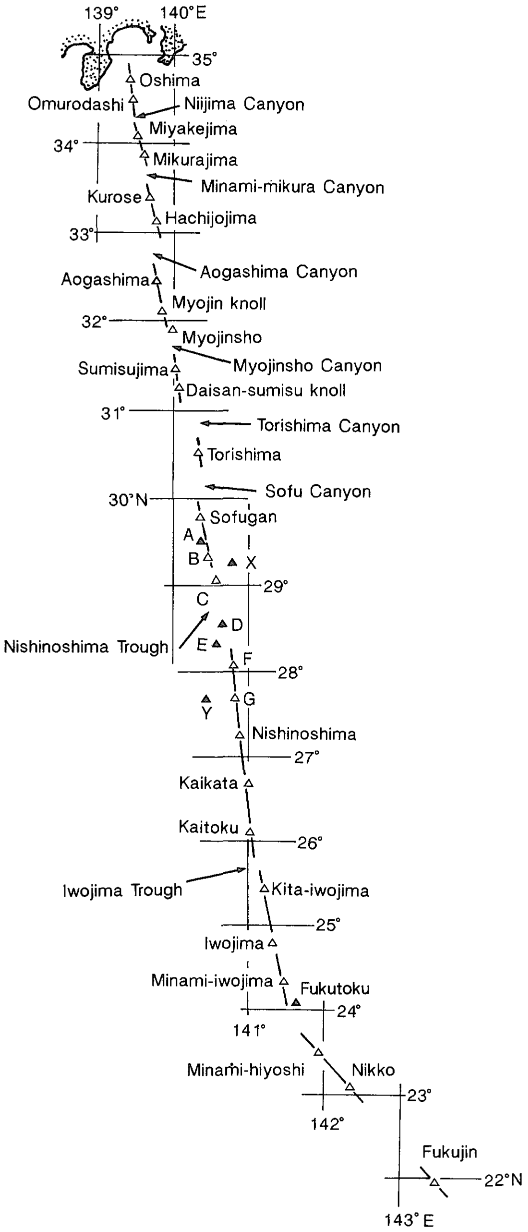


Fig. 25 Distribution of volcanoes along the Shichito-Iwojima Ridge. Troughs and canyons crossing the ridge are also shown. Open triangles: Quaternary volcanoes, and solid ones: older volcanoes. Alphabets A to G, X and Y are the same in Fig.18. Getsuyo Seamount (symbol B) is regarded as a younger seamount in this figure.

discontinuities and the segmentation of the volcanic front is often observed in several arcs (Stoiber and Carr, 1973; Oide, 1974; Marsh, 1979; Carr, 1984). Volcanic islands and recent submarine volcanoes on the Shichito-Iwojima Ridge are shown by open triangle in Fig. 25. The linear distribution of volcanoes forming the volcanic front is defined here as the first order distribution of volcanoes. In the trace of the volcanoes from the south to the north, there are at least three gaps among them. The first order distribution is separated in each segment by these gaps and the arrangement of volcanoes in each segment is called the second order distribution. In the northward of Minami-iwojima, a small gap is present between Kita-iwojima and Kaitoku Seamount. That is, Iwojima and Kita-iwojima islands make a segment with Minami-iwojima Island. Next segment starts from Kaitoku Seamount to Nishinoshima Islands through Kaikata Seamount and continues further north to Kin'yo and Doyo seamounts, south of Nishinoshima Trough. This segment, however, is interrupted near at lat. 28° north. The third segment starts from Kayo Seamount, the central part of Nishinoshima Trough to Sofugan Island. The fourth segment comprises only Torishima Island. Torishima Island is located slightly on the forearc side. Further north, five segments are recognized as shown in Fig. 25. That is, they are the segments consisting of Daisan-sumisu Knoll to Sumisujima Island, Myojinsho (or Bayonnaise Rocks) to Aogashima Island, Hachijojima to Kurose, Mikurajima to Miyakejima islands, and Omurodashi to Oshima Island. Thus the first order arrangement of volcanoes on the Shichito-

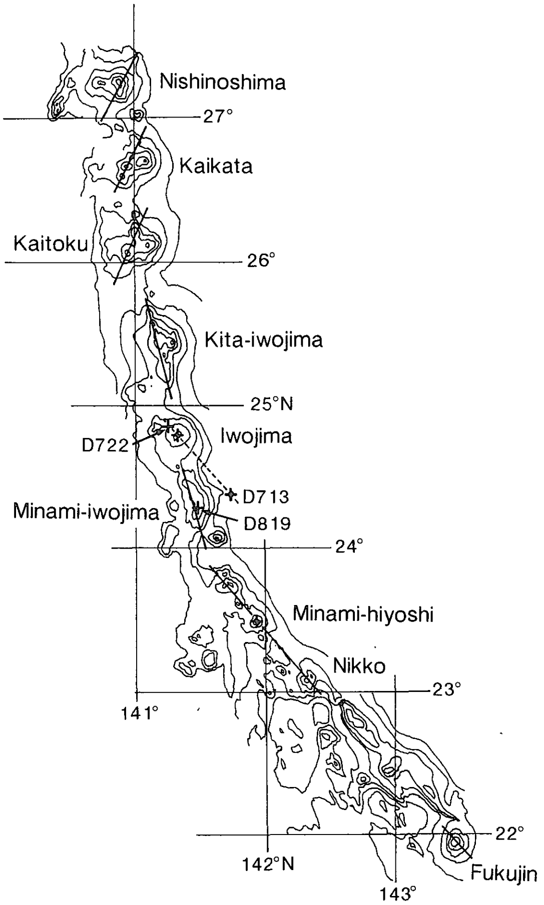
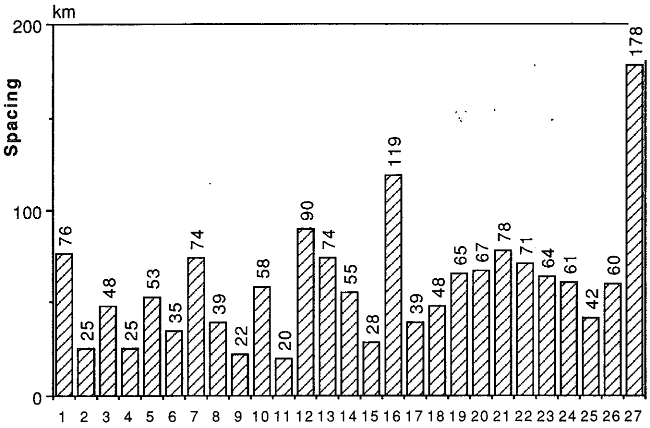


Fig. 26 Distribution trends of highs (solid lines) on the larger composite volcanoes in the southern part of the Shichito-Iwojima Ridge. Note the remarkable difference in the trend between Nishinoshima—Kaitoku volcanoes and Kita-iwojima—Minami-iwojima volcanoes. Crosses show the localities of benmoreitic trachyte around Iwojima Island. A broken line indicates their arrangement.

Table 2 Volcano spacing for the younger volcanoes in the Nishinoshima Trough.

Island / seamount	Spacing km	Canyon / Trough
Sofugan		
	55	
(Getsuyo Seamount)		
	28	
Kayo Seamount		
	119	Nishinoshima Trough
Kin'yo Seamount		
	39	
Doyo Seamount		
	48	
Nishinoshima		



1: Sagami Trough, 3: Niijima Canyon, 5: Mikura Canyon,
7: Aogashima Canyon, 10: Myojin Canyon, 12: Torishima Canyon,
13: Sofu Canyon, 16: Nishinoshima Trough (Sofugan Tectonic Line),
20: Iwojima Trough

Fig. 27 Volcano spacings along the Shichito-Iwojima Ridge from north (left) to south (right). Numerals on the columns are the interval in km. See also Table 1. Nichiyo, Suiyo, Mokuyo, Ohmachi and Sawa seamounts are neglected in the figure.

Iwojima Ridge is divided into nine segments. There are some canyons and troughs on the boundary among these segments (Fig. 25).

There are characteristic arrangements in distribution of individual peaks on the large composite volcanoes. This arrangement is defined as the third order distribution. To give a few instances, the distributions of individual highs on the composite volcanoes of Nishinoshima, Kaikata and Kaitoku show NNE-SSW trend, whereas those on the southern volcanoes of Kita- and Minami-iwojima show NNW-SSE trend (Fig. 26). The dikes on the Kita-iwojima Island also show the same trend (Kikuchi and Imaizumi, 1984).

The spacings of volcanoes are shown in Fig. 27. It is remarkable that the spacings of southern volcanoes, Nishinoshima to Minami-iwojima islands, are relatively constant, 65-78 km, whereas those of the northern volcanoes vary greatly and have a wide range from 20 to 90 km.. The spacings only for the younger volcanoes within the Nishinoshima Trough are shown in Table 2. Maximum spacing is about 119 km at the boundary between Kayo and Kin'yo seamounts. The irregular spacing in the northern volcanoes is represented by both narrow (20-25 km) and wide spacings (35-90 km) as shown in Table 1 and Fig. 27. The distribution of volcanoes (Fig. 25) and the projected sections (Fig. 28) show that there are some pairs of narrow spacing in the northern arc and the interval between each pair is wider. There are some canyons or troughs incising from the back-arc side or trench side in the wider spacing part (Table 1 and Fig. 25). Of these canyons, the Minami-mikura Canyon, for instance, incises along the fault (Oshima *et al.*, 1981; Yuasa, 1985b) and the different distribution pattern of earthquake aftershock area is recognized between the north and the south of the canyon (e.g., Kasahara *et al.*, 1974). The canyon makes a tectonic boundary here. There are the same possibilities for the other canyons or troughs. If so, it may be inferred that the volcanic spacing within the same structural block is narrow, while the volcanic spacing on the block boundary is wider along the volcanic front of the northern Izu-Ogasawara Arc. There is another remarkable example in the Nishinoshima Trough where the arc is divided into two parts, northern and southern. A major fault, Sofugan Tectonic Line, limits the western edge of the trough (Yuasa, 1985a). The volcanic spacing is as wide as about 119 km where the tectonic line crosses the volcanic front. These facts suggest that the fracture controls the distribution of volcano in the opposite sense of Vogt (1974a), i.e., volcanoes are not found for a long distance where the fracture crosses the arc.

The similar relations between volcano and fracture are known in the Northeast Japan Arc. On the basis of the distribution map of volcanoes and tectonic line in Tohoku area, Mukaiyama *et al.* (1983) showed that the

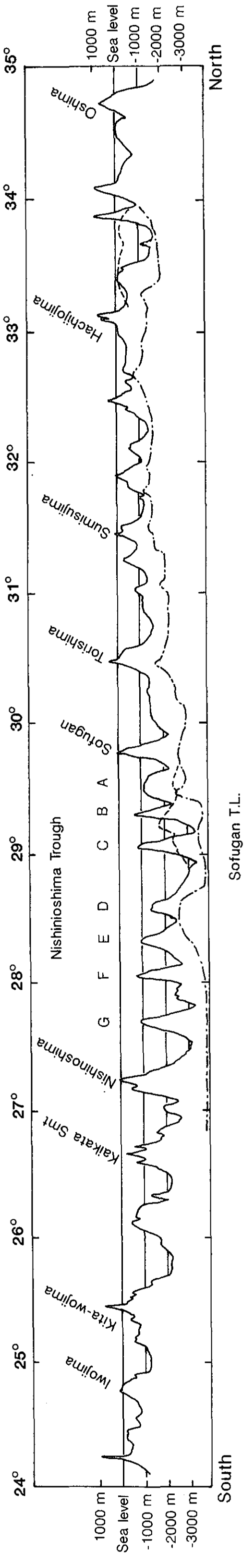


Fig. 28 A projected section of submarine topography along the Shichito-Iwojima Ridge. Solid and chain lines show the highest part of the ridge and the lowest part of the back-arc depressions just west of the ridge, respectively. Broken line indicates the highs belonging to the Shinkurose Ridge. Alphabets A to G are the same in ig.18.

spacing of volcanoes in the same crustal block bounded by the tectonic lines is narrow but the spacing between volcanoes in the different blocks is wide. Horikoshi (1979) examined the relation between volcanic distribution and basement geologic structure in the Kuril and Northeast Japan arcs and concluded that the characteristic features of non-volcanic area are continental suture (or plate boundary) or subsidence zone. On the basis of Central American volcanoes Carr (1984) also emphasized that at segment boundaries volcanoes are widely spaced.

3.2 Height and size of volcanoes

A projected section of the submarine topography along the Shichito-Iwojima Ridge is shown in Fig. 28. This figure is a projection through the highest parts of the ridge, showing a sky-line of the ridge observed from the east. The elevation (or depth) of each volcano is somewhat uneven as a whole. However, in the northern half it tends to decrease from Oshima to the south, while in the southern half it increases from the Nishinoshima Trough to the south. The variation in volcanic elevation shows a symmetry between the northern and the southern sides of Nishinoshima Trough (28-29°N). The elevation of volcanoes and depth of submarine volcanoes are meridionally arranged in Fig. 29. The elevation shows a zigzag pattern and decreases from north to south in the northern part, then it increases southward in the southern part. On the other hand, height of each of the volcanoes indicates different pattern as arranged in Fig. 30. Here the height is taken as the distance from top of the volcano to the changing point of slope inclination of the volcanic edifice. In this figure the height is nearly constant for each of the northern and southern parts divided by Nishinoshima Trough and does not show the tendency to change systematically toward the trough as represented by the variation in elevation. The zigzag pattern observed in the volcanic heights of the northern part may be caused by the mixture of different types of volcanoes, such as those erupted acid volcanic rocks and intermediate to basic volcanic rocks. In general, the height of volcanoes erupted acid volcanics is lower than the others in the northern part, and the height of these volcanoes is nearly constant. This suggests that the basement height decreases toward Nishinoshima Trough. Fig. 31 shows the basement depth of volcanoes (subtracting elevation from height or adding depth of the top of seamount to its height). The variation pattern indicated by the basement depth is similar to that by volcanic elevation. That is, the elevation of volcano reflects the basement depth. The maximum depth of water on the Shichito-Iwojima Ridge is near lat.29° N, where water depth is over 3400 m. In the southern part, the basement height increases from this deep to the south. Nishinoshima Trough intersects the Shichito-Iwojima Ridge at this deepest point. The trough forms a boundary between the north and the south of the Shichito-Iwojima Ridge. There are some different features of volcanic topography between them. For quantitative presentation of the topographic features, the relation between height and basal diameter of the volcanoes on the Shichito-Iwojima Ridge is shown in Fig. 32.

As easily recognized from this figure, these volcanoes are classified into some groups of geographic distribution or volcano types in terms of the relation between the height and basal diameter. There are seven groups including the Northern Mariana volcanoes as shown in Fig. 32. Four groups are distinguished by the geographic classification, such as the northern and the southern parts of the Shichito-Iwojima Ridge, the Nishinoshima Trough, and northern Marianas. In the northern Shichito-Iwojima Ridge, caldera volcanoes with acid volcanic rocks (dacitic or rhyolitic pumice) are distinguished from stratovolcanoes consisting of intermediate to basic volcanics. The seamounts in the Nishinoshima Trough are divided into two types, younger and older ones. Moreover, Ohmachi

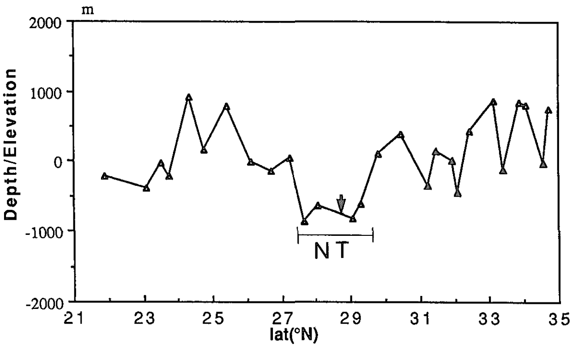


Fig. 29 Elevation and depth of volcanoes along the Shichito-Iwojima Ridge. Solid triangles show the volcanoes erupted acid volcanic rocks in the northern part. Nishinoshima Trough crosses the volcanic front between the range shown as NT. Arrow indicates the position where the Sofugan Tectonic Line intersects the volcanic front. Nichiyo, Suiyo, Mokuyo, Ohmachi and Sawa seamounts are neglected in the figure.

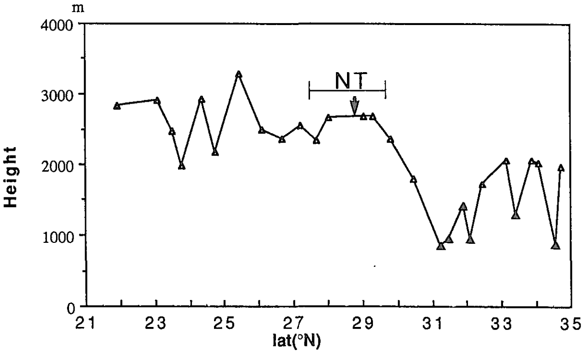


Fig. 30 Height of volcanoes along the Shichito-Iwojima Ridge. Solid triangles show the volcanoes erupted acid volcanic rocks in the northern part. Higashi-aogashima Caldera is plotted separating from Aogashima Volcano. NT and arrow same as in Fig. 29. Nichiyo, Suiyo, Mokuyo, Ohmachi and Sawa seamounts are neglected in the figure.

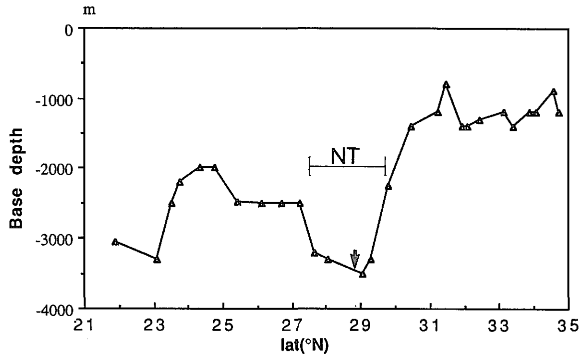


Fig. 31 Variation in depth of the base of volcanic edifice for the volcanoes along the arc axis of the Shichito-Iwojima Ridge. NT and arrow are the same as in Fig. 29. Nichiyo, Suiyo, Mokuyo, Ohmachi and Sawa seamounts are neglected in the figure.

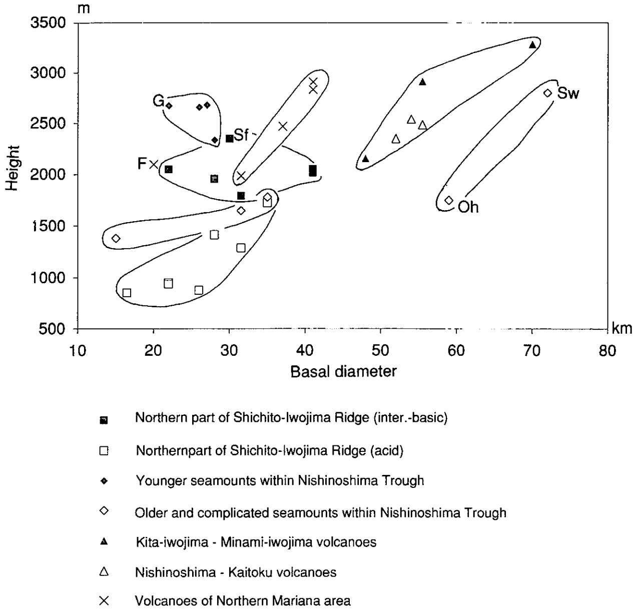


Fig. 32 Relation between height and basal diameter of volcanoes.
G: Getsuyo Seamount, Oh: Ohmachi Seamount, Sw: Sawa Seamount,
Sf: Sofugan Volcano, F: Fukutoku Seamount.

and Sawa seamounts off the axis of the volcanic front in the trough form another group. Sofugan Volcano including subaqueous part plots near to the younger volcano group in the trough rather than the group of stratovolcanoes in the northern part of the Shichito-Iwojima Ridge. From these classifications, the following regularity can be shown in the properties of seamount geomorphology.

First, the height of volcanoes in the northern part of Shichito-Iwojima Ridge is smaller than that in the southern part. This fact corresponds to the difference in the size of basal diameter between them, i.e., the basal diameter of the southern seamounts of Shichito-Iwojima Ridge is larger than that of the northern ones. Second, the height and basal diameter of caldera volcanoes with acid volcanics are both smaller than the others. Third, the height of stratovolcanoes with intermediate to basic volcanics on the northern Shichito-Iwojima Ridge is relatively uniform, whereas that of the southern volcanoes tends to be larger with increasing of the basal diameter. Forth, the height of younger seamounts within the Nishinoshima Trough is higher than that of the older ones. Ohmachi and Sawa seamounts are larger than those of the others in the Trough. These seamounts have ceased their activity since long geologic time ago so that their volcanic features were worn out by structural movement, sedimentation and erosion.

3.3 The origin of regularity of the volcanic topography

Regularity of the volcanic topography above mentioned shows conspicuous differences between the north and the south areas of the Sofugan Tectonic Line.

3.3.1 The differences in topography between northern and southern volcanoes

The differences between the two parts are summarized as follows;

	Northern part	Southern part
Height	low	high
Elevation	decrease to south	decrease to north
Spacing	narrow (irregular)	wide (constant)
Height of basement	decrease to south	decrease to north
Basal diameter	small	large

In addition to the above, there is difference in volume of volcanoes between the northern and the southern parts. As the volume can be regarded as a function of its height (Francis and Abbott, 1973), the difference in volume is not listed above. The existence of caldera volcanoes consisting of acid volcanic rocks is characteristic of the northern arc. These calderas form a group of low-height volcano. The origin of them is discussed in the next paragraph.

Ben-Avraham and Nur (1980) indicated that the elevation of volcanoes is constant within arcs on oceanic crust but varies on continental crust, while edifice heights are greatly variable on oceanic crust but constant on continental crust. In the Izu-Ogasawara Arc, the height of both northern and southern volcanoes is nearly constant, which corresponds to the characteristics of arc volcanoes on the continental crust. In addition to the height, the elevation or depth of volcanoes is variable, corresponding also to those on the continental crust. This contradicts their own description of the arc. They treated the volcanoes on the Izu-Ogasawara and Mariana arcs as a continuous arc on the oceanic crust and indicated that this is the best example which shows the pattern of oceanic volcanoes. They showed in their figure that the height of volcanoes decreases northward from the Mariana to the Izu-Ogasawara arcs. In the figure, however, if the volcanoes are divided into two parts, Izu-Ogasawara and Mariana arcs, it is also possible to interpret on the basis of their plots that the height of volcanoes in the Mariana Arc is higher than that in the Izu-Ogasawara Arc, but the height of volcanoes in each arc is almost constant. That is, if we regard the two arcs are independent, the height of volcanoes is constant for each and it is not a suitable example for that the height of volcanoes on the oceanic crust varies conspicuously. The same consideration has to be pointed out for the different topographic features between the northern and the southern parts of the Izu-Ogasawara Arc as summarized earlier, i.e., the northern and southern parts are of different units.

The height of volcanoes for each unit of the arc may not be related to whether the underlying crust is oceanic or continental. In each unit, the elevation (or depth) of volcanoes depends on the basement level (Fig. 31). In the case of the Izu-Ogasawara Arc (Shichito-Iwojima Ridge), two units are distinguished and each unit extends about 500-600 km along the axis. The misunderstanding of Ben-Avraham and Nur (1980) may be caused mainly from their disregarding of the submarine volcanoes and division of arc unit.

Submarine volcanism has taken place under the different environment from the subaerial condition. The rest angle of submarine volcanic edifice is supposed to be larger than that of subaerial one, and the submarine edifice grows up higher, if other conditions are the same. For this reason, pumice cones which are rarely found on land exist often under the sea, as will be mentioned in the next paragraph. On the other hand, the size and growth rate of subaerial volcanic edifice is smaller because its small rest angle and erosion by wind and rain, if other conditions are the same. Thus, it is expected that the height of volcanic edifice on the subaqueous arc becomes higher with increasing the proportion of its subaqueous part.

There are some discussions on what the spacing of volcanoes means. Vogt (1974a) noticed the relation between the spacing and crustal thickness and pointed out that the wide spacing of volcanoes is found on the arc with thicker crust and vice versa. In the Izu-Ogasawara Arc, volcano spacing is narrow in the northern part and wide in the southern part. According to Vogt (1974b), the underlying crust may be expected to be thinner in the northern part than the southern part. Crustal sections have been obtained near 32°N (Hotta, 1970) and 23.5°N (Murauchi *et al.*, 1968) in the Izu-Ogasawara Arc. The thickness of the crust on both sections is almost the same each other and shows about 15-17 km thick. Although the similar thickness is reported for the crust between the northern and the southern parts, the following facts suggest the difference between both crusts.

In the northern part of the arc, many calderas which erupted acid volcanics exist. If we considered that the acid rocks have been derived from remelting of crustal rocks like in those of Niijima and Kozushima islands (Onuma *et al.*, 1983), the heat source of remelting may be caused more from the thicker crust rather than the subducting plate. Because there are no different in age of subducting plates between the northern and the southern parts. The abundant occurrence of rocks belonging the hypersthenic-rock series, as will be mentioned elsewhere (Yuasa and Nohara, in prep.), also indicates the thicker crust of the northern part. Miyashiro (1974) emphasized the positive correlation between the crustal thickness and the proportion of calc-alkali series in whole volcanic rocks of each arc. The vast of arc mass shown by the 2000 m isodepth line may reflect the existence of thicker crust in the northern part. These facts suggest that the crust of the northern part is thicker than that of the southern part. The argument by Vogt (1974b) is inconsistent with the above.

Lingenfelter and Schubert (1974) argued that the spacing of arc volcanoes reflects the depth of partial melting and the length of spacing does not exceed the distance of magma source depth, i.e., the deeper partial melting, the wider spacing. As already mentioned in Yuasa and Tamaki (1982), there are some differences in chemistry of volcanic rocks on the volcanic front between the north and the south of the arc, i.e., low-alkali tholeiite occurs in the northern part whereas high-alkali tholeiite-alkaline volcanic rocks occur in the southern part. This suggests that the degree of partial melting of mantle source may be lower in the southern part than in the northern part. As will be shown in other volume (Yuasa and Nohara, in prep.), SB systematic diagram shows the same trend of the degree. Tatsumi *et al.* (1983) shows that the degree of partial melting is considered to depend on the temperature in the mantle wedge, and the degree increases with rising the temperature, i.e., the transfer to low pressure side in the wedge. This indicates that the higher degree of partial melting corresponds to the shallower depth of the melting. Therefore, it is possible that the depth of partial melting tends to be shallower in the north and deeper in the south.

This corresponds to the argument by Lingenfelter and Schubert (1974) concerning the spacing. That is, the narrower spacing of volcanoes in the northern part indicates the shallower depth of partial melting of mantle source than in the southern part of the arc.

3.3.2 Origin of submarine caldera

There are many volcanoes with calderas in the northern part of the volcanic front, but only one caldera is known in the southern part (Table 1). Recently, several submarine calderas have been newly found to the east of Aogashima Island, to the north of Bayonnaise Rocks, on the north of Sumisujima Island, etc. (Yuasa and Murakami, 1985; Murakami and Ishihara, 1985). The calderas concentrate in the northern part of the Izu-Ogasawara Arc (Yuasa and Murakami, 1985) and are recognized at 10 of 16 volcanoes on the volcanic front from Oshima Island to Nishinoshima Trough. The appearance rate of caldera exceeds 60 % here, which is remarkably high relative to the average rate of about 20 % for the world's arcs (Suzuki, 1977). Six of the ten calderas are accompanied with eruption of acid volcanic rocks (dacitic or rhyolitic pumice) and these calderas all occur under the sea. They are Kurose, Higashi-aogashima, Kita-Bayonnaise, Myojinsho, Sumisu and Minami-sumisu calderas from north to south. On the other hand, in the southern part of the arc there exists only one caldera associated with Kaikata Seamount. The seamount consists of andesitic and basaltic rocks, and no acidic volcanic rocks have been obtained yet from the seamount.

As mentioned above, the calderas producing acid volcanics in the northern Shichito-Iwojima Ridge all occur as the submarine volcanoes. Their basal diameter is very small relative to that of the subaerial caldera volcanoes which erupted a large volume of pyroclastic flow (Moriya, 1979), whereas the height of the submarine calderas is higher than that of the subaerial calderas (Figs. 32 and 33). The floor of these submarine calderas is almost at the same level of the surroundings. This shape may correspond to the feature of pyroclastic cones. Their dimension, however, is much larger than the subaerial cones (Wood, 1980). Stratified layers are often observed in seismic profiles of the caldera flank (e.g., Figs. 4, 7 and 9). This suggests that volcaniclastic materials cover the volcanic edifice. Ishihara (1987) showed that the density (2.43 and 2.38) of caldera seamounts (Higashi-aogashima and Sumisu calderas) is lower than the other non-caldera volcanoes (2.62-2.97). This supports that the caldera seamounts are possibly constructed by light materials.

According to the geophysical observations, these submarine calderas are associated with high gravity anomalies but in many cases their magnetic anomalies show narrow amplitude. Such calderas with the above mentioned features are not included in the general classification of calderas proposed by Aramaki (1983). Yokoyama (1974) classified calderas into two types, high gravity anomaly type and low gravity anomaly type. Examples of the former type are Oshima and Hawaii which erupted mafic lavas. The high gravity anomalies of these calderas are caused by the accumulation of high density lava into the crater. Shikotsu, Toya, Aso and Aira calderas belong to the latter, low gravity type caldera. These calderas were formed by the explosion erupting huge acidic volcanics (pumice). From these view points, the above submarine calderas are the high gravity anomaly type caldera in terms of gravimetric data, although the products of these calderas have characteristics of low gravity anomaly type caldera. In this area, there exists the typical high gravity anomaly type caldera, Oshima Volcano (Yokoyama, 1969).

Remarkable magnetic anomaly which reflects the dense lavas accumulating under the caldera floor is recognized in the volcano (Kato *et al.*, 1962; Nakatsuka, *et al.*, 1980). The amplitude of magnetic anomaly is characteristically small in these submarine calderas, and any dipole anomaly pattern corresponding just to the caldera is not recognized (Oshima *et al.*, 1981; Murakami and Ishihara, 1985). Even if there are some dipole anomaly pattern near the caldera, the anomaly corresponds only to a part of somma.

Although they are not accompanied with the loss of mass as observed in Shikotsu Caldera, it is also difficult to consider the accumulation of high density lava into the crater for the compensation for the loss as observed in the Oshima Volcano. From the above geological and geophysical features, it is concluded that the edifice is a huge submarine pumice cone.

Submarine pumice eruptions have been often observed as the pumice rafts on the sea or on the beach (Gass *et al.*, 1963; Kato, 1988). However, the eruption under the condition of deep water causes the deposition of the relatively high density pumice (for instance, woody pumice of Kato, 1987) near the crater, and their repetition will form the submarine pumice cone. In the case of subaerial pumice eruption the activity is explosive and the pum-

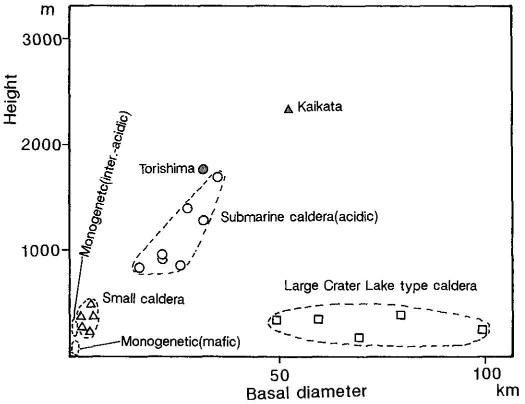


Fig. 33 Comparison between submarine caldera volcanoes and the Quaternary on-land volcanoes of Japan (after Moriya, 1979). Volcano types are classified by the difference in their development. Submarine calderas erupting pumice on the Shichito-Iwojima Ridge are plotted by open circle symbols in this diagram. Kaikata and Torishima calderas are also plotted by solid symbols.

ice is dispersed far from the vent as pumice fall and flow. So it is difficult to form a steep pumice cone under the subaerial condition (Moriya, 1984). Under the submarine condition, however, hot pumice just erupted immediately precipitates and deposits at the nearest place. The experiment by Whitham and Sparks (1986) has revealed that water is sucked into most of the vesicles immediately in the hot condition and even pumice with a density of 0.2 g/cm^3 will sink if the temperature exceeds 700°C. Then the hot pumice does not float on the surface of water as far as the eruption is kept in submarine condition. This is the reason why the pumice cone is easily formed under the submarine condition. When the pumice cone grows near the surface of water, the top of cone is to be easily eroded by wave. In this case, the growth rate of the cone becomes small. If pumice eruption occurs under the shallow water condition, the erupted pumice partly or mainly goes out of water and begins to float above mentioned. When the edifice itself grows above the surface of water, explosive pumice eruptions occur under the subaerial condition and no pumice cone grows more. At the same time, the edifice is eroded out by wave within a relatively short period. The submarine eruption and formation of a new island near the Satsuma-iwojima (io-zima) described by Tanakadate (1935) is an example of this case. Omurodashi, south of Oshima Island, may be such an eroded remnant of pumice cone.

As mentioned above, submarine calderas associated pumice in the northern part of the Izu-Ogasawara arc are the pumice cones which is difficult to be formed under the subaerial condition but easy under the subaqueous condition. The edifice seems to be constructed mainly of pumice deposits around the crater. Therefore these calderas are not accompanied with low gravity anomaly in spite of pumiceous eruption. It is concluded that acid volcanism occurs under subaqueous condition in the northern part of the Izu-Ogasawara Arc as shown in Fig. 29 and they form the pumice cones with large crater which is recognizable as caldera. Therefore the appearance rate of caldera is remarkably high in the northern part of the Izu-Ogasawara Arc.

As compared with the above pumice caldera, the caldera of the Kaikata seamount is different. It consists of andesitic lavas, dikes and volcanic breccias. Diameter of the caldera is as small as about 3 km. In the northwestern part of the floor, a basaltic central cone exists. The dikes intruding in the caldera wall run parallel to the wall (Yuasa *et al.*, 1988) and they may form a ring-dike system though it is not ascertained yet. There are some indications of hydrothermal activity, and altered volcanic rocks with sulfide minerals were obtained (Urabe et al., 1987). Submersible study by "Shinkai 2000" showed that some dikes intrude the alteration zone but they are not altered themselves (Urabe, personal communication), suggesting that hydrothermal alteration occurred prior to the dike intrusion. Although the caldera may be assigned to the Haruna-type (or funnel-type) of Aramaki (1983) because of its small diameter, it is not clear whether the gravity anomaly observed on the caldera is high or low. The caldera wall retreats in several places and a large amount of talus breccia is deposited on the base of wall. The dikes parallel to the wall are exposed in the canyon formed by wall retreating. Accordingly, the original caldera is considered to be smaller than the present.

4. Conclusions

1) Morphology of the volcanic edifices on the Shichito-Iwojima Ridge, the volcanic front of the arc, shows certain difference for the height, basal diameter and spacing of volcanoes between the northern and southern parts of the arc. The height and basal diameter of the northern volcanoes are low and small, while those of the southern volcanoes are high and large. Spacing between the edifices is narrow and irregular in the former, and wide and regular in the latter. The irregularity of spacing in the northern volcanoes seems to be caused from the structural discontinuity, e.g., the volcanic spacing within the same structural block is narrow, while that on the block boundary is wider.

2) The volcanoes on the volcanic front are classified into seven groups in terms of the relation between the height and basal diameter. Four groups are distinguished by the geographic classification, i.e., the northern and the southern parts of the Shichito-Iwojima Ridge, the Nishinoshima Trough, and northern Marianas. In the northern Shichito-Iwojima Ridge, caldera volcanoes with acid volcanic rocks are distinguished from the others consisting of basic volcanics. The seamounts in the Nishinoshima Trough are divided into two types, younger and older ones by chronological relation.

3) Regularity of the volcanic topography shows conspicuous differences between the north and the south areas of the Sofugan Tectonic Line. These two parts are regarded essentially as independent units of the arc. There is each characteristic feature for the height of edifice of each unit. It does not seem to be related to whether the underlying crust is oceanic or continental. It is expected that the height of volcanic edifice on the subaqueous arc becomes higher with increasing the proportion of its subaqueous part. In each unit, the elevation of volcanoes depends on the basement level. The difference of edifice spacing between both units of arc may reflect the depth of partial melting of mantle source.

4) Topographic features of seamounts in the Nishinoshima Trough are distinguished from the nearby seamounts in the relation between height and basal diameter. These seamounts are subdivided into three types, and it coincides with the other division by magnetic anomaly and seismic profiling features.

5) Existence of submarine calderas producing acidic ejecta is a special feature in the northern Shichito-Iwojima Ridge. These calderas have higher edifices and narrower basal diameter than the subaerial Crater Lake-type calderas. Low density determined from gravimetric data and weak magnetic amplitude shows that the caldera seamounts are possibly constructed by light and acidic volcanic materials. The caldera floors are nearly at the same level of the surroundings. The shape of the caldera seamounts corresponds to the feature of pyroclastic cone, especially pumice cone in this case. Pumice cones are difficult to form under the subaerial condition but easy under the subaqueous condition.

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(J): in Japanese, (JE): in Japanese with English abstract.

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伊豆・小笠原弧火山フロントの海底火山地形

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要　旨

伊豆•小笠原弧の火山フロントである七島-硫黄島海嶺の海底火山地形を記載し，それらの配列，比高，底径，山体の間隔等に見られる規則性を総括した．各火山および地域ごとのグループにみられる上記要素に関する規則性は，伊豆・小笠原弧を南北に二分する構造線，孀婦岩構造線を境に次のようにまとめられる．

	北部	南部
比高	低い	高い
高さ	南へ減少	北へ減少
間隔	狭い，不規則	広い，一定
基盤高度	南へ低下	北へ低下
基底の直径	小さい	大きい
海底カルデラ	多い	少ない

南北間に見られる上記の規則性の違いは，本島弧の南部および北部で島弧地殻の厚さが異なっていることを暗示している．

南部および北部の間に存在する西之島トラフ内の海山は，その南北の火山とは独立した特徴を示している．これらは，海底地形，音波探査プロファイルにみられる特徴の違いに基づいて，火山フロント上にならぶ新期および古期海山，および火山フロントをはさんで分布する大型の古期海山の，３つのタイプに分けられる．

伊豆・小笠原弧北部には，酸性火山岩を噴出している海底カルデラが多く出現することが特徴となっている．これらのカルデラは，その形態および地球物理データから海底で生じた軽石丘と考えられる．陸上では軽石丘の存在はまれとされているが，海面下という条件のもとでは比較的形成され易いのであろう．このため伊豆・小笠原弧北部のカルデラ出現率が高くなっている．

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