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Gravity anomalies over the Izu-Ogasawara (Bonin) and northern Mariana Arcs

Takemi ISHIHARA* and Toshitsugu YAMAZAKI*

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Abstract: Detailed marine gravity surveys of the Izu-Ogasawara (Bonin) and northern Mariana Arcs were conducted from 1984 to 1989 using LaCoste-Romberg S-63 and SL-2 sea gravimeters.

The following features of gravity anomalies were observed: (1) Free-air anomalies of the spreading center area at about 18°N in the Mariana Trough have a minimum of 5 mgal and maximum of 85 mgal, which correspond to a maximum water depth of 5000 m and a minimum of 3000 m, respectively. Free-air anomalies and water depths south of 22°N in the northern Mariana Trough have similar amplitudes, and an active spreading is suggested in this area. In the north of 22°N, the trough becomes shallower northward, while the free-air anomalies remain in the same range as in the south. A simple model calculation results in crustal thickness of 6.1 to 9.3 km in the south of 22°N and 9.0 to 9.7 km in the north. Free-air anomalies over the seamounts of the Mariana and the West Mariana Ridges exceed 10 mgal. (2) Free-air anomalies have an amplitude of 100 to 200 mgal over the seamounts and islands along the Shichito Ridge and west of it. Taking the water depths and the sizes of seamounts into consideration, Sofugan Island and Mokuyo Seamount are associated with relatively high amplitudes of anomalies, which suggests the island and the seamount are made of high density rocks. High Bouguer anomalies are observed over the Sumisu and Aogashima Calderas. Intrusion of high density rocks is inferred in the centers of these calderas. (3) The free-air anomaly maximum over the Higashi Seamount of the Ogasawara Plateau is only 175 mgal, while the maximums over the tops of Yabe, Hanzawa and Katayama Seamounts all exceed 200 mgal. The water depths of the seamounts are almost the same. Thus, it is inferred that the crust of the Ogasawara Plateau is thicker than that of the eastern islands.

1. Introduction

Marine gravity surveys conducted by the Geological Survey of Japan in 1979 revealed general features of free-air gravity anomalies in the Izu-Ogasawara (Bonin) and northern Mariana Arcs (Ishihara *et al.*, 1981). In these surveys, ship's tracks were taken at intervals of 15 nautical miles in general. The Geological Survey of Japan carried out detailed marine geological and geophysical surveys in this region from 1984 to 1989 for studying hydrothermal activity here. More detailed information on gravity anomalies associated with many seamounts and other topographic features in the Izu-Ogasawara and northern Mariana Arcs was obtained from these surveys and is described in this report. The spacing of the survey lines of this new project was 2 to 4 nautical miles (Figure 1).

* Marine Geology Department

Keywords: marine gravity survey, free-air anomaly, seamount, crustal thickness, Izu-Ogasawara Arc, northern Mariana Arc

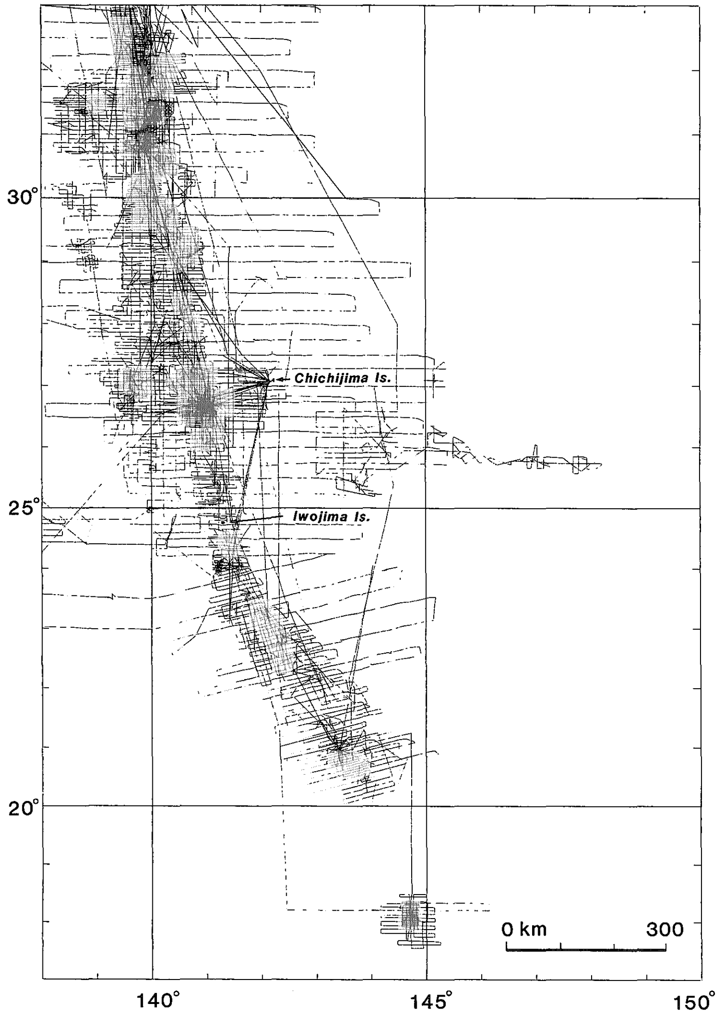

Fig. 1 Ship's tracks of gravity measurements conducted by the Geological Survey of Japan. Tracks of the surveys in 1979 (15 miles interval) (Ishihara *et al.*, 1981) are included.

2. Method of gravity measurements

Gravity measurements were carried out by a LaCoste-Romberg air-sea gravimeter S-63 during cruises of the survey vessel Hakurei-maru from 1984 to 1986. A new LaCoste-Romberg air-sea gravimeter SL-2 has been used since 1987. Both gravimeters are on gyrostabilized platforms. The old gravimeter had an analog computer to calculate cross-coupling corrections, whereas no cross-coupling corrections are necessary for the new straight-line gravimeter because the sensor moves vertically in a straight line (LaCoste, 1983). The new gravimeter uses silicon fluid damping instead of air damping of the old one. In order to suppress noise due to ship's vertical movement, an analog low-pass filter was applied to the raw output of the sensor in the old gravimeter. On the other hand, a PC is combined with the new gravimeter and output of a low-pass filter is calculated digitally.

The gravimeters were calibrated at Funabashi Port and Futami Port, Chichijima Island to obtain absolute gravity values in the

IGSN 71 system. Linear drifts of the gravimeters were assumed between ports. The IAG 1967 gravity formula was used for the latitude correction.

Ship's positions were determined by a satellite-Loran C integrated navigation system. This system generally has an accuracy of about 0.1 nautical mile. The Eötrös correction, which is a function of ship's heading and velocity, is usually expected to have an accuracy of about 1 mgal with this navigation system, and the total system of the gravity measurement probably has an accuracy of the same order.

3. Features of free-air anomalies

3.1 Spreading center at 18°N in the Mariana Trough

The Mariana Trough is known as one of active backarc basins in the world (Karig, 1971). The trough is widest at about 18°N. Figure 2 shows free-air anomalies and topography in a small box at 18°N which includes a spreading center. Free-air anomalies in this area are generally positive with an average value of about 40 mgal. This is probably due to the gravity effect of a high density cold sinking slab of the Pacific plate.

There is a low gravity anomaly belt with values less than 30 mgal extending in the NNW-SSE direction from 18°30'N, 144°40'E to 17°40'N, 144°55'E. This belt approximately corresponds to a topographic low at the spreading center (axial graben). A minimum value of 5 mgal was obtained at 17°57'N, 144°49'E, where the axial graben also becomes deepest (the water is almost 5000m deep).

Free-air anomaly maximums (up to 85 mgal) occur on topographic hills on both sides of the spreading center. Beyond the western hilly area, there is another graben more than 4000m deep. The free-air anomaly minimum associated with this graben is more subdued than that in the axial graben. Along the E-W traverse of 18°01'N, a minimum of 34 mgal lies in the western graben, where the water depth is about 4200m, while a minimum of 13 mgal, which is about 20 mgal less than in the former area, occurs in the central graben with an axial high about 3800m deep. This fact indicates that free-air anomalies in the central axial graben are lower than the values expected from its water depth. This observation may be interpreted as the gravity effect of a cooling oceanic lithosphere, which has a minimum value at the spreading center and increases as the lithosphere moves away from the spreading center (Prince and Forsyth, 1988).

3.2 Northern Mariana Arc

Figure 3 shows free-air anomalies and the outline of topography over the northern Mariana Arc from 20°N to 24°N.

Large amplitude positive anomalies are associated with seamounts along the Mariana and West Mariana Ridges. Maximum free-air anomaly values occur above the tops of Kita-Hiyoshi (143 mgal), Minami-Hiyoshi (158 mgal), Nikko (158 mgal), Sanpuku (171 mgal), Shoyo (150 mgal), Fukujin (177 mgal), Kasuga (114 mgal), Minami-Kasuga (149 mgal), Daikoku (136 mgal) and Minami-Daikoku (128 mgal) Seamounts from north to south along the Mariana Ridge (volcanic arc), and on the top of Takasu Seamount (169 mgal) on the West Mariana Ridge (remnant arc).

Taking depths and sizes of the seamounts into consideration, the free-air anomaly maximums associated with the seamounts in the northern part of the arc are lower than those in the southern part. For example, Minami-Kasuga Seamount, which has a top deeper than 500m, is associated with a maximum greater than that of Kita-Hiyoshi Seamount, which has a top shallower than 300m and a seamount size (diameter) bigger than Minami-Kasuga Seamount. This suggests that the crust becomes thicker toward the north.

In the northern Mariana Trough, a tectonic boundary exists at about 22°N, which extends

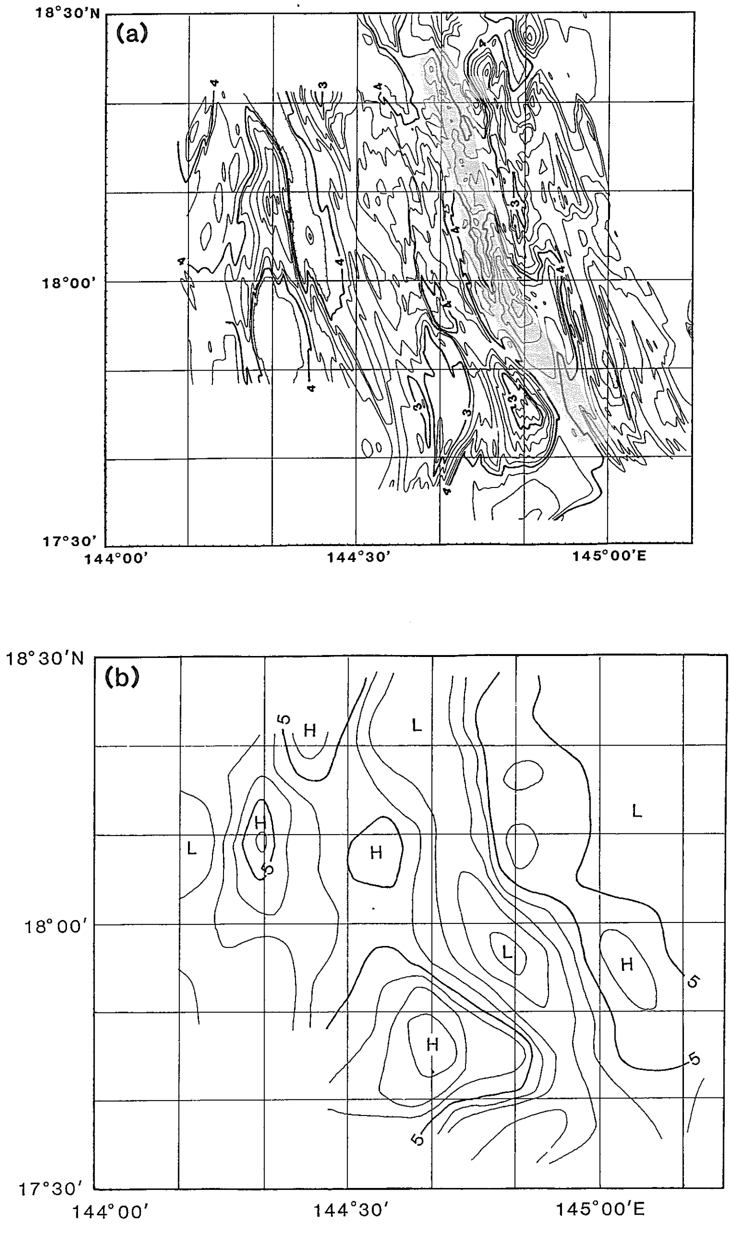

Fig. 2 (a) Bathymetric contour map at 18°N of the Mariana Trough close to a spreading center (shaded). Contours are at 200m intervals. Unit of the figures in this map is 1000m. (b) Free-air gravity anomaly map in the same area. Contours are at 10 mgal intervals. Unit of the figures in this map is 10 mgal.

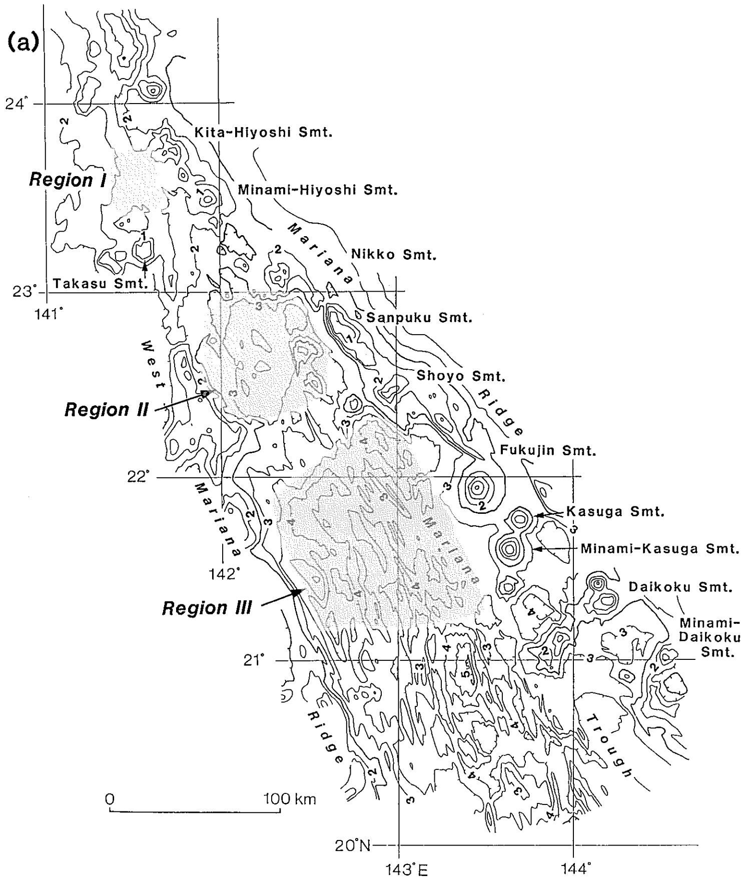

Fig. 3 (a) Simplified topography of the northern Mariana Trough from 20°N to 24°N. Contours are at 500m intervals. Unit of the figures is 1000m. Regions I, II and III are three regions with different crustal models shown in figure 8. (b) Free-air anomalies in the same area. Contours are at 10 mgal intervals. Unit of the figures is 10 mgal.

southwestward from Shoyo Seamount. The trough widens from about 80 to 120 km and deepens from about 3000 to 4000m rather abruptly at this boundary. It is considered from magnetic anomalies and geological structure that north of this boundary the trough is now in a rifting stage and that the trough has developed to a spreading stage south of it (Yamazaki *et al*., 1988; Murakami *et al*., 1989).

On the south of the boundary at 22°N, free-air anomalies are generally positive with an average value of 40 to 50 mgal. A free-air minimum belt of less than 50 mgal, which is associated with the central grabens being interpreted as spreading centers from the analysis of magnetic anomalies and geological structure, is extending in the SSE direction from 22°10'N, 142°55'E to 20°30'N, 143°30'E, bending eastward to 20°30'N, 143°55'E, and then extending toward SSE again. Free-air anomaly minimum of 2 mgal occurs in a deep along the central grabens at 20°55'N, 143°23'E, and a minimum of 4 mgal at 20°35'N, 143°30'E. Free-air anomalies are generally greater than 50 mgal in hilly areas on both sides of the central grabens with a maximum of 88 mgal at about 20°20'N, 143°43'E, where the water depth becomes shallower than 3000m. The above observations including the range of water

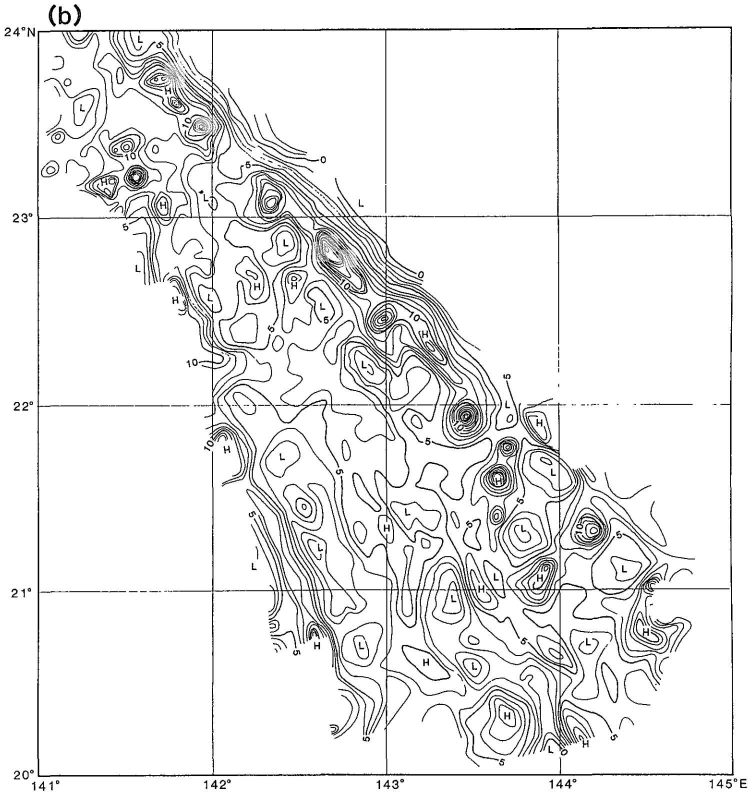

Fig. 3 continued

depths are very similar to those at the spreading center at 18°N, which was described in the previous section. It is hence strongly suggested that the sea-floor spreading is also active in this area.

Free-air minimums up to 5 mgal occur in the western margin of the trough, where topographically no prominent deeps exist. These minimums are probably due to crustal thickening below the West Mariana Ridge. Similar effect is observed also in the eastern margin of the trough. A basin between Kasuga and Daikoku Seamounts is 3000 to 3200m deep, but the free-air anomalies are less than 20 mgal, much lower than the values for the same water depth in the central grabens. The crust also thickens toward the Mariana Ridge.

On the north of the boundary at about 22°N, the water depth of the trough becomes shallower northward. It reaches about 2500m at about 23°20'N, south of Minami-Hiyoshi Seamount. Free-air anomalies are, however, almost the same on an average, ranging from 30 to 60 mgal with a minimum of 25 mgal in a basin south of Nikko Seamount. This fact also suggests northward crustal thickening. The water depth of the trough decreases further north to 1200-1300m in an area between Kita-Hiyoshi and Takasu Seamounts, where free-air anomaly values increase by a relatively less amount to about 85 mgal.

3.3 Southern Izu-Ogasawara Arc: Minami-Iwojima Island to Kaikata Seamount

Figure 4 shows free-air anomalies and topography of the southern Izu-Ogasawara Arc from 24°N to 27°N, south of Minami-Iwojima Island to north of Kaikata Seamount.

The Ogasawara Trough is associated with a

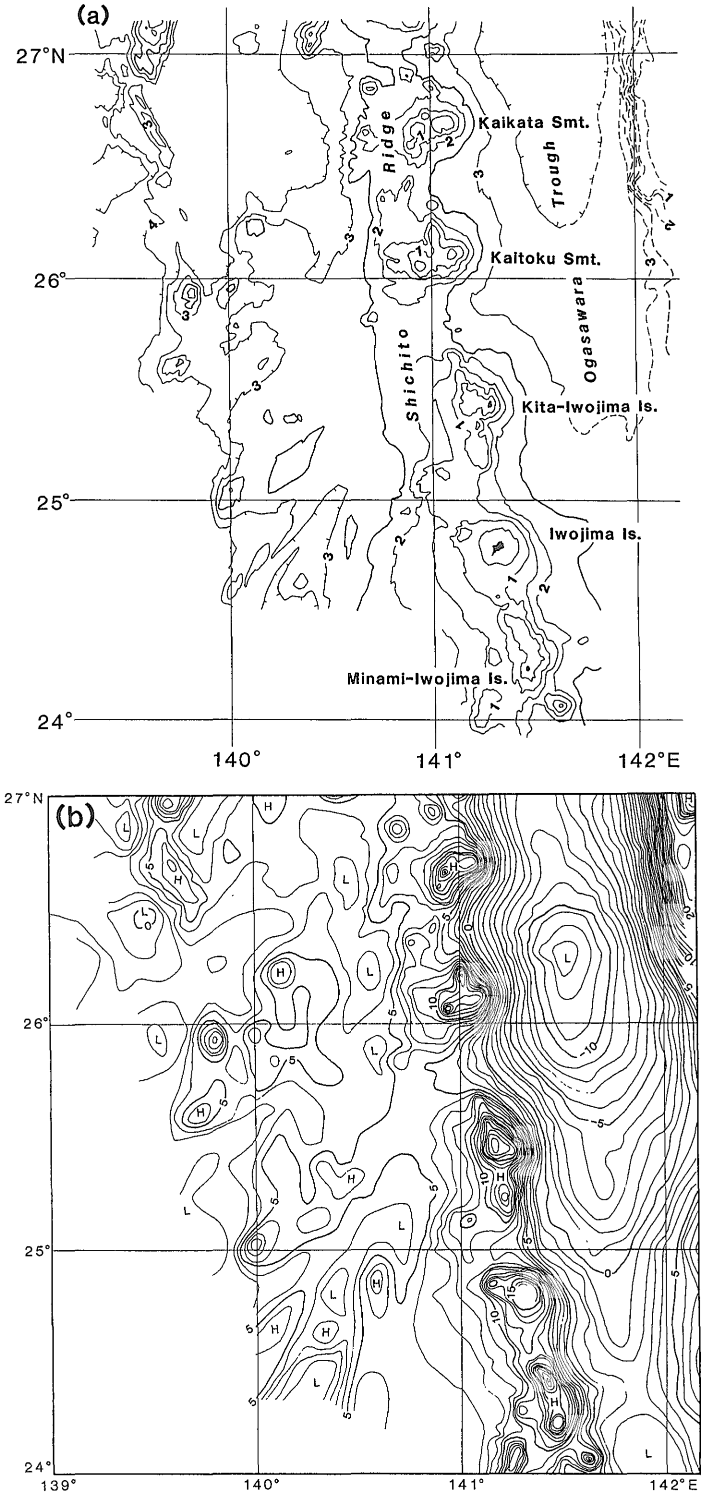

Fig. 4 (a) Outline of topography of the southern Izu-Ogasawara Arc from 24°N to 27°N. Contours are at 500m intervals. Unit of the figures is 1000m. Solid contours are based on the data of the Geological Survey of Japan, and dashed contours are based on charts of the Hydrographic Office. (b) Free-air anomalies in the name area. Contours are at 10 mgal intervals. Unit of the figures is 10 mgal.

large amplitude negative free-air anomaly belt . A minimum value of -134 mgal occurs in the south of the trough. A Bouguer anomaly map compiled using previous data revealed that an area with anomalies less than 200 mgal extends in the N-S direction from 27°30'N to 23°N and covers not only the Ogasawara Trough but also the Shichito Ridge (Ishihara *et al.*, 1982). This suggests the ridge in this area has thicker crust.

Free-air anomalies greater than 150 mgal occur on the tops of islands and major seamounts along the Shichito Ridge: 190 mgal in a shallow area north of Minami-Iwojima Island, 181 mgal on Iwojima Island (Ehara, 1985), 185 mgal at 25°28'N, 141°10'E, just west of Kita-Iwojima Island, 155 mgal at the southwestern peak of Kaitoku Seamount, 150 mgal at the central peak of Kaikata Seamount and 190 mgal on Nishinoshima Island (Oh-Kawa and Yokoyama, 1977).

On saddles between neighboring seamounts and islands of the ridge, free-air anomalies decrease to almost 50 mgal. The large-amplitude negative anomalies associated with the Ogasawara Trough cause the axis of maximums to be shifted westward from the topographic crest of the Shichito Ridge. This is most clearly visible on the saddle between Kita-Iwojima Island and Kaitoku Seamount. Free-air anomaly maximums are located about 20 km west of the topographic crest.

The water depth generally increases westward from the Shichito Ridge. Free-air anomalies are, however, almost comparable to those on the saddles between the islands and seamounts constituting the Shichito Ridge; generally 50 to 70 mgal in hilly areas with water depth less than 2800m, and 20 to 40 mgal in topographic lows. This fact suggests that the crust thins westward from the Shichito Ridge. There are small-amplitude minimums on the western flank of the Shichito Ridge (at 25°52'N, 140°35'E; 26°15'N, 140°35'E; 26°40'N, 140°28'E), where water depths generally increase westward. These observations also suggest westward crustal thinning. Small-amplitude maximums occur over seamounts in this area. A prominent one with amplitude of 91 mgal lies at 25°55'N, 139°48'E.

3.4 Middle Izu-Ogasawara Arc: Nishinoshima to Sofugan Islands

This section describes the feature of free-air anomalies in the middle Izu-Ogasawara Arc from 27°N to 30°N, between Nishinoshima and Sofugan Islands. A free-air anomaly map and simplified topography are presented in Figure 5.

In the western part of the Ogasawara Trough, an axis of negative free-air anomalies with amplitude of -55 to -30 mgal lies to the north of 28°45'N, where the topography is almost flat. The latter fact suggests basement uplift in the eastern part of the Ogasawara Trough.

Maximum anomalies generally greater than 120 mgal lie over seamounts along the Shichito Ridge. Maximums of 200 mgal and 150 mgal occur on Sofugan Island and over Mokuyo Seamount, respectively. These values are anomalously high in comparison with neighboring seamounts considering their sizes and water depths. Densities of 2.90 ± 0.03 g/cm^3 and 2.97 ± 0.04 g/cm^3 were obtained for these seamounts, respectively, from detailed calculation based on a simple assumption of homogeneous density (Ishihara, 1987). Over the base region of these seamounts, free-air anomalies decrease to 70 to 80 mgal, and minimum values up to 25 mgal occur in small basins among the seamounts.

The Nishinoshima Trough, extending south-southwestward to the west of the Shichito Ridge, is associated with a low gravity belt with free-air anomalies less than 30 mgal. A free-air anomaly maximum of 145 mgal occurs over a seamount on the west of the southern part of the trough (Tenpo Seamount). Another trough (unnamed) extending south-southwestward from 29°N, 139°50'E parallels the Nishinoshima Trough, and is associated with a belt of free-air anomalies less than 40 mgal. A hilly area

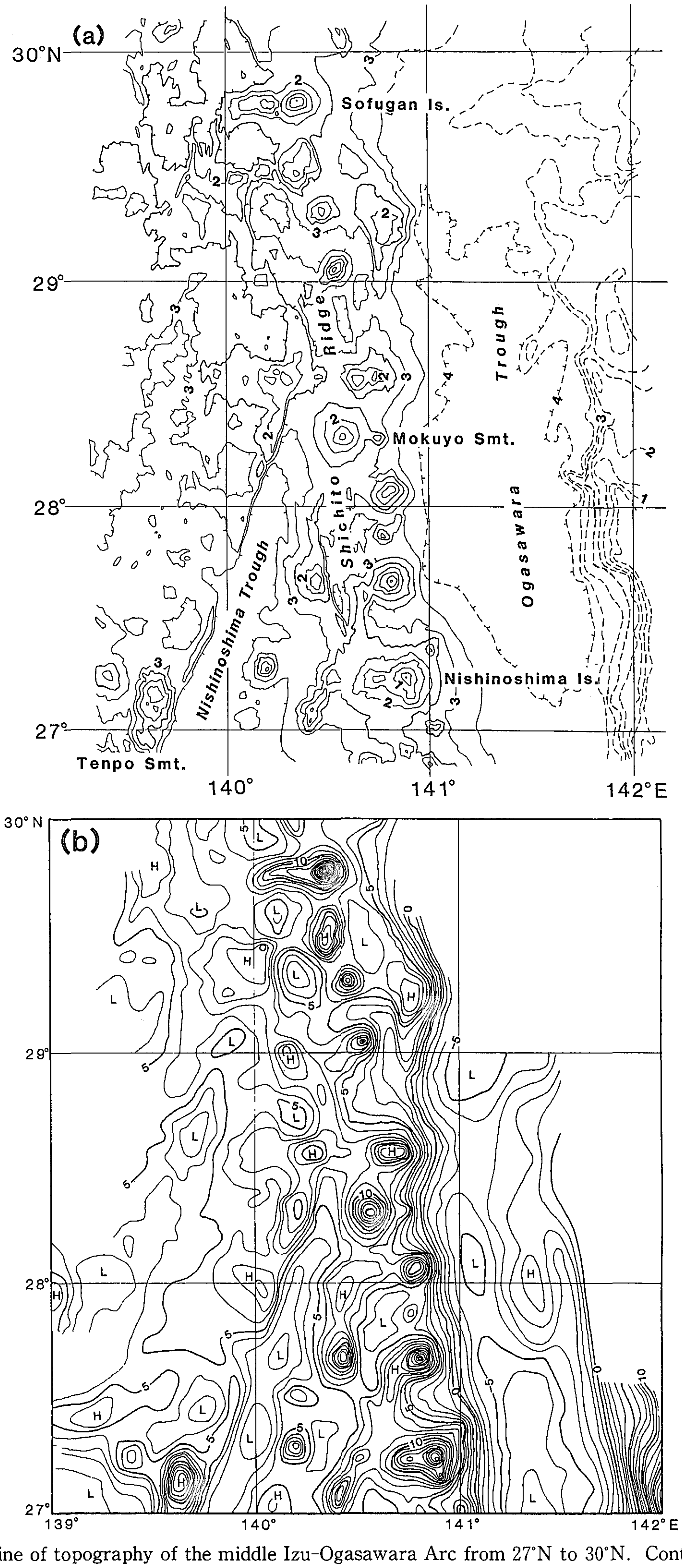

Fig. 5 (a) Outline of topography of the middle Izu-Ogasawara Arc from 27°N to 30°N. Contours are at 500m intervals. Unit of the figures in 1000m. Solid contours are based on the data of the Geological Survey of Japan, and dashed contours are based on charts of the Hydrographic Office. (b) Free-air anomalies in the same area. Contours are at 10 mgal intervals. Unit of the figures is 10 mgal.

between both troughs has free-air anomalies generally greater than 50 mgal.

3.5 Northern Izu-Ogasawara Arc: Torishima to Aogashima Islands

Maximums ranging from 140 to 180 mgal lie over seamounts along the Shichito Ridge including Torishima, Sumisujima and Aogashima Islands (Figure 6). Sumisu and Aogashima submarine calderas have high Bouguer anomalies, which suggest existence of high-density rocks under these calderas (Murakami and Ishihara, 1985; Ishihara, 1987).

Small grabens on the west of the Shichito Ridge are associated with minimum values in the range of 45 to 65 mgal. These grabens are considered to be active backarc rifts from geological structure (Karig and Moore, 1975; Honza and Tamaki, 1985; Murakami, 1988).

Ridges trending NE-SW to the west of the Shichito Ridge are associated with large-amplitude anomalies. Maximums of 100 to 150 mgal occur over many seamounts on the ridges.

3.6 Ogasawara Plateau and neighboring seamounts

The Ogasawara Plateau, which is now encountering the Izu-Ogasawara Trench, is the western extension of the Marcus-Wake Seamount Chain. Gravity survey was carried out over the Ogasawara Plateau and three seamounts east of the plateau (Figure 7).

Free-air anomalies exceed 200 mgal over the tops of the eastern seamounts: 223, 230 and 258 mgal on those of Yabe, Hanzawa and Katayama Seamounts, respectively.

Higashi Seamount, which is a peak located on the northeastern part of the Ogasawara Plateau, is associated with a maximum of 175 mgal, which is significantly lower than the anomaly maximums above the eastern seamounts. If we consider that the tops of this seamount and the eastern seamounts have water depths in the same range, i.e., 800 to 1500 m, it is inferred that the Ogasawara Plateau has thicker crust than the eastern seamounts.

Minimum values accompanied by the Izu-Ogasawara Trench increases to -43 mgal at the junction of the Ogasawara and Mariana Trenches, where Nishi Seamount on the plateau is subducting. The axis of negative free-air anomaly belt almost coincides with the trench axis in this area. This is in contrast to the observation at major trenches such as the Japan Trench, at which the former axis is shifted landward from the latter.

4. Discussion

It is inferred that in the northern Mariana Trough the crustal thickness increases northward. Here, this problem is studied in a simplified but more quantitative manner.

Only three layers, i.e., sea water, crust and upper mantle are considered, and the gravity effect of these three layers is approximated by a simple infinite horizontal slab model:

$$g_F = 2\pi G(\rho_W - \rho_M) h_W + 2\pi G(\rho_C - \rho_M) h_C + g_0 \qquad (1)$$

where g_F is a free-air anomaly, G is the gravitational constant (=6.672 if mgal, g/cm^3 and km are used as units of gravity anomaly, density and thickness (or depth), respectively) and ρ_W, ρ_C, ρ_M are densities for sea water, the crust and the upper mantle, respectively. In the following calculations, ρ_W, ρ_C and ρ_M are assumed to be 1.03, 2.67 and 3.30 g/cm^3, respectively. As a natural consequence it follows that $\rho_W - \rho_M = -2.27$ g/cm^3, and $\rho_C - \rho_M = -0.63$ g/cm^3. A parameter g_0 is assumed to be a constant throughout the trough, and is considered as an imaginary free-air anomaly when the trough is filled with upper mantle material and neither sea water nor crustal layer exists there. According to this equation, a free-air anomaly depends only on the water depth h_W and the crustal thickness h_C.

Murauchi *et al.* (1968) obtained crustal structure of the northern end of the Mariana Trough by a seismic refraction method. They divided the crust into four different seismic velocity layers, but we consider them

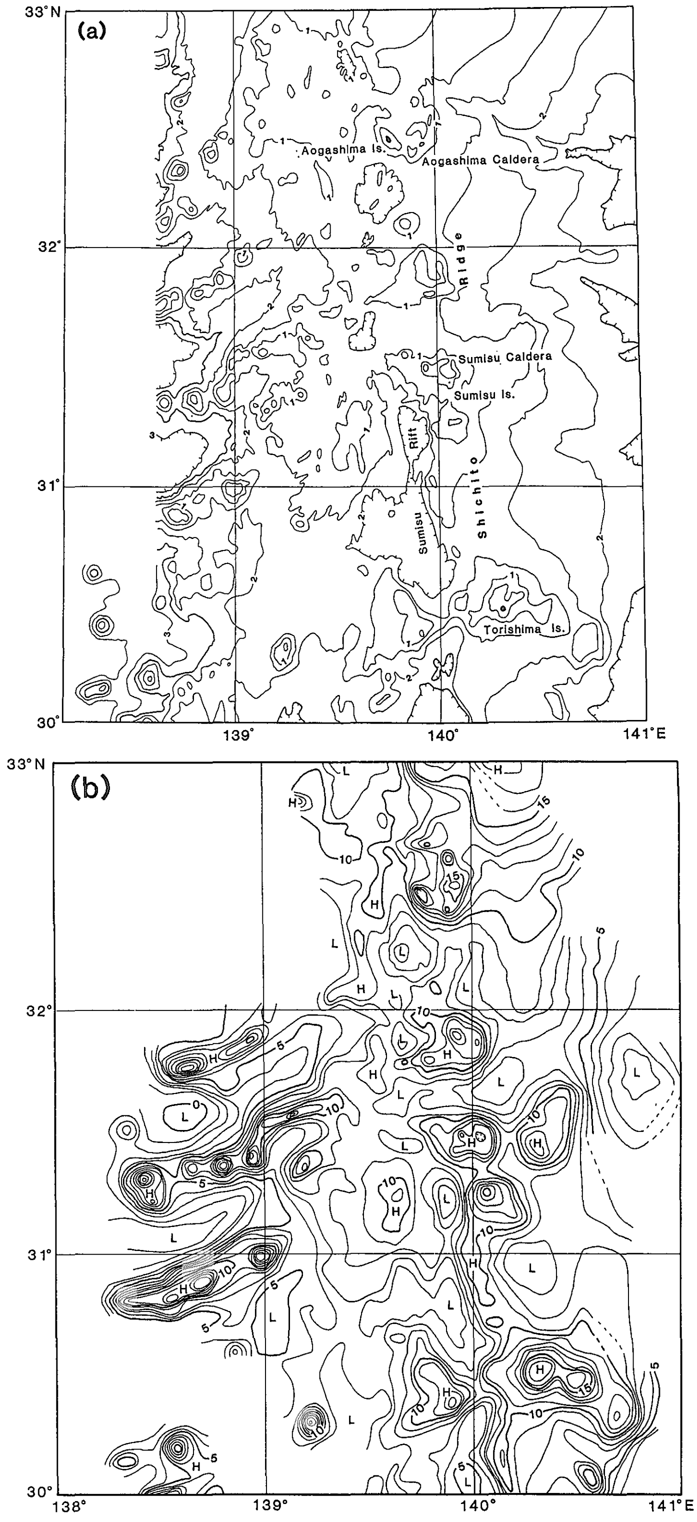

Fig. 6 (a) Outline of topography of the northern Izu-Ogasawara Arc from 30°N to 33°N. Contours are at 500m intervals. Unit of the figures is 1000m. (b) Free-air anomalies in the same area. Contours are at 10 mgal intervals. Unit of the figures is 10 mgal.

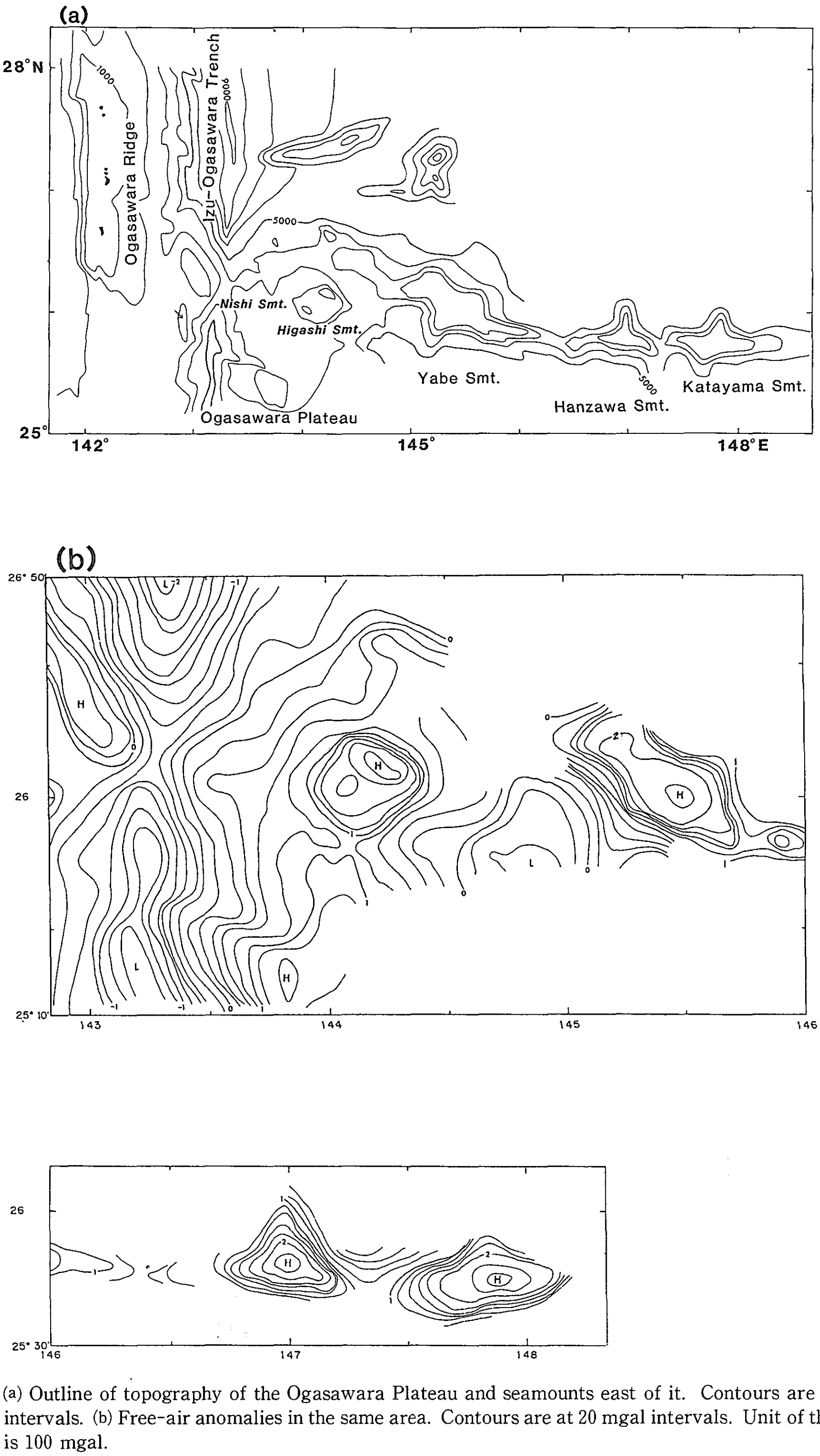

Fig. 7 (a) Outline of topography of the Ogasawara Plateau and seamounts east of it. Contours are at 1000m intervals. (b) Free-air anomalies in the same area. Contours are at 20 mgal intervals. Unit of the figures is 100 mgal.

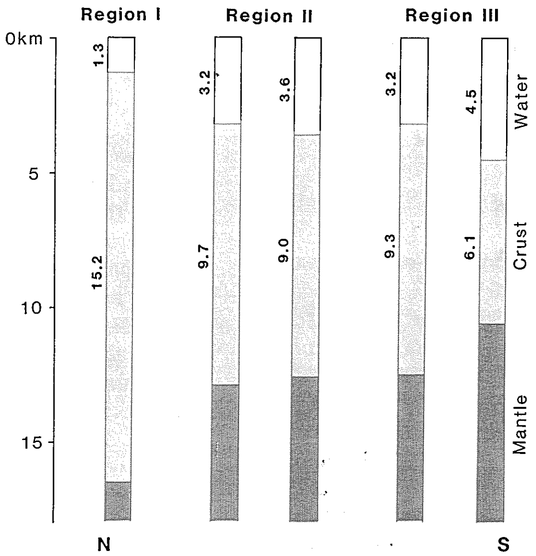

Fig. 8 Crustal models for northern Mariana Trough. Region I: northern end of the trough (about 23°30'N), Region II : north of the boundary at 22°N, Region III: south of the boundary at 22°N (see Figure 3a). Figures on the left side of each column indicate thichnesses in km.

as one layer in our density model for the sake of simplicity. The total crustal thickness increases southward from 13.8 km at 23°50'N, 141°33'E to 16.6 km at 23°12'N, 141°40'E along the refraction line, where southward decrease of free-air anomaly values is observed from our data. We adopt the average of the crustal thickness at both ends, i.e., 15.2 km as a crustal thickness representing this area (Region I). A free-air anomaly value at this location is about 85 mgal. Then g_0 is calculated to be 610.1 mgal from equation (1).

Once g_0 is given, the crustal thicknesses for other locations in the trough, which have different water depths and free-air anomalies, can be calculated using equation (1). Figure 8 shows the crustal thicknesses obtained by this equation. Two crustal models are shown for the area north of the boundary at about 22°N in the Mariana Trough (Region II). The two models represent shallow water areas ($h_W = 3.2$ km, $g_F = 50$ mgal) and deep water areas ($h_W = 3.6$ km, $g_F = 30$ mgal), respectively. The results show the crust of 9 to 10 km in thickness, which is thinner than in the northern end of the Mariana Trough (Region I), but is still thicker than the normal oceanic crust.

Two crustal models for the area south of the boundary at 22°N (Region III) are also shown in Figure 8. The two models again represent shallow water areas ($h_W = 3.2$ km, $g_F = 60$ mgal) and deep water areas ($h_W = 4.5$ km and $g_F = 20$ mgal), respectively. The results show that crustal thickness of the shallow water areas is comparable to that of Region II, but in deep water areas it becomes thinner to about 6 km, which is comparable to the normal oceanic crust. This discussion assumes that $g_0 =$ const., i.e., gravity effect of mantle is the same in the three regions. If a light material such as hotter asthenosphere occurs only in Region III, g_0 becomes smaller and a crust thinner than obtained above is expected in this region.

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伊豆小笠原および北マリアナ弧の重力異常

石原文実・山崎俊嗣

要　旨

1984年から1989年にかけて，伊豆小笠原からマリアナ北部の海域で測線間隔 2 - 4 kmの詳細な重力調査を実施した．用いた重力計は，LaCoste — Romberg社製S-63およびSL-2 船上重力計で，後者はクロスカップリング補正を要しない新型の重力計である．

海底地形図とフリーエア異常図を対応させて示した．フリーエア異常の主な特徴は次のようになる．(1)18°N付近のマリアナトラフ中軸部では5000-3000mの水深に対応して 5 -85mgalのフリーエア異常が観測される．トラフ北部でも22°以南ではほぼ同様の水深と異常値が観測され，海洋底拡大が進行していると考えられる．22°以北では水深が3000-2500mと浅くなっているのにフリーエア異常は30-60mgalと余り変わらない．簡単なモデル計算では22°N以南で6.1-9.3km，以北で9.0-9.7kmの地殻の厚さが推定される．北部マリアナトラフ両側のマリアナ海嶺および西マリアナ海嶺では100mgalを超えるフリーエア異常が観測される．海山の水深・規模を考えると北部の海山の方がより低異常となっており，やはり地殻が北へ厚くなっていることを示唆している．(2)南硫黄島から青ヶ島にかけての七島海嶺上と30°N以北を中心にその西側に分布する島や海山では100-200mgalのフリーエア異常が観測される．孀婦岩と木曜海山ではそれぞれ200mgal，150mgalとその形状から考えられるものより高い異常値が観測され，高密度の岩体等が推定される．スミスカルデラ，青ヶ島カルデラでは高ブーゲー異常となり，中心部により高密度の岩体の貫入が推定される．(3)伊豆小笠原海溝の東側にある小笠原海台の東海山で175mgalのフリーエア異常が観測されるのに対し，その東側の矢部，半沢，片山海山では200mgalを超える異常が観測される．頂部の水深が同程度であることを考えると小笠原海台では地殻が厚くなっていることが推定される．

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