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Origin of along-arc geologic variations on the volcanic front of the Izu-Ogasawara (Bonin) Arc

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YUASA Makoto (1992) Origin of along-arc geologic variations on the volcanic front of the Izu-Ogasawara (Bonin) Arc. *Bull. Geol. Surv. Japan,* vol. 43 (7), p. 457-466, 4fig., 1tab.

Abstract: The Izu-Ogasawara Arc is divided into two parts, north and south segments, based on the different features of submarine topography, chemical composition of volcanic rocks, and distributions of hypocenters and backarc rifts. These two segments were originally independent arcs that developed differently and are now joined. The northern arc was produced first by subduction of the Pacific Plate under the northern part of the Kyushu-Palau Ridge from the north before opening of the Shikoku and Parece Vela basins. The southern arc was produced by subduction of the same plate from the east after the change of plate motions 42 Ma. A wedge of oceanic crust due to opening of the Parece Vela Basin broke in between the northern and southern parts of the Izu-Ogasawara Arc. This wedge corresponds to the Nishinoshima Trough. The western boundary of the wedge is the Sofugan Tectonic Line.

The recent volcanic front is overprinted on the above arrangement. The different alkalinity of the volcanic rocks on the front may be explained as due to difference in crustal thickness and duration of subduction between the northern and southern parts. Subduction started 48 Ma in the northern part of the arc and at 42 Ma in the southern part. The thermal structure of the mantle beneath the northern part is different from the southern part. Partial melting of source mantle in the north probably occurs in higher degree and at a shallower level than in the south.

The seamounts in the Nishinoshima Trough are divided into three groups, younger, older and intermediate-type ones, based on their geological and geochemical features. It is interpreted that seamounts with different age and origin are mixed in the trough.

1. Introduction

The Izu-Ogasawara (Bonin) Arc, situated on the eastern edge of the Philippine Sea Plate (Fig. 1), has grown due to subduction of the Pacific Plate (Karig and Moore, 1975; Bandy and Hilde, 1983: Honza and Tamaki, 1985). Geologic and geophysical phenomena observed in the arc, therefore, reflect the interaction of both plates. Topographic and petrographic characteristics of volcanoes on the volcanic front of the Izu-Ogasawara Arc reflect changes in the mutual relations between the two plates with time. The subjects of this paper are; (1) origin of the contrasting characteristics between the northern and southern parts of the arc and (2) origin of seamounts in the Nishinoshima Trough.

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Keywords: Izu-Ogasawara Arc, Bonin Arc, along-arc variation, Philippine Sea Plate, Pacific Plate, Kyushu-Palau Ridge, subduction, Parece Vela Basin, Shikoku Basin, retreating trench model, Sofugan Tectonic Line, Nishinoshima Trough, Shichiyo Seamounts, caldera, Central Basin Ridge, volcanic front, Ohmachi Seamount, alkalinity of volcanic rocks

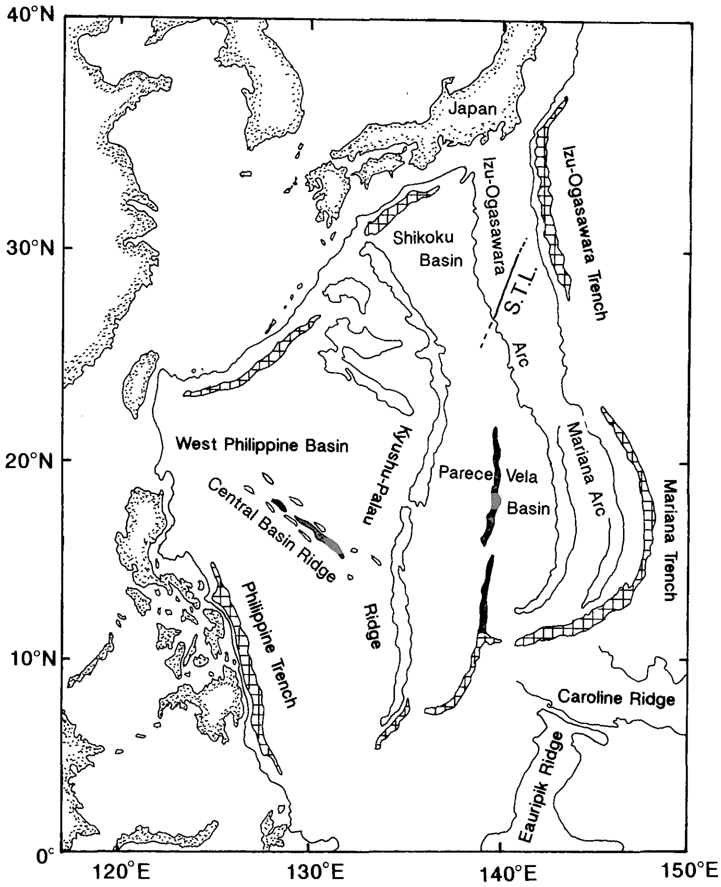

Fig. 1 Index map of the Philippine Sea and adjacent area. Solid area is the deep associated with past spreading center. S.T.L.: Sofugan Tectonic Line.

2. Sofugan Tectonic Line

Some contrasting differences in the geological and geophysical phenomena exist between the northern and southern parts of the Izu-Ogasawara Arc. These include the submarine topographic features, chemistry of the rocks on the volcanic front, and the distributions of hypocenters and backarc rifts (Table 1). Yuasa (1983 and 1985) described the above contrasting differences and proposed that there is a major fault, the Sofugan Tectonic Line, between the northern and southern parts of the arc (Fig. 2). Yuasa (1985) stated that the Sofugan Tectonic Line represents a boundary within a plate in which different parts are subducting at different modes or it is a lateral fault with respect to differential movements of the Shikoku and the Parece Vela basins. From the view point of interaction between the Pacific and Philippine Sea plates, it can be said that the above boundary and lateral fault relate to the subducting Pacific Plate and the overriding Philippine Sea Plate, respectively. Although the Sofugan Tectonic Line has been regarded as a boundary fault between the northern and southern parts of the arc, the present investigation shows that the boundary is represented not by a line but a zone (Nishinoshima Trough) and that the western boundary of the zone corresponds to the Sofugan Tectonic Line.

Table 1 Contrasts in geology and geophysics between the northern and the southern parts of the Izu-Ogasawara Arc (After Yuasa, 1983 and 1985 ; Yuasa *et al.*, 1991).

	Northern part	Southern part
Submarine topography		
Forearc ridge	Shinkurose Ridge	Ogasawara Ridge
Back-arc en echelon seamounts	Nishi-shichito Ridge	None
Water depth	Shallow	Deep
Number of submarine caldera	A few	Few
Back-arc rifts	Existing	None
Height of volcanoes	Low	High
Spacing of volcanoes	Narrow and variable	Wide and constant
Chemical composition of volcanic rocks		
Intermediate to basic volcanic rocks	Low-alkali	High alkali to alkali
Acid volcanic rocks	More abundant	Less abundant
Seismic activity		
Frequency	High	Low
Angle of Wadati-Beniof Zone	Gentle	Steep

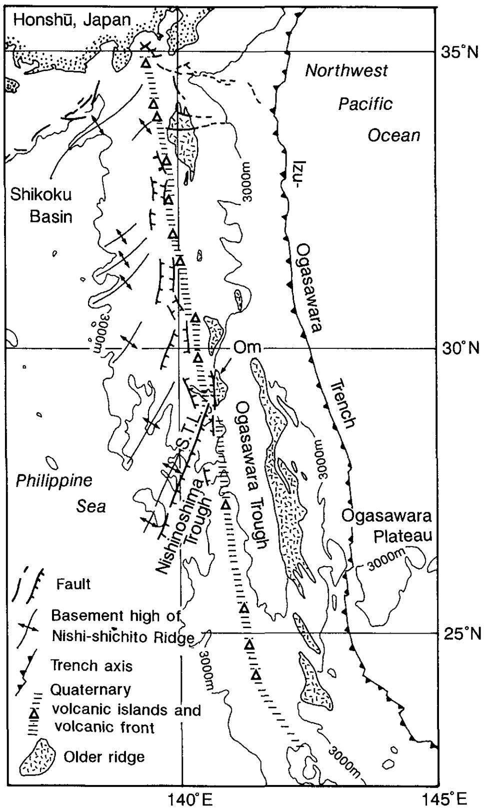

Fig. 2 Structural framework of the Izu-Ogasawara Arc region (modified from Yuasa, 1985). S. T.L. : Sofugan Tectonic Line, Om : Ohmachi Seamount.

Yuasa *et al.* (1991) described the detailed topography of volcanoes on the volcanic front, especially their submarine parts and concluded that the different pattern in the height, basal diameter and spacing of the volcanic edifices in each part of the arc resulted originally from the different crustal thickness between them, that is, the crust of the northern part seems to be thicker than that of the southern part. Notsu *et al.* (1983) indicated that the source mantle of magma is the same between the northern and southern parts of the arc on the basis of Sr isotopic study ; therefore the different chemical compositions of volcanic rocks between them is considered to result from different degrees of partial melting of the source. That is, the volcanic rocks poorer in alkali elements in the northern part of the arc show larger degrees of partial melting of the source mantle.

Moreover, there are many caldera volcanoes consisting of acid volcanics in the northern part, but lesser amounts of acid volcanics are produced in the southern part (Yuasa *et al.,* 1991 ; Yuasa and Nohara, 1992). Most acid volcanics will be derived from crustal anatexis (Kobayashi, 1987) rather than crystal fractionation of basaltic magma. The thicker crust of the northern part possibly melts to produce acid volcanics.

High heat flow regions are known in the backarc rift floor of the arc (Yamazaki, 1988) and there are indications of hydrothermal activity on the topographic highs in the rift (Taylor *et al.*, 1990; Yamazaki *et al.*, 1991). These facts show that the backarc rifts are thermally active and the restricted existence of the rifts only in the northern part of the arc indicates that the northern part has more thermal activity relative to the southern part.

The differences between the northern and southern parts inferred from the topographic features and rock chemistry mentioned above suggest that the northern part with thick crust is thermally active and the southern part is less so.

Here I describe the relationship between the formation of the Sofugan Tectonic Line and the origin of contrasting features of the northern and southern parts of the Izu-Ogasawara Arc in connection with the development of the Philippine Sea.

3. Origin of the contrasting phenomena between the northern and the southern parts of the Izu-Ogasawara Arc

The interaction between Pacific and Philippine Sea plates is related to the geologic and geophysical phenomena of the Izu-Ogasawara Arc. The Sofugan Tectonic Line dividing the arc into two parts, north and south, is situated at the bend where the subducting Pacific Plate changes its subduction angle and the tectonic line also corresponds to the extension of the boundary between the backarc basins (Shikoku and Parece Vela basins) on the overriding Philippine Sea Plate. Therefore, the origin of the contrasting phenomena between the northern and southern parts of the arc is considered in relation to the development of the Philippine Sea.

Fig. 3 illustrates a reconstruction of the Philippine Sea after 48 Ma based on the retreating trench model (Seno and Maruyama, 1984). In addition to the framework of plate boundaries and positions of the main island arcs by Seno and Maruyama (1984), a different development between the northern and southern parts of the Izu-Ogasawara Arc and mode of backarc basin opening are shown as follows:

<u>48 Ma</u>

Subduction of the Pacific Plate from the north occurred due to spreading of the Central Basin Ridge at the boundary between the Pacific and the Philippine Sea plates. At this stage no subduction occurred at the east end of the ridge. The subduction of the Pacific Plate under the Philippine Sea Plate was a passive movement caused by the faster northward motion of the Philippine Sea Plate (Seno and Maruyama, 1984).

The island arc formed by this subduction corresponds to the northern parts of the Kyushu-Palau Ridge and Izu-Ogasawara Arc. However, no island arc was present along their southern extension. Consequently, a geometric discontinuity of the descending slab arose at the bend shown by an arrow in Fig. 3 top-left (48Ma), i.e., the Pacific Plate was thrust down under the region corresponding to the present northern Izu-Ogasawara Arc by the northward motion of the Philippine Sea Plate, and the Pacific Plate was torn into two parts. This situation continued until the change in Pacific Plate motion about 42 Ma (e.g. Clague and Jarrard, 1973). This earlier development of the northern part became a major factor in determining the contrasts between the northern and southern parts of the Izu-Ogasawara Arc. As shown by the high basement rise and shallow water depth in the northern part of the Izu-Ogasawara Arc, island arc crust is well developed there. On the other hand, the discontinuity in the downgoing slab at the above mentioned bend continued like an unzipping fastener.

<u>42 Ma</u>

At this stage the Pacific Plate motion changed from NNW to a WNW trend (Clague and Jarrard, 1973) and subduction

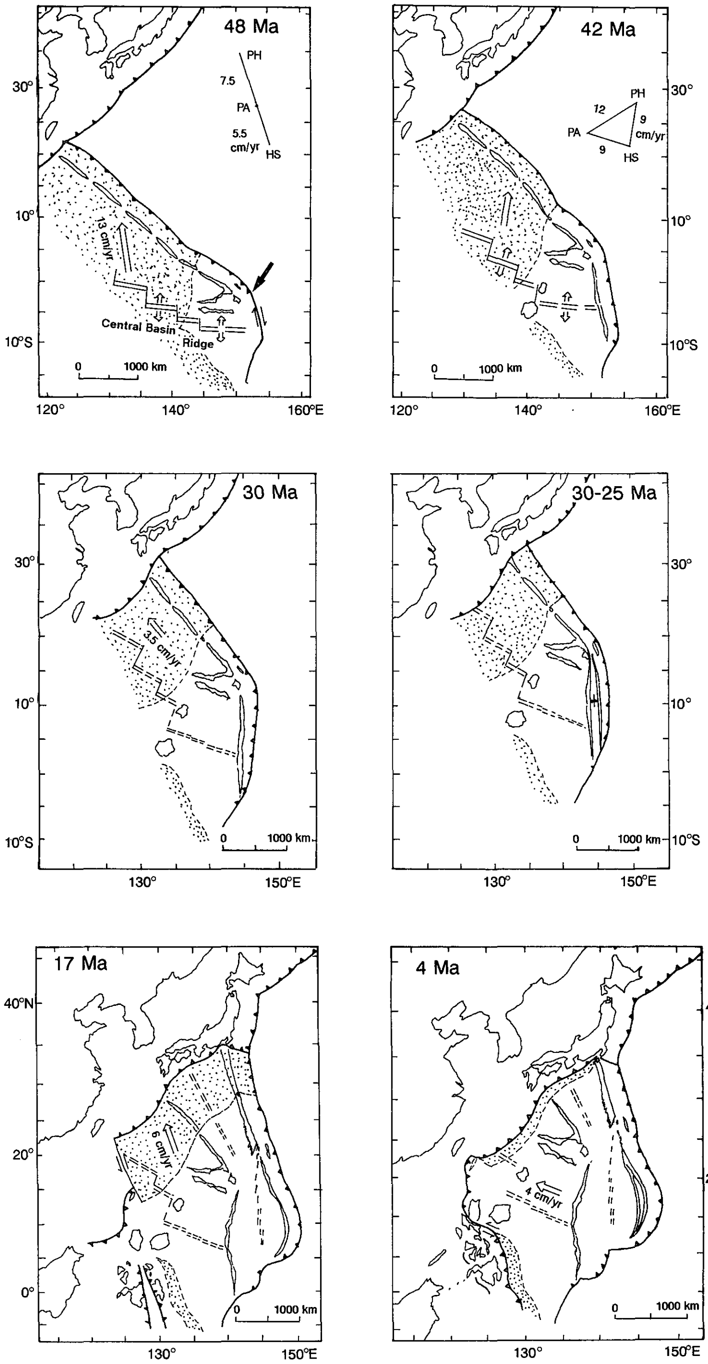

Fig. 3 Paleogeographic reconstruction of the Philippine Sea at 48, 42, 30, 30–25, 17, and 4 Ma (after Seno and Maruyama 1984, modified). Dotted is the part of the Philippine Sea floor subducted until recent. Double lines indicate active ridge axes, and double broken lines extinct ones. PH and PA mean the velocity and direction of Philippine Sea and Pacific plates based on hot spots (HS). Recent geographic outline is shown in Fig. 1.

started under the area corresponding to the present southern Izu-Ogasawara and Mariana arcs. In consequence, island arc crust was formed equivalent tō the present situation. The subduction of the Pacific Plate under the northern part of the Kyushu -Palau Ridge and Izu-Ogasawara Arc became active like in the southern part. It is expected that the discontinuity propagated between the northern part previously subducted and the southern part subducted later. The discontinuity may be like an overlapping or fingering of the descending slab.

30 Ma

Subduction stimulated backarc spreading in the southern part (Mrozowski and Hayes 1979), while in the northern part backarc spreading was retarded because of its oblique subduction. Backarc rifting started along the southern axis of the pre-existing arc, and the present southern part of the Kyushu-Palau Ridge was separated from the southern part of the Izu-Ogasawara and Mariana arcs. Because the rift tip extended to the bend in the trench and cut the pre-existing arc, the northern edge of the backarc basin became like a wedge into the arc between the northern and southern parts. The present straight and steep cliff along the Sofugan Tectonic Line, which is traceable for more than 200 km (Fig. 2), corresponds to the western edge of the rift. Similarly, the western slope of Ohmachi Seamount in the Nishinoshima Trough (Om in Fig. 2), from which weakly metamorphosed and brecciated volcanic rocks with slickensides were dredged (Yuasa *et al.*, in press), may correspond to the eastern edge of the rift.

Other remnant parts on the eastern side of the rift might be nearly obliterated by the later stages of arc volcanism. The rifting and spreading resulted in formation of the Parece Vela Basin between the Kyushu-Palau Ridge and the southern part of the Izu-Ogasawara and Mariana arcs. The oceanic crust of the northern end of the basin propagated into the Izu-Ogasawara Arc like a thin wedge. The existence of thin crust in the arc is suggested by gravimetric data in the Nishinoshima Trough (Ishihara and Yamazaki, 1991). When the Nishinoshima Trough expanded to its present width, spreading in this part of the Parece Vela Basin stopped. Since the rifting ceased from both ends toward the center with the waning of spreading, the central part expanded more and the present spindle-like basin was formed.

After 25 Ma

Spreading of the Shikoku Basin started at 25 Ma (Shih, 1980) and the northern parts of the Izu-Ogasawara Arc and the Kyushu -Palau Ridge were separated from each other. At 17 Ma the Shikoku and Parece Vela basins ceased to spread (Shih, 1980; Mrozowski and Hayes, 1979). After that, rifting of the Mariana Trough started at 5-6 Ma (Hussong and Uyeda, 1981) and the present configuration of arcs and basins was accomplished.

As described above, the position of the Sofugan Tectonic Line should correspond to the bend in the pre-existing arc about 30 Ma. This position also corresponds to the tear in the Pacific Plate. The bending possibly caused the separation of the Izu-Ogasawara Arc into two parts, and its southern part is regarded essentially as a northern extension of the Mariana Arc. That is, the northern and southern parts of the Izu-Ogasawara Arc were originally formed as two different arcs. The recent volcanic front is overprinted on the above arrangement. The different alkalinity of the volcanic rocks may be explained as due to the difference in crustal thickness and duration of subduction between the two parts. The thickness of the crust in the northern part is expected to be greater than in the southern part based on the occurrence of large amounts of acid magma. Subduction started sooner beneath the northern part of the arc. The thermal structure of the mantle beneath the northern part is different from the southern part. That is, isotherms are higher in the northern part. Partial melting of source mantle in the northern part probably occurs at higher degrees and shallower levels than in the southern part.

4. Origin of seamounts in the Nishinoshima Trough

The Nishinoshima Trough was formed in relation to the separation of the northern part from the southern part of the arc. As shown in Yuasa *et al.* (1991) and Yuasa and Nohara (1992), there are three kinds of seamounts in the trough. The three kinds of seamounts correspond to the chronologically different groups of volcanoes. Sr isotope ratios of volcanic rocks for the seamounts in the trough are lower than those from outside of the trough. Also they differ between the older and younger seamounts. The age of Ohmachi Seamount of the older seamount group in the trough is older than 30 Ma based on fossil evidence (Nishimura, in press) and its K-Ar age (Yuasa *et al.,* 1988). It is considered to be part of the eastern fragment of the pre-existing northern arc rifted by Parece Vela spreading. This seamount was formed related to older subduction from the north. The younger Getsuyo, Kayo, Kin'yo and Doyo seamounts are island arc volcanoes related to the recent subduction process. The intermediate-type seamounts are presumed to be of an intermediate age between the above two kinds of volcanoes as inferred from their structural and topographical features.

It is suggested that the nature of the parent magma is different among the three types of seamounts in terms of incompatible element behavior (Yuasa and Nohara, 1992). Fig. 4 shows the Rb vs. Ba relations for the rocks of the seamounts in the trough. The rocks of the younger and older seamounts, all of which were formed by island arc volcanism, are rich in both elements, whereas those of the Suiyo and Mokuyo seamounts are mostly poor in them. These seamounts are close to each other within a distance of about 220 km along the arc. The different chemical characteristics seem to be related to differences in their ages. It is presumed that the chemical differences among the different seamounts originates not from heterogeneity of source materials, but in the different conditions affecting magma generation and ascent. Suiyo and Mokuyo seamounts are assumed to be formed under conditions different from the others in the trough, though the exact age of the seamounts and the situation of plate

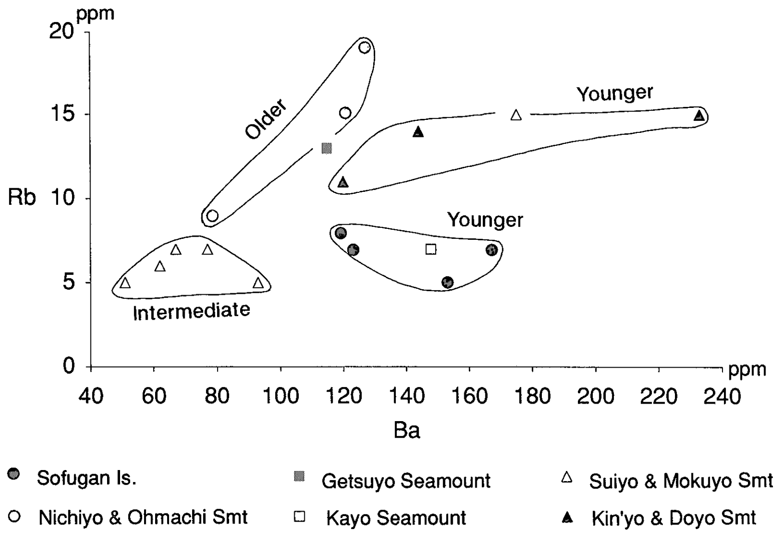

Fig. 4 Rb vs Ba diagram of volcanic rocks from the seamounts in the Nishinoshima Trough and Sofugan Volcano (analytical data available in Yuasa and Nohara, 1992).

subduction have not been explained. A rock from Suiyo Seamount is rich in both Rb and Ba, similar to rocks from the younger volcanoes. This rock is dacitic pumice with basaltic xenoliths, whose composition is similar to other rocks from the intermediate-type seamounts. The magnetic anomaly of Suiyo Seamount is explained as a transition between two different magnetic fields, the recent and an older one. This suggests the existence of younger volcanism on the seamount. The dacitic pumice may be from the younger activity.

5. Conclusions

The northern and southern parts of the present Izu-Ogasawara Arc were originally independent arcs which developed differently and were joined together at the bend in a pre-existing arc. They were divided into two parts by a wedge of oceanic crust which formed during the opening of the Parece Vela Basin. This wedge corresponds to the Nishinoshima Trough where seamounts of three different groups in age and origin are mingled. The recent volcanic front is overprinted on the above arrangement.

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伊豆・小笠原弧火山フロントの地学現象にみられる島弧軸方向の変化の起源

湯浅真人

要　旨

伊豆・小笠原弧は，海底地形，火山岩化学組成，震源分布，背弧リフトの分布等にみられる違いから，南北二つのセグメントに分割することが可能である．これら二つのセグメントは，元来別々の構造発達史を持つ独立した島弧であり，それが結合して一つの島弧になっている．すなわち，北部島弧は四国・パレスベラ海盆拡大以前に，九州-パラオ海嶺北部における太平洋プレートの北側からの沈み込みにより形成されはじめ，南部島弧は太平洋プレートの運動方向変換後西向きの沈み込みにより形成されはじめたものである．南北の間には，その後のパレスベラ海盆の拡大に起因する，楔状の海洋性地殻が割り込んだ形になっている．この楔状部分が西之島トラフに対応し，その西縁が孀婦岩構造線である．

現世火山フロントはこのような配置の上にオーバープリントされたものである．フロント上の火山岩のアルカリ元素含有量にみられる南北の違いは，南北間での地殻の厚さの違いおよび沈み込みの継続期間の違いで説明できるだろう．沈み込みは伊豆・小笠原弧の北部で先行してはじまり，継続期間も南部より北部における方が長い．このため，伊豆・小笠原弧北部下のマントルの熱構造は南部のそれとは異なっていた．北部におけるソースマントルの部分溶融度は南部におけるよりも高く，かつ浅いレベルで

生じたのだろう.

西之島トラフ内の海山群は地質学的特徴および地球化学的特徴から，新期，古期，中間タイプの3グループに分けられる．これらは時代的にも成因上も異なる海山グループが，トラフ中に混在しているものと解釈した.

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