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PALEOGEOGRAPHIC RECONSTRUCTION AND ORIGIN OF THE PHILIPPINE SEA

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ABSTRACT

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Our reconstruction of the Philippine Sea suggests that it formed by two distinct episodes of back-arc spreading, each of which resulted from seaward retreat of the trench. In the first episode, the proto-Izu–Bonin Trench retreated northward and the West Philippine Basin formed behind the northern half of the Palau–Kyushu Ridge. In the second episode, the Izu–Mariana Trench retreated eastward and the Shikoku and Parece Vela Basins formed behind it.

During the last 17 Ma, the Philippine Sea basin has been moving northwestward with respect to Eurasia shifting the TTT triple junction off central Japan westward by about 50 km. The motion of the Philippine Sea with respect to Eurasia at the triple junction changed from north-northwestward to west-northwestward 10–5 Ma ago. For the period before 17 Ma ago, we construct two models, retreating trench model and anchored slab model. The Izu–Bonin Trench migrated from south to northeast rotating in a clock-wise sense since 48 Ma ago in the retreating trench model. In the anchored slab model, the trench has been fixed with respect to Eurasian margin since 43 Ma ago. We prefer the retreating trench model because the deformation of the plate boundary along the eastern margin of Eurasia during 30–17 Ma ago is much simpler for this model than for the anchored slab model. Furthermore rotations of the Bonin–Mariana islands are consistent with those predicted from the retreating trench model.

The 48 Ma ages of the northern part of the Palau–Kyushu Ridge and of Chichi-Jima of the Bonin Islands indicate that there was subduction beneath the northern half of the ridge beginning at least 48 Ma ago. From this and the subparallelism in trend between the northern part of the Palau–Kyushu Ridge and the Central Basin Ridge, we propose that the major part of the West Philippine Basin formed by back-arc spreading in a N–S direction behind the northern part of the Palau–Kyushu Ridge. The Pacific plate was moving northward with respect to hot-spots from 48 to 43 Ma ago, which implies that the Pacific plate is not likely to have been subducting beneath the West Philippine Basin during this time. We speculate that

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another plate existed south of the Pacific plate and that it was subducting beneath both the West Philippine Basin and Australia. The annihilation of this plate might be a cause for the sudden change of the Pacific plate motion at 43 Ma ago.

INTRODUCTION

The Philippine Sea is one of the largest marginal seas of the world and has been most extensively studied. Even so, its origin, especially the origin of the West Philippine Basin, is disputed. Uyeda and Ben-Avraham (1972) proposed that the basin was originally a part of the Kula and Pacific plates and became a marginal sea by entrapment when the Pacific plate changed its motion 43 Ma ago. By contrast, Karig (1975) proposed that the basin formed by back-arc spreading behind the Oki–Daito Ridge in the Eocene. Recently, Lewis et al. (1982) proposed that the basin formed by back-arc spreading associated with subduction to the northeast along the eastern Philippines. Although the age and depth of the basin suggest that the West Philippine Basin did not form by mid-ocean ridge spreading (Sclater et al., 1976; Kobayashi and Sato, 1980), the entrapment origin of the basin is still not abandoned (Ben-Avraham and Uyeda, 1983; Uyeda and McCabe, 1983). The purpose of the present study is to reconstruct the Philippine Sea and elucidate the origin and development of the basin. We will propose a back-arc origin for the West Philippine Basin resulting from the subduction beneath the northern part of the Palau–Kyushu Ridge based on the ages on the Palau–Kyushu Ridge and the Bonin Islands, and our reconstruction at 17 Ma ago.

There are two basic kinematic ideas for the formation of back-arc basins (e.g., Dewey, 1980; Uyeda, 1982; Taylor and Karner, 1982). Molnar and Atwater (1978) suggested that actively spreading marginal seas are located behind subduction zones where older slabs are subducting, and proposed that the retreat of the trench line due to the gravitational pull exerted on the subducting slab is a cause for back-arc spreading. We call this the "retreating trench" model. On the other hand, Chase (1978) and Uyeda and Kanamori (1979) suggested that active marginal seas are located where an overriding plate has an absolute velocity away from the trench. Uyeda and Kanamori proposed that the subducting slab and the trench line are fixed with respect to the upper mantle and the landward retreat of a portion of the overriding plate causes back-arc spreading. We call this the "anchored slab" model.

For the period of the last 17 Ma, the Philippine Sea can be uniquely constructed based on the land geology data of Japan and paleomagnetic data from sediment cores in the West Philippine Basin and two seamounts in the Shikoku Basin. However, for the period before 17 Ma ago, available data are not sufficient to allow a unique reconstruction. Thus we have used both the retreating trench model and the anchored slab model to reconstruct the Philippine Sea. We then compare the results from each of the two models with the paleomagnetic data of the Izu–Mariana

Islands and discuss these models on the basis of the deformation of plate boundaries along east Asia and the geology of Japan. The results of this analysis support the retreating trench model for the opening of the West Philippine Basin and the Shikoku–Parece Vela Basins.

Our reconstruction also suggests that during the early Tertiary in the western Pacific there was another plate south of the Pacific plate which was subducting beneath Australia. We will propose that the complete annihilation of this plate beneath Australia may have caused the sudden change of the motion of the Pacific plate 43 Ma ago.

AGE AND DEVELOPMENT OF THE PHILIPPINE SEA BASIN

The history of each of the several basins within the Philippine Sea is basic to our reconstruction. In this section, we reconstruct the shape of the Philippine Sea at 17, 30, 42, and 48 Ma ago based on identifications of magnetic anomalies and syntheses of the Deep Sea Drilling Project with other marine geophysical and geological data. We use the results of Hussong, Uyeda et al. (1981) for the Mariana Trough, Kobayashi and Nakada (1978) for the Shikoku Basin, Mrozowski and Hayes (1979) for the Parece Vela Basin, and Mrozowski et al. (1982) for the West Philippine Basin. According to these studies, the Mariana Trough, the Shikoku and Parece Vela Basins, and the West Philippine Basin formed by spreading between 6–0 Ma, 30–17 Ma, and 48–40 Ma ago, respectively.

Since Karig (1971) proposed a back-arc spreading origin for the Mariana Trough, extensive work conducted in the Philippine Sea has shown that the Mariana Trough and the Shikoku and Parece Vela basins formed by back-arc spreading. However, there are still some questions regarding magnetic anomaly identifications in the Shikoku and Parece Vela basins and the West Philippine Basin, and the details of the model of spreading of these basins. Watts and Weissel (1975) proposed a one-limb spreading model and Kobayashi and Nakada (1978) and Shih (1980b) proposed two-limb models for the Shikoku Basin. We do not use Watts and Weissel's results because the age of the basement inferred by DSDP results is not in accord with their magnetic anomaly identification (Kobayashi and Nakata, 1978; Shih, 1980b). Kobayashi and Nakada (1978) suggested anomalies 7—5D (25–17 Ma) and Shih (1980b) anomalies 7—5B (25–14 Ma) for the magnetic anomaly pattern for the Shikoku Basin. Shih (1980b) used a 15–17 Ma age of the sediments above the basement at Sites 443 and 444 (Fig. 1) as a constraint for his model. However, as Kobayashi and Nakada (1978) point out, the sediments are not basal but above intrusive sills. Nannofossils from the sediments underlying the sills yield an age of 21 Ma, which is consistent with the anomaly identification by Kobayashi and Nakada (Kobayashi and Sato, 1980). We thus use the model of Kobayashi and Nakada (1978). In this model the Shikoku Basin formed simultaneously with the Parece Vela Basin (Mrozowski and Hayes, 1979).

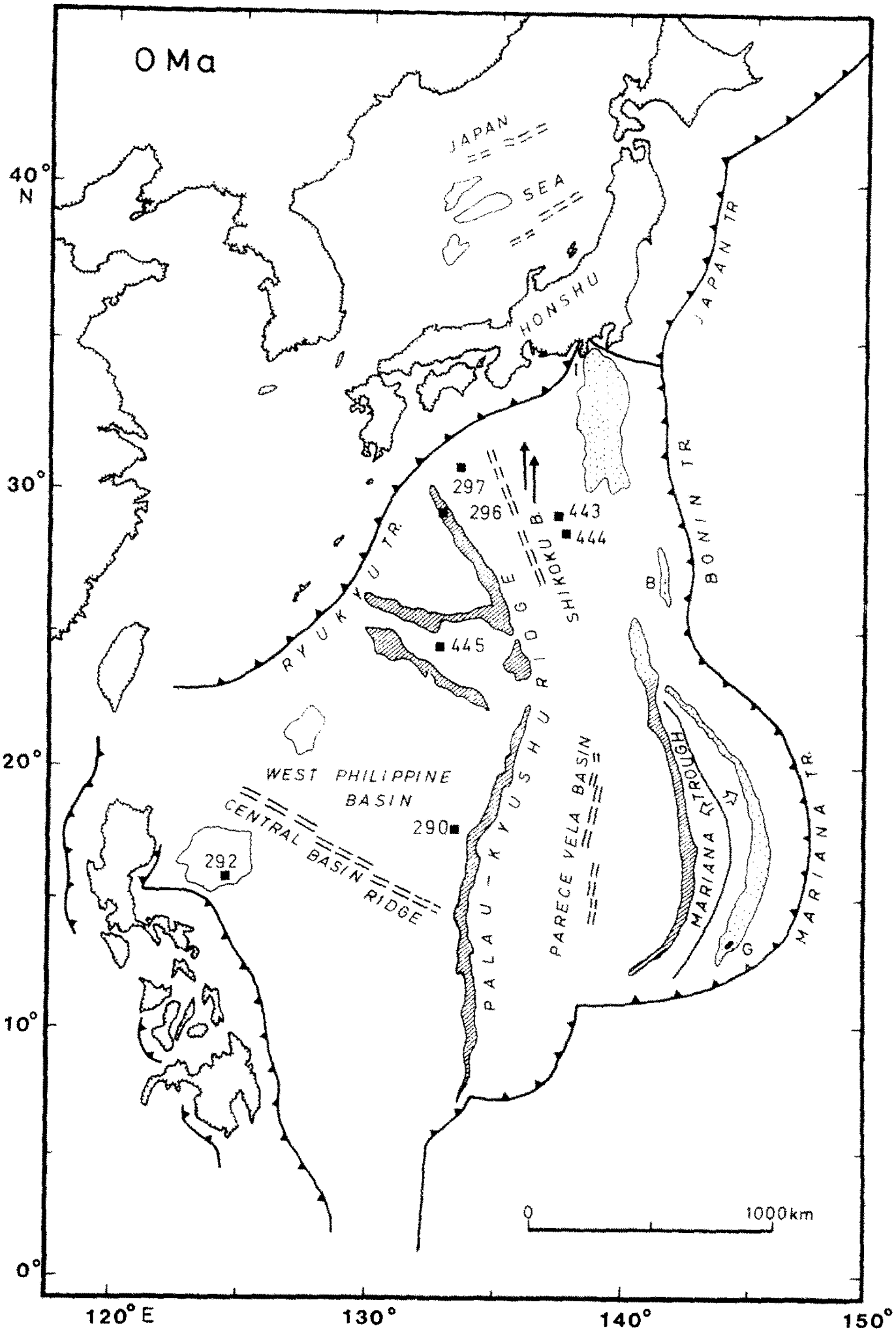


Fig. 1. Tectonic elements in the Philippine Sea. Deep Sea Drilling Project sites are indicated by solid squares with site numbers. I, B and G denote Izu Peninsula, Bonin Islands and Guam, respectively. Volcanic ridges are spotted and remnant arcs are hatchured. Arrows indicate declinations of paleomagnetism of two seamounts in the Shikoku Basin (Vaccquier and Uyeda, 1967).

Mrozowski et al. (1982) identified anomaly 17 to possibly anomaly 21 in the West Philippine Basin, which is almost identical to the results of Louden (1976) and one model proposed by Watts et al. (1977), but significantly different from those by Shih (1980a) and Lee and Hilde (1982). Shih (1980a) proposed that the basin formed between 59 and 25 Ma ago (anomalies 25—7A), but there is an inconsistency between the age of the Mariana fore-arc and the younger part of the West Philippine Basin in his model. The formation of the central part of the Mariana fore-arc dates back to at least 42 Ma ago (e.g., Hussong et al., 1981) and originally was juxtaposed with the central part of the southern Palau–Kyushu Ridge and a part of the West Philippine Basin near the Central Basin Ridge. However, this part of the West Philippine Basin would not have formed 42 Ma ago in Shih's model. Thus we do not use his model in our reconstruction. We also do not use Lee and Hilde's (1982) model because after subduction initiated along the Mariana arc, the West Philippine Basin continued opening tangential to the arc during several millions of years in their model. Thus we use the model of Mrozowski et al (1982).

We note here that there is a discrepancy in age and morphology between the northern and southern parts of the Palau–Kyushu Ridge. The ridge can be separated into two parts from the difference in trend at 23°N. Ages of about 48 Ma have been obtained for the northern part of the ridge. Ozima et al. (1977) obtained an Ar–Ar age of 47.5 Ma for a volcaniclastic rock at the bottom of Site 296, located on the northermost part of the Palau–Kyusku Ridge (Fig. 1). The K–Ar age of a quartz-diorite dredged at Minami Takatori Seamount, located on the Palau–Kyushu Ridge at about 3° south of Site 296, is 48 Ma (Mizuno et al., 1977). Recently, ages of 46.5–48 Ma were obtained from nannofossils in the tuffaceous sediments between the underlying boninite and the overlying two-pyroxene, plagioclase andesite in the northwestern part of Chichi-Jima of the Bonin Islands (Y. Takayanagi, pers. commun., 1981). These data indicate that there was active arc volcanism and thus, apparently, subduction along the northern part of the Palau–Kyushu Ridge at least 48 Ma ago. In contrast to the northern part of the Palau–Kyushu Ridge and the Bonin Islands, there is no evidence which indicates that the southern half of the Palau–Kyushu Ridge or the Mariana Islands are older than 43 Ma. Kobayashi and Sato (1980) pointed out that the morphology of the ridge is also different between the two parts; the size of each seamount in the northern half is much bigger than in the southern half. We assume in this study that subduction started about 43 Ma ago along the southern half of the Palau–Kyushu Ridge (proto-Mariana arc) at the time of the sudden change of the Pacific plate motion. In contrast to the southern half of the Palau–Kyushu Ridge, the northern half of the ridge (proto-Izu–Bonin arc) had initiated subduction by 48 Ma ago. This difference in development between the northern and southern halves of the Palau–Kyushu Ridge bears great importance on the investigation of the origin of the West Philippine Basin.

Given the opening history of each basin, it is a simple matter to determine the approximate shape of the Philippine Sea at each stage by removing the accreted sea

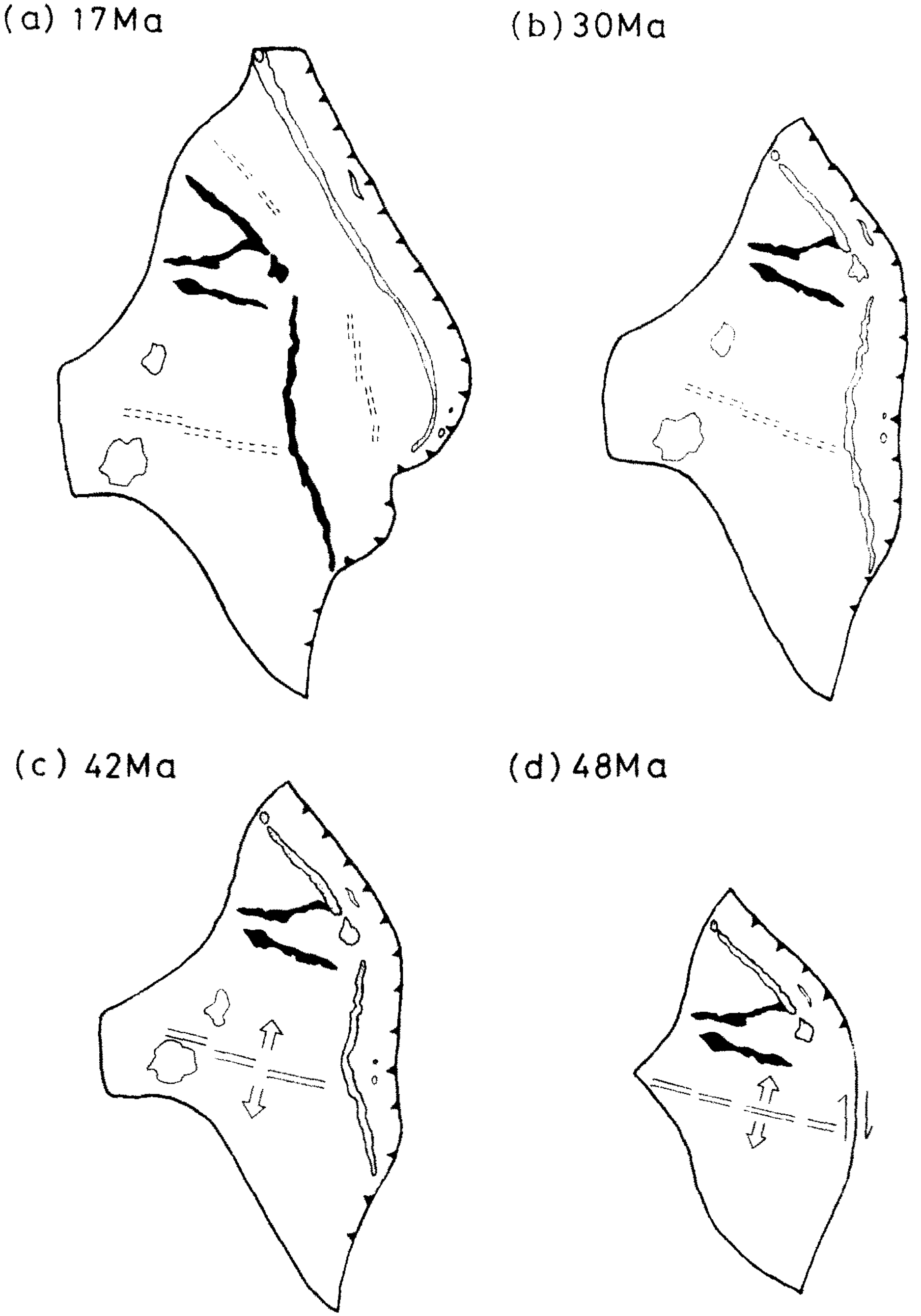


Fig. 2. Basin shape of the Philippine Sea at −17 Ma (a), −30 Ma (b), −42 Ma (c) and −48 Ma (d). Volcanic arcs are spotted and remnant arcs are filled.

floor. For example, we obtain the Philippine Sea basin at 17 Ma ago by removing the Mariana Trough. Similarly, we obtain the 30 Ma stage by removing the Shikoku and Parece Vela basins. The basin shape during the period when it was opening can be obtained based on the magnetic anomaly isochrons. Figure 2 shows the shape of the Philippine Sea at 17, 30, 42, and 48 Ma ago.

A problem in this procedure is estimating locations of the Izu–Bonin or Mariana trenches with respect to the Palau–Kyushu Ridge at 30, 42 and 48 Ma ago. The glassy matrix of tuffs and lapilli tuffs drilled at Site 296 on the northern Palau–Kyushu Ridge are indicative of a near-direct accumulation from a volcanic source (Ingle et al., 1975), and from the lapilli tuff near the bottom the age of 48 Ma was obtained (Ozima et al., 1977). The late Eocene volcaniclastic apron west of the southern Palau–Kyushu Ridge near Site 290 (Ingle et al., 1975) indicates that the southern half of the ridge was also close to the volcanic front in the Late Eocene. We thus estimated that the Palau–Kyushu Ridge was close to the volcanic front of the Izu–Mariana arc, as shown in Fig. 2, when subduction initiated. In the next section we will position the basins shown in Fig. 2 with respect to Eurasia.

CONSTRAINTS FOR THE POSITION OF THE PHILIPPINE SEA

We use paleomagnetic data from sediment cores at Sites 292 and 445 (Louden, 1977; Kinoshita, 1980; see Fig. 1 for location) to determine the paleolatitude of the basin. Figure 3 shows the paleolatitude of these sites plotted versus time. The present difference in latitude between the two sites is about 10°. Note that there is a systematic difference of about 10° in paleolatitude between the two sites for the last 30–40 Ma; the solid triangles in Fig. 3 show that the paleolatitudes of Site 445, reduced by 10°, are consistent with the paleolatitudes of Site 292. The data for Site 292 record an equatorial crossing at about 35 Ma ago. Kinoshita (1980) also suggested that an equatorial crossing possibly occurred at about 45 Ma ago for Site 445, but this is not so clear as for Site 292, and in Fig. 3 we adopted no equatorial crossing for Site 445, as was shown in the original figure of Kinoshita (1980). To obtain the paleolatitude of the basin, we use a hypothetical shift of the paleolatitude for Site 292 as indicated by the broken line in Fig. 3.

It is a more difficult problem to obtain the paleolongitude and orientation of the Philippine Sea basin at each stage. We have used mainly land geology data from Japan to obtain the paleolongitude and orientation of the basin for the reconstruction back to 17 Ma ago. For the period before 17 Ma ago, we have obtained those based on the two following assumptions: (1) that the trench line is fixed in an absolute frame of reference (anchored slab model, Uyeda and Kanamori, 1979) and (2) that retreat of the trench is the cause of back-arc spreading (retreating trench model, Molnar and Atwater, 1978). These two assumptions, along with the paleolatitudes described above, are almost enough to constrain the paleoposition of the Philippine Sea before 17 Ma ago. The results derived from both models can then be

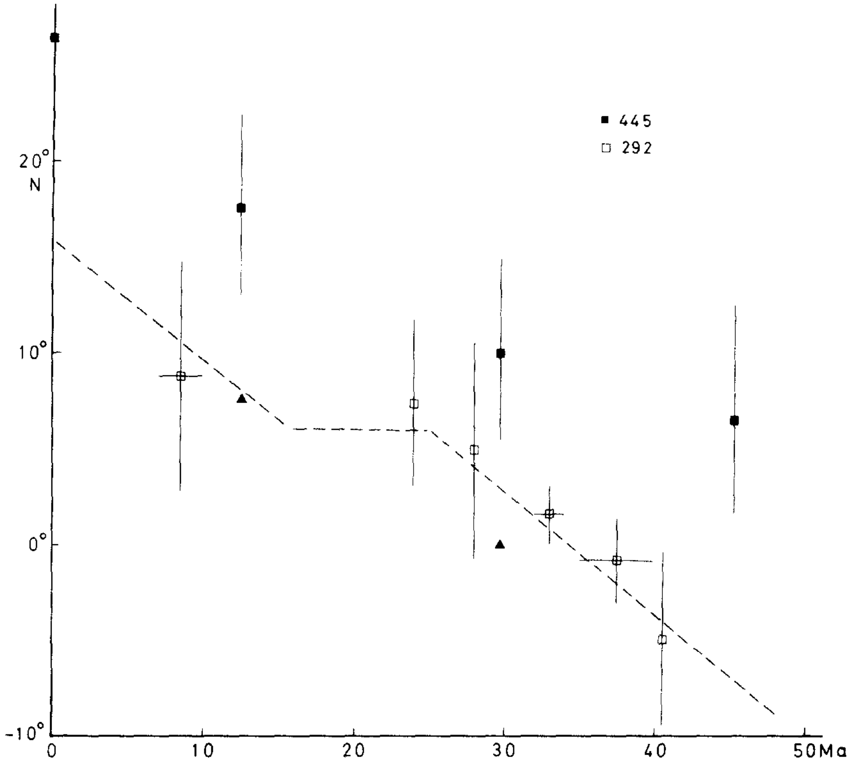


Fig. 3. Paleolatitudes of Sites 292 (squares) and 445 (solid squares) after Louden (1977) and Kinoshita (1980), respectively. Solid triangles are the latitudes of Site 445 reduced by 10 degrees.

compared with the geology and tectonic development in the vicinity of the Japanese and Bonin–Mariana islands to determine which model is preferable.

RECONSTRUCTION AT 4 MA AGO

In the reconstruction of the Philippine Sea at 4 Ma ago, we first use the volcanic front in central Honshu during the Pliocene–early Pleistocene to locate the Japan–Bonin–Ryukyu Trench triple junction off central Honshu relative to Eurasia. Then we rotate the Philippine Sea with respect to Eurasia using the relative rotation pole between these two plates (Seno, 1977) to fit the location of the triple junction, because the Philippine Sea plate is likely to have moved around this pole since at least 4 Ma ago (Matsubara and Seno, 1980).

Figure 4 shows the distribution of extrusive rocks in central Honshu during the Miocene–early Pliocene, Pliocene–early Pleistocene, and late Pleistocene–Holocene, based on the geological map of Japan (1 : 1,000,000, Geol. Surv. Japan, 1982). The distribution of these volcanic rocks has a cusp produced by the triple junction

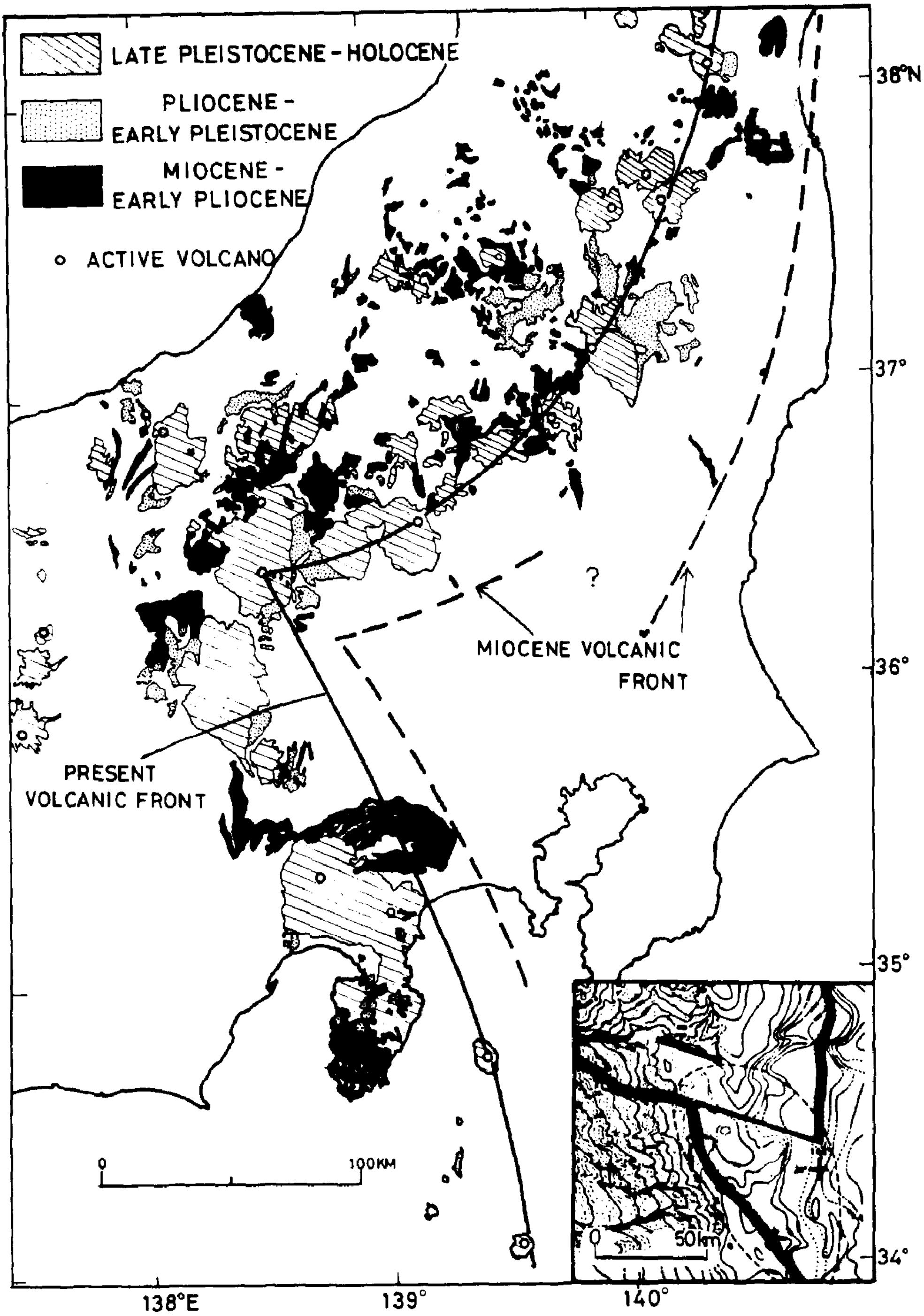


Fig. 4. Distribution of extrusive rocks in central Honshu since the Miocene (after Geol. Surv. Japan, 1982). The present and Miocene volcanic fronts are indicated by the solid and broken lines, respectively. The inset at right bottom shows a 50 km offset between the Japan and Izu–Bonin trenches at the triple junction off central Honshu (~~Nakamura and Shimazaki, 1981~~).

geometry off central Honshu. It shows almost no difference between the Pliocene, Pleistocene and Holocene periods. The rocks of these periods extruded slightly (10–20 km) east of the line of the presently active volcanoes. We thus estimated the location of the triple junction at 4 Ma ago at 20 km east of the present junction, by assuming that the dip of the slab has not changed during the last 4 Ma.

Furthermore, looking at the morphology near the present triple junction in detail, Nakamura and Shimazaki (1981) noticed that the triple junction does not have a simple TTT type geometry; the axis of the Japan Trench offsets in a right-lateral sense by about 50 km to the axis of the Izu–Bonin Trench (see the inset of Fig. 4). We can thus rotate back the Philippine Sea plate with respect to Eurasia about 70 km to fit the triple junction at 4 Ma ago. Figure 5 shows the reconstruction at 4 Ma

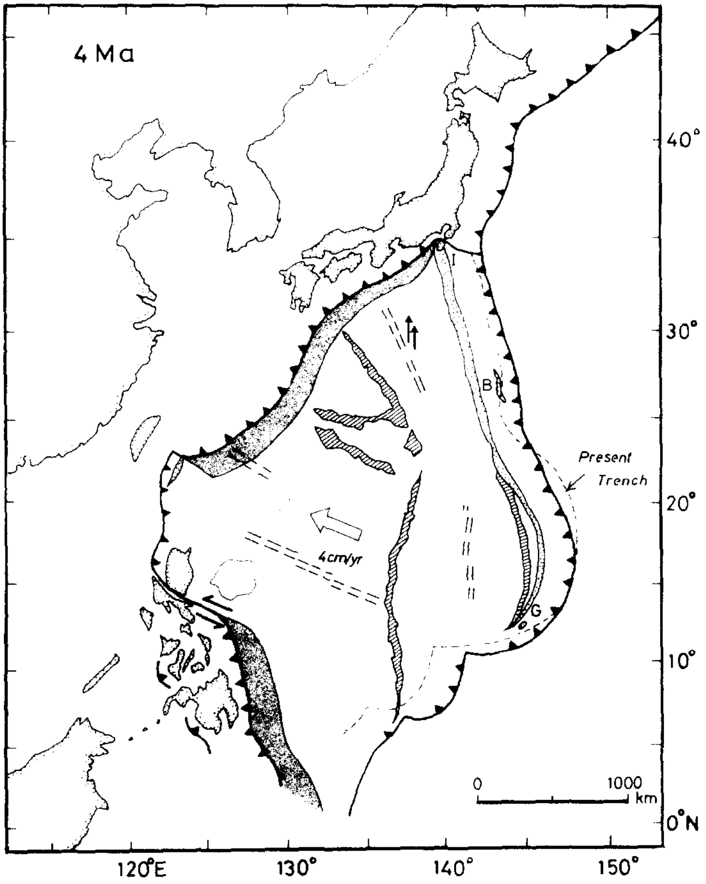


Fig. 5. Reconstruction of the Philippine Sea at 4 Ma ago. The present location of the trench line is indicated by the thin broken line. Shaded area is part of the Philippine Sea floor subducted since 4 Ma ago. I, B, and G denotes Izu, Bonin, and Guam islands, respectively. Broken lines indicate extinct ridge axes. Solid arrows indicate declination of paleomagnetism of two seamounts (Vaccquier and Uyeda, 1967).

ago. We removed a part of the Mariana Trough which opened during the last 4 Ma, based on the results of Hussong et al. (1981). The speed of migration of the Philippine Sea relative to Eurasia near the junction is about 1.8 cm/yr for the last 4 Ma, which is two thirds of that of the present motion (Seno, 1977).

In Fig. 5, the location of the present trench line is indicated by the broken line. The Mariana Trench has almost been fixed to Eurasia since 4 Ma ago, as Matsubara and Seno (1980) have already pointed out. It is likely that the westward motion of the Philippine Sea has caused the back-arc spreading within the Mariana Trough. In the discussion section, we will see that for the Shikoku, Parece Vela and West Philippine Basins, the retreat of the trench line is likely to have caused their opening. Thus it suggests a change of mechanism of back-arc spreading for the Philippine Sea between the present stage of opening and the past stages.

RECONSTRUCTION AT 17 MA AGO

Until 17 Ma ago, the Shikoku and Parece Vela basins had been opening (Kobayashi and Nakada, 1978; Mrozowski and Hayes, 1979). The Miocene extrusive rocks in central Honshu are distributed east of the present volcanic front (Fig. 4); this indicates that the triple junction was located east of the present junction at some time during the Miocene. Although the ages of many of those rocks have not yet been dated, the available K–Ar ages of intrusive and extrusive rocks near the Miocene volcanic front are 20–10 Ma (Geol. Survey of Japan, 1982). We reason that 17 Ma ago, the junction was located at the easternmost position with respect to Eurasia, because at this time the formation of the Shikoku and Parece Vela Basins stopped. Thus we interpret the Miocene volcanic front as the 17 Ma volcanic front. Note that the distance between the present volcanic front and the Miocene one is greater in the north of the cusp than in the south. This means that the motion of the Philippine Sea plate had a northward component. The distance measured in a northwest direction at 36°N, 139°E is about 50 km. In our 17 Ma reconstruction, we thus located the triple junction 50 km southeast of the present junction. To constrain further the orientation of the basin at 17 Ma ago, the paleomagnetic data for two seamounts in the Shikoku Basin (Vaccquier and Uyeda, 1967) are used. The declinations of the magnetization of these seamounts are indicated by the solid arrows in Fig. 1, which do not show any significant rotation since their formation. These are located near the spreading axis of the basin and formed at the latest stage of the Shikoku Basin opening (Kobayashi and Nakata, 1978). Thus the Philippine Sea did not rotate significantly since 17 Ma ago and it moved north-northwestward along the strike of the Izu–Bonin Trench. Figure 6 shows the reconstruction at 17 Ma ago. The speed of migration of 6 cm/yr is derived from the difference between the 17 and 4 Ma reconstructions. This motion has a more northward component than the present motion. Although we cannot date exactly when this change in motion of the Philippine Sea plate occurred, it would be from 10 to 4 Ma ago because of the following reasons. In southwest Japan and the northernmost Ryukyus, there was Miocene volcanism of high Mg-andesites and related acidic rocks 100–150 km inland from the Nankai Trough and this volcanism is believed to be caused by subduction of the hot lithosphere of the Shikoku Basin (e.g., Takahashi, 1981; Tatsumi and Ishizaka, 1982). The ages of these rocks are from 17 to 10 Ma with a peak at 14 Ma (Takahashi, 1981). Turbidite deposition is recorded at DSDP Site 297, located in the Shikoku Basin just south of the Nankai Trough, only in a very limited core section between 4–5 Ma ago (Ingle et al., 1975). This indicates that the trough was not deep enough to trap turbidites from the Japanese islands at 5 Ma ago. Thus by 5 Ma ago, subduction along the Nankai trough would have stopped. Taking into account the time period needed for the trough to become shallow, the

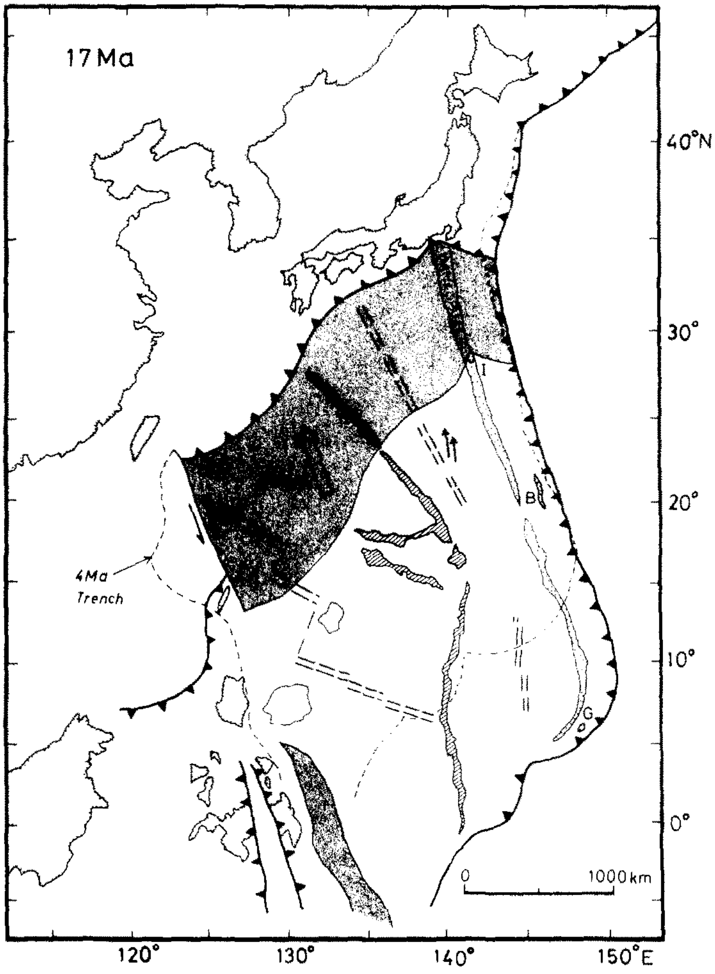


Fig. 6. Reconstruction at 17 Ma ago. Shaded area is part of the Philippine Sea floor subducted since 17 Ma ago. Other symbols are same as Figs. 1 and 5.

cessation of the Miocene volcanism at 10 Ma ago and the time of the turbidite deposition at 4–5 Ma ago are consistent.

In Fig. 6, we have arbitrarily extended the Palau–Kyushu Ridge, the spreading axis of the Shikoku Basin and the Central Basin Ridge into part of the ocean floor subducted since 17 Ma ago. Note that the crossing point of the spreading axis of the Shikoku Basin and the Palau–Kyushu Ridge with the Ryukyu Trench–Nankai Trough is located further to the south than at present. Furthermore, the spatial distribution of the Miocene volcanism in southwest Japan and the Ryukyus stated above (Takahashi, 1981, Fig. 1) coincides with the extent of the Shikoku Basin adjacent to these areas at 17 Ma ago.

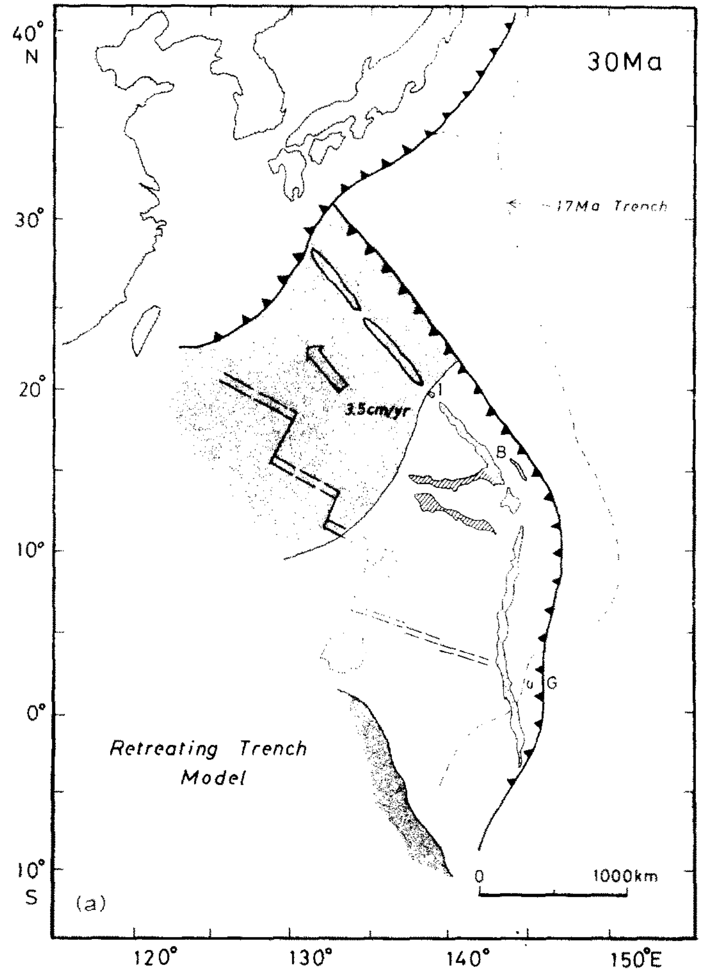
In Fig. 4, the Miocene volcanic front appears to be dislocated by 50 km at 36.2°N in a right-lateral sense. Although the cause for this apparent offset is not clear, it may be related with the opening of the Japan Sea, which might have caused a differential movement between northeast and southwest Honshu. Further studies on the age of volcanic rocks during the Miocene are needed to substantiate and interpret the apparent offset.

RECONSTRUCTION AT 30 MA AGO

The most important problem in the reconstruction at 30 Ma ago is to know the location of the triple junction between the Eurasian, Pacific and Philippine Sea plates at this time, when the spreading in the Shikoku–Parece Vela basins started. The retreating trench model places the reconstructed position of the triple junction southeast of Kyushu, whereas the anchored slab model suggests no movement of the junction between 30 and 17 Ma ago. The Izu–Bonin arc should migrate eastward along the Nankai Trough in the case of the trench retreat, and is fixed in the anchored slab case. Because the absolute motion of the Eurasian plate was small during this period (e.g., Engebretson et al., 1981), we assume that the Izu–Bonin Trench was fixed with respect to the Eurasian plate in the anchored slab model.

Figures 7a and b show the 30 Ma reconstruction based on the trench retreat and anchored slab models, respectively. In these reconstructions southwest Japan and northeast Japan were rotated by 20° counter-clockwise and clockwise, respectively, to their positions before the opening of the Japan Sea. This rotation is based on well-documented paleomagnetic data for Paleogene rocks in Japan (Jarrard and Sasajima, 1980). Although there might have been latitudinal and/or longitudinal shifts of the Japanese islands associated with the opening of the Japan Sea during the Oligocene–Miocene, we did not incorporate these motions because they are not known in sufficient detail. In the anchored slab reconstruction, the location of the triple junction off central Honshu at 30 Ma ago was shifted to the north (Fig. 7b) according to the rotation of northeast Japan.

In the retreating trench model, the Philippine Sea moved northwestward with a velocity of 3.5 cm/yr from 30 to 17 Ma ago, and simultaneously the



Izu–Bonin–Mariana Trench retreated eastward, resulting in the formation of the Shikoku and Parece Vela basins. In the anchored slab model, the Philippine Sea moved northwestward with a velocity of 10 cm/yr, and the westward component of the migration resulted in the opening of the Shikoku and Parece Vela basins. We will discuss which model is preferable on the basis of the geological and paleomagnetic data in the discussion section.

RECONSTRUCTIONS AT 40, 42, AND 48 MA AGO

The reconstruction at 40 Ma ago, when the West Philippine Basin ceased to open, is also based on the above two assumptions. Since there was no spreading in the Philippine Sea basin between 30 and 40 Ma ago, no seaward migration of the trench occurred during this time in the retreating trench model, and the Philippine Sea

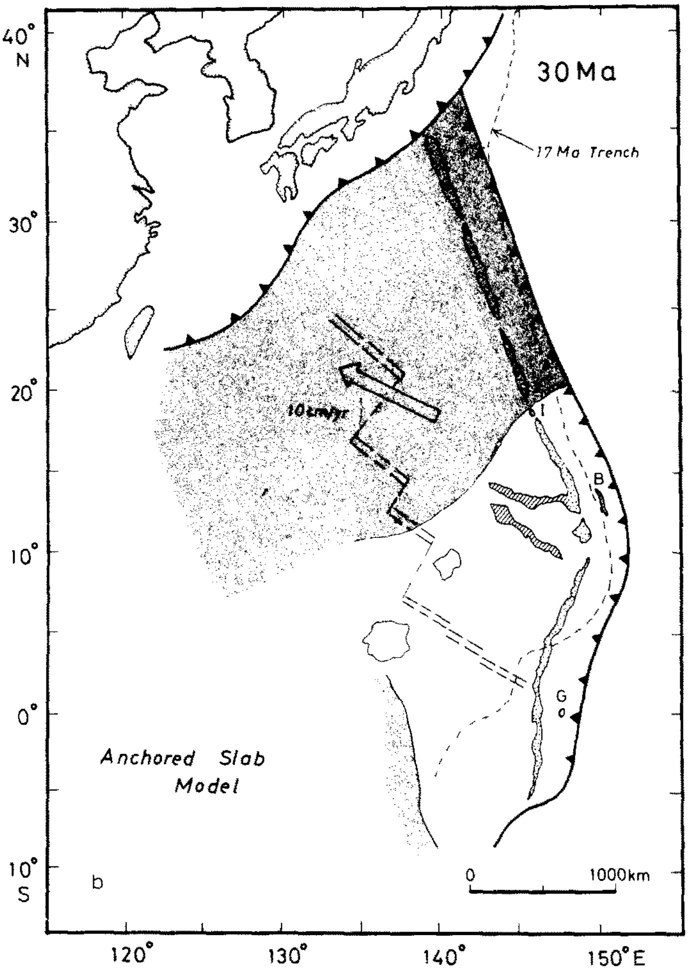
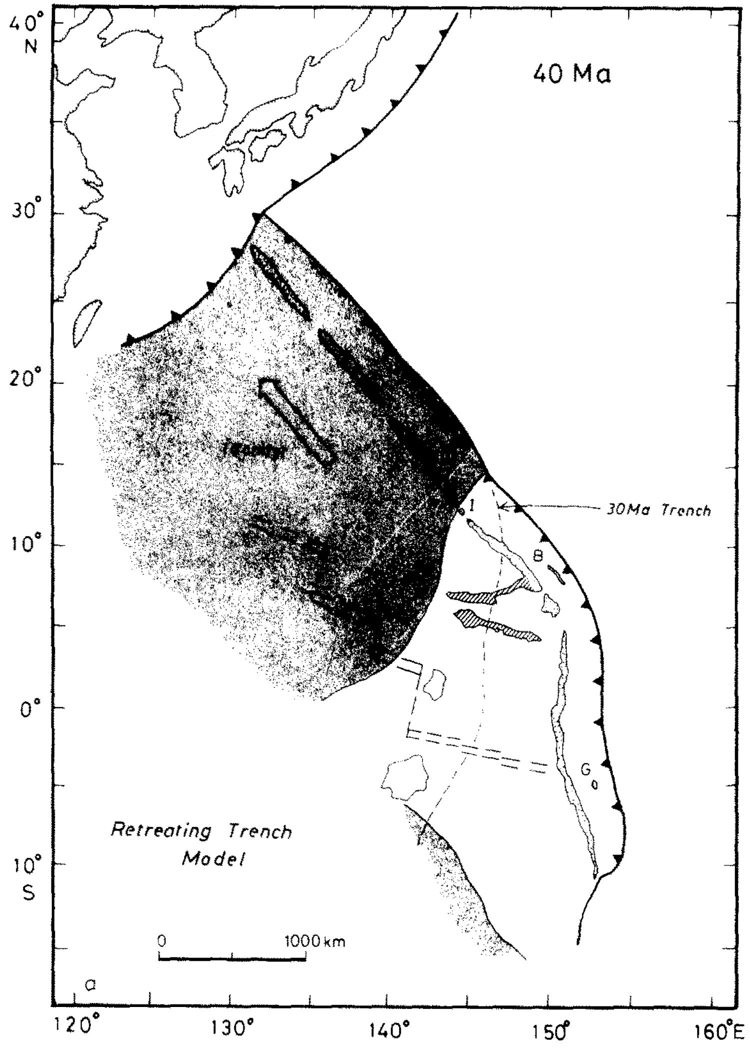


Fig. 7. Reconstruction at 30 Ma ago. a. Based on retreating trench model. b. Based on anchored slab model.

plate cannot have moved away from the trench in the anchored slab model. However, because the trend of trench is different between the Izu–Bonin and Mariana arcs, it is impossible to fix both of these arcs. We fixed the Izu–Bonin arc trend. Thus the Philippine Sea plate had to move along the strike of the Izu–Bonin Trench. Figures 8a and b show the 40 Ma reconstructions. During 40–30 Ma ago, the Philippine Sea was moving northwestward or north-northwestward at a speed of about 10 cm/yr preserving the triple junction geometry in both models.

Figures 9a and b show the 42 Ma reconstructions. At 43 Ma ago the Pacific plate changed its motion with respect to hot-spots from north-northwest to west (Clague and Jarrard, 1973). We have assumed that onset of subduction along the Mariana



arc corresponds with this change in Pacific plate motion. In contrast to the Mariana arc, the Izu–Bonin arc has already formed as evidenced from the 48 Ma age of arc volcanism along the northern part of the Palau–Kyushu Ridge and the Bonin Islands. Assuming trench retreat, the Izu–Bonin Trench retreated to the north during 43–40 Ma ago as indicated in Fig. 9a according to the opening of the West Philippine Basin. In the anchored slab model, the northern half of the West Philippine Basin moved to the northwest along the Izu–Bonin Trench and the southern half moved to the southwest with respect to the northern half, resulting in opening of the West Philippine Basin. Possible velocity–space diagrams between the

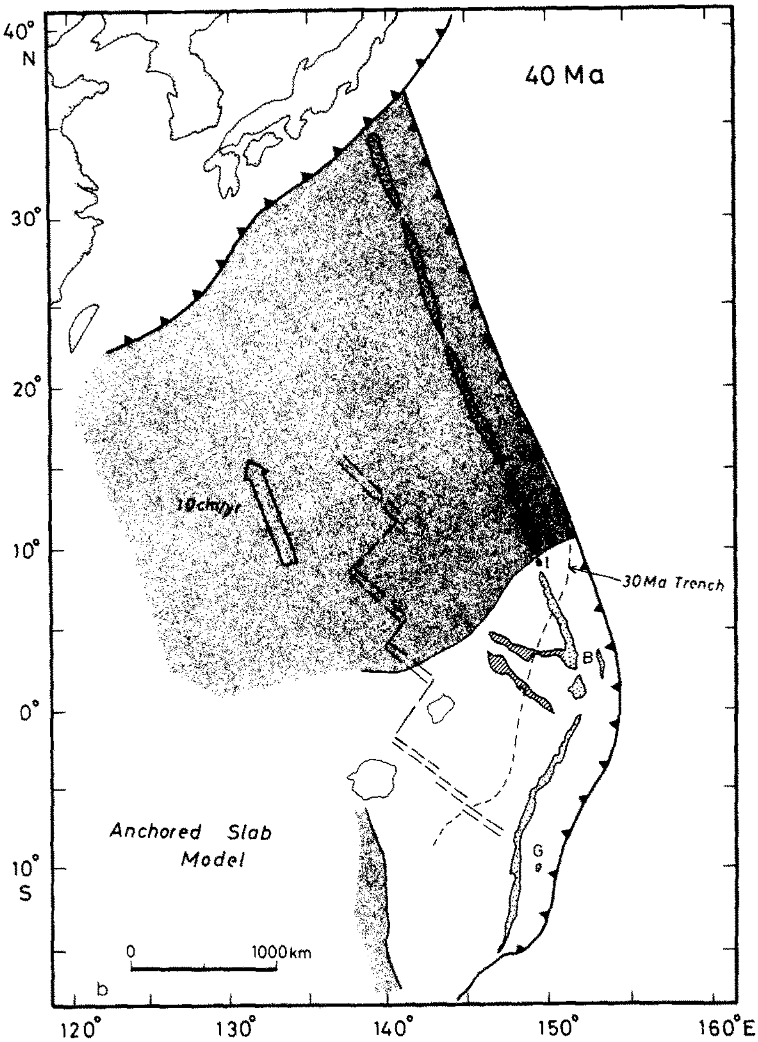
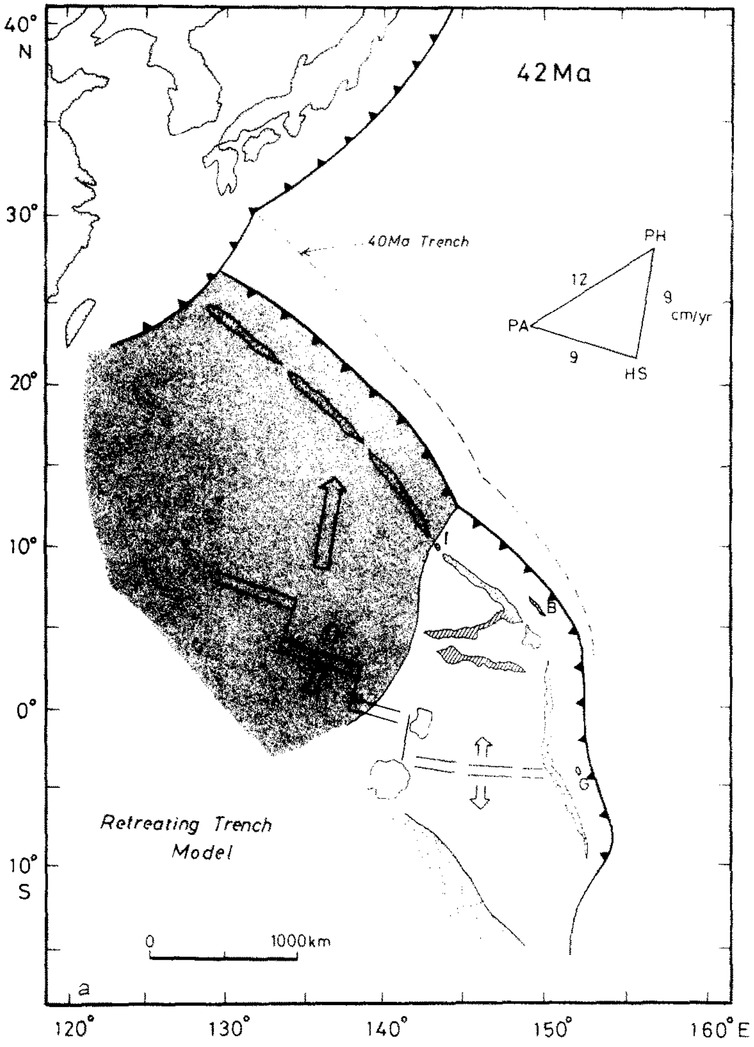


Fig. 8. Reconstruction at 40 Ma ago. a. Based on retreating trench model. b. Based on anchored slab model.

Philippine Sea, Pacific and hot-spots are indicated in these reconstructions.

The 48 Ma reconstruction in the retreating trench model is also straightforward. The trench migrated north-northeastward according to the opening of the West Philippine Basin (Fig. 10a). In the anchored slab case, the situation is not simple; the basic assumption of the fixed trench does not hold any more. Since the Pacific plate motion with respect to hot-spots was known (e.g., Clague and Jarrand, 1973; Engebretson et al., 1981), the lack of subduction along the Mariana arc before 43 Ma ago provides a constraint for the motion of the Philippine Sea between 43 and 48 Ma ago. The relative motion between the Philippine Sea and Pacific plates should



be parallel to the strike of the Mariana arc between 43–48 Ma ago. This requires northward motion of the Philippine Sea with respect to hot-spots (see velocity–space diagram in Fig. 10b). Obviously this northward motion of the West Philippine Basin violates the basic assumption for this model: the fixed Izu–Bonin Trench. In contrast, the retreating trench model can be reconciled to the requirement on the relative motions from the Mariana arc trend (see velocity–space diagram in Fig. 10a).

In the reconstructions for the period 42–48 Ma ago, however, there appears a difficulty in the kinematics of plate motions in both models. During this period, the Pacific plate was moving north-northwestward with respect to hot-spots. Since the

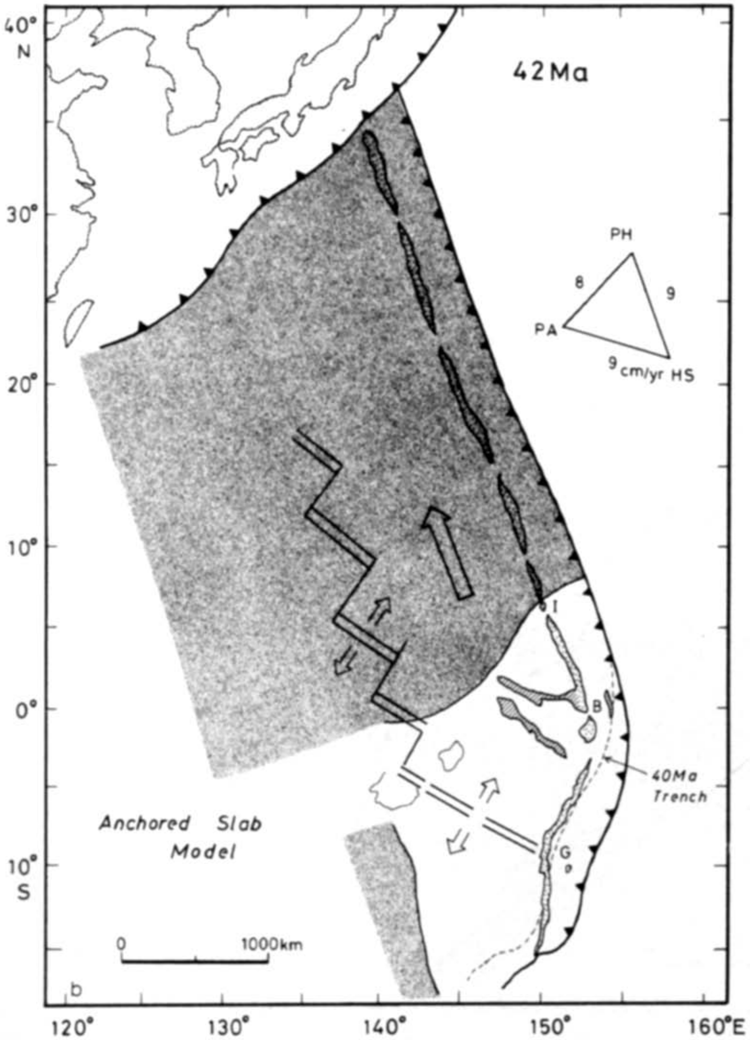
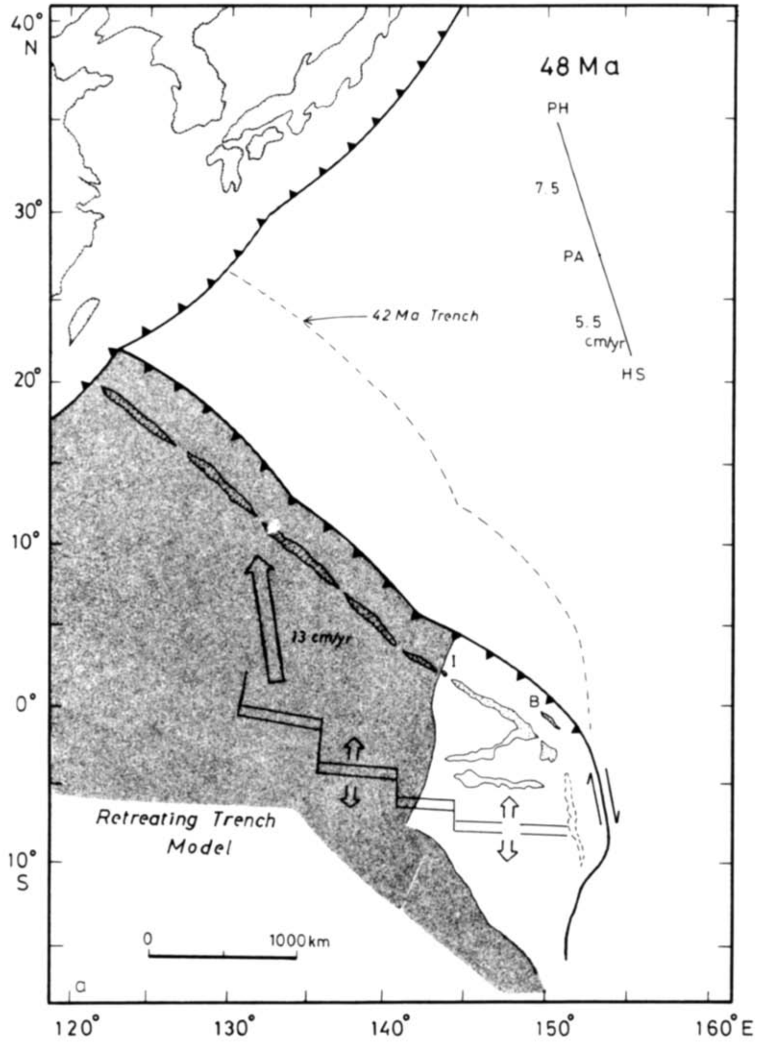


Fig. 9a. Reconstruction at 42 Ma ago based on retreating trench model. A possible velocity-space diagram between the Philippine Sea, Pacific and hot-spots is also shown. Although the direction of the Philippine Sea-hot-spots motion is obtained from the difference between the 42 and 40 Ma reconstructions, the value of the velocity is not well constrained because of the short time period between these two reconstructions.

b. Reconstruction at 42 Ma ago based on anchored slab model. A possible velocity-space diagram is shown; the reliability of this diagram is same as stated in the caption of Fig. 9a.

spreading rate at the Central Basin Ridge in the initial stage of opening is quite large (4.4 cm/yr for half spreading rate, Mrozowski et al., 1982), convergence can occur between the northern half of the West Philippine Basin and the Pacific plate. However, the absolute motion of the Pacific plate is northward and away from the



Izu–Bonin Trench. it is quite difficult to imagine that subduction can occur when the subducting oceanic plate is moving away from the trench in an absolute frame. This point will be discussed in the next section.

DISCUSSION

Retreating trench model and anchored slab model

We discuss in this sub-section which of the two models proposed in the former sections is preferable on the basis of development of the plate boundary in east Asia,

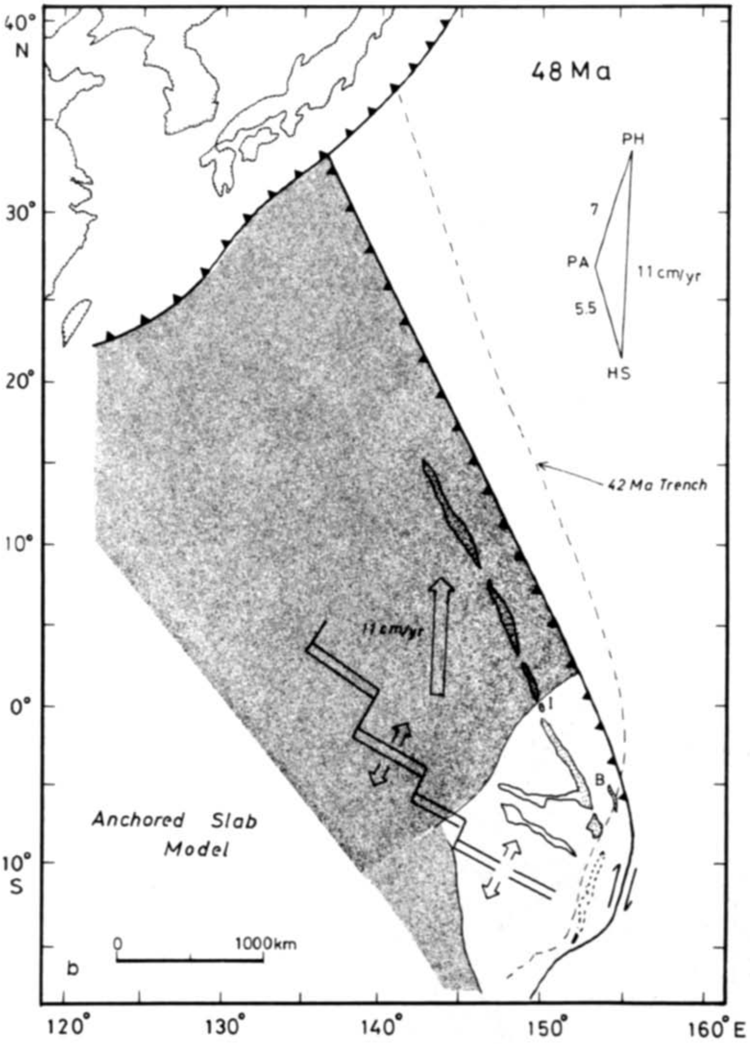


Fig. 10. a. Reconstruction at 48 Ma ago based on retreating trench model. The velocity-space diagram shown is obtained from the Pacific plate absolute motion (Engebretson et al., 1981) and the difference between the 42 and 48 Ma reconstructions.
b. Reconstruction at 48 Ma ago based on anchored slab model. The velocity diagram shown is obtained samely as that in Fig. 10a.

and the paleomagnetic data of the Bonin and Mariana islands. First, from the viewpoint of development of the plate boundary, the retreating trench model is much simpler than the anchored slab model. We note here that the island arcs migrated seaward from the margin of Eurasia to form the Japan Sea and the South Okhotsk Basin approximately at the same time as the opening of the Shikoku and Parece Vela basins. Although the exact time of the opening of the Japan Sea and the

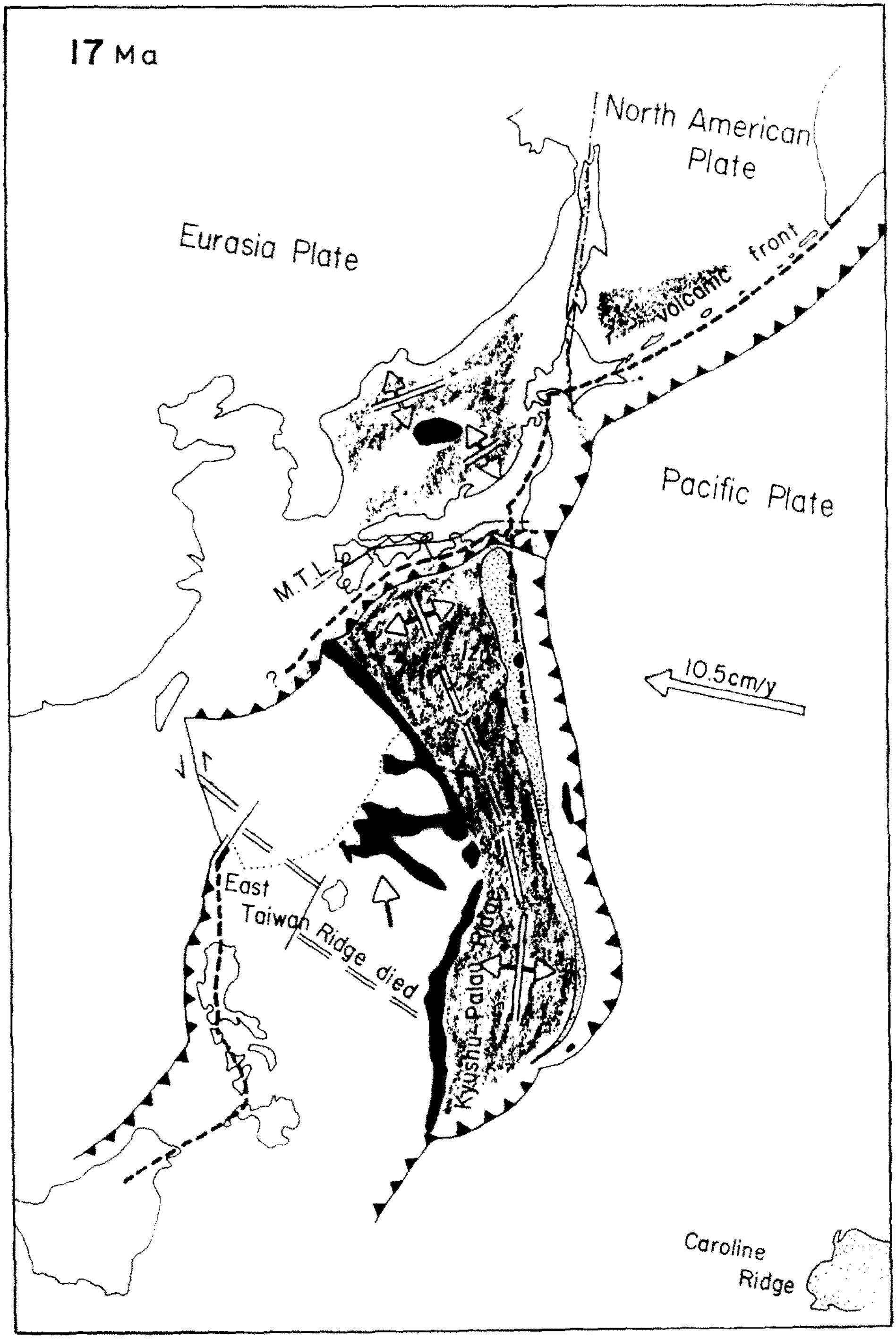


Fig. 11. Reconstruction at 17 Ma ago based on retreating trench model. Marginal basins which formed during the late Oligocene to middle Miocene are shaded.

South Okhotsk Basin is not yet definitely determined, the basement depth and the heat flow of these basins are similar to those observed in the Shikoku and Parece Vela basins (e.g., Sclater, 1972; Sclater et al., 1976), which suggests that all of these basins were formed approximately simultaneously. Tamaki (1982) also estimated the time of formation of the Japan Sea and the South Okhotsk Basin as the late Oligocene to Miocene based on the sediment distribution. In the 17 Ma reconstruction, we notice that the landward edges of these basins are continuous (Fig. 11, shaded area). Moreover, the South Okhotsk Basin and the Shikoku Basin are symmetric with respect to Japan; the former is bounded by the convergent plate boundary between the Eurasian and North American plates from Hokkaido to Sakhalin and the latter by the Nankai Trough, the convergent boundary between the Eurasian and Philippine Sea plates. Both basins have a fan shape open to the Japanese islands. The simultaneous retreat of the Kurile, Japan, and Bonin–Mariana trenches during 30–17 Ma ago could produce the simultaneous opening of these basins, associated with shifting of the two triple junctions oceanward. In contrast, the anchored slab model requires a more complex development of the Eurasian plate margin. This is because the formation of the Japan Sea requires a retreat of the Japan Trench with respect to Eurasia and, in contrast, the formation of the Shikoku and Parece Vela basins requires the Izu–Bonin Trench to be fixed with respect to Eurasia. Also remind that in the 48 Ma reconstruction for the anchored slab model, the fixed Izu–Bonin Trench assumption was also violated.

Next we compare the rotations of the Izu–Mariana arc and the West Philippine Basin predicted from our models with those inferred from paleomagnetic data and magnetic anomaly skewness data. Rotations about the vertical axis have been reported for the Bonin, Guam and Saipan islands (Kobayashi, 1972; Larson et al., 1975; Fuller et al., 1980; Keating et al., 1982; Kodama et al., 1983; McCabe and Uyeda, 1983). It has also been inferred from magnetic anomaly skewness data that the West Philippine Basin has rotated significantly since its formation (Louden, 1977; Shih, 1980a). Table I shows the comparison. The rotations of most of the islands except Chichi, Ani and Ototo islands group of the Bonin islands and except the rotation of the West Philippine Basin are consistent with those predicted from our retreating trench model. In contrast, the anchored slab model predicts smaller rotations than those observed.

There is a difference of 70° in rotation between the paleomagnetic data from two groups of the Bonin Islands; Kodama et al. (1983) suggested a tectonic rotation among these islands due to an oblique subduction of the Pacific plate along the Izu–Bonin Trench. Of course, it is not possible to explain the different rotations within the Bonin Islands by a simple development of the plate boundary. However, the clockwise rotations of the Bonin–Mariana islands show overall agreement with those predicted from the retreating trench model.

Our models give a smaller rotation for the West Philippine Basin than those estimated by Louden (1977) and Shih (1980a). However, we note that magnetic

TABLE I

Comparison between observed rotations and models *

Location	Age (Ma)	Rotation (degrees)			Reference
		Obs.	Model A	Model B	
Bonin					
Chichi, Ani, Ototo	48	~ 100	50	25	Keating et al. (1982),
Haha, Muko, Jome	42	~ 33	30	10	Kodama et al. (1983)
Saipan	36–41	~ 45	50	20	McCabe and Uyeda (1983)
Guam	25–41	~ 60	60	40	Larson et al. (1975), McCabe and Uyeda (1983)
West Philippine Basin	40	60?	30	0	Louden (1977), Shih (1980a)

* Model A: retreating trench model, Model B: anchored slab model. Obs. denotes the rotation obtained from paleomagnetic data.

anomaly skewness data only give us a half of the great circle on the globe on which the paleopole can exist. To fix the paleopole, we need an assumption on the intensity of magnetization of the basin at its formation. Because the assumptions made by Louden and Shih do not seem to have been well substantiated, the discrepancy in rotation of the West Philippine Basin in Table I does not have much meaning.

On the basis of the above evidence, we prefer the retreating trench model. Matsuda (1978) maintained that the Izu–Bonin Trench has been fixed to the Japanese Islands at least since 43 Ma ago. His model for the development of the Philippine Sea is a modification of that proposed by Uyeda and Ben-Avraham (1972); they proposed that a transform fault between the Kula and Pacific plates, located in the southwest Pacific, was turned into the subduction boundary, the Izu–Bonin–Mariana Trench, when the Pacific plate changed its motion 43 Ma ago. Matsuda (1978) modified the location of the transform fault to join at south Fossa Magna, central Honshu, in order to explain the cusp-shape deformation of subduction terrains of pre-Miocene age in south central Honshu (Fig. 12). Note that our anchored slab model approximates his model. He cited two pieces of evidence for the fixed Izu–Bonin Trench at the present position since the Paleogene. One is the bending and dislocation of the subduction terrains in south-central Honshu, which has been believed to have occurred during the Paleogene and before, and the other is the paleocurrent analysis for the middle Miocene turbidite deposition in a north–south trending trough in the western edge of south Fossa Magna. Much coarse debris from the Kanto mountains, which are located northeast of the trough, came from the east. If the bending of the terrain is after the deposition, the debris had to come from the south when deposited, which is difficult to explain because there is no source of turbidites to the south. However, the time of the deposition is around 7 Ma ago (T. Matsuda, pers. commun., 1982), which implies that the bending had occurred before 7 Ma ago. Thus this is not a contradictory fact to our preferred model, because at that time the triple junction had already arrived at the present position.

Next the exact time of the bending and dislocation of the subduction terrains of Cretaceous and Paleogene age in Fig. 12 has not yet been determined but has been a matter of debate. He maintained that the Miocene rocks at the west of south Fossa Magna have not been subjected to any significant offset by the Akaishi Tectonic Line (Fig. 12) in contrast to the pre-Miocene subduction terrains there. However, this is true only for the terrains which have a time of formation close to Pliocene. The Wada formation of early Miocene age, located at the northernmost end of the Akaishi fault zone, is deformed severely by the fault (N. Matsushima, personal communication, 1982). Kimura (1961) maintained that the Futamata group of early Miocene age, located at the southernmost end of the fault zone, does not seem to be displaced much by the fault; however, its distribution is clearly bounded by the fault, which suggests that there has been some tectonic movement since early Miocene time along the fault. N. Matsushima (pers. commun., 1982) recently

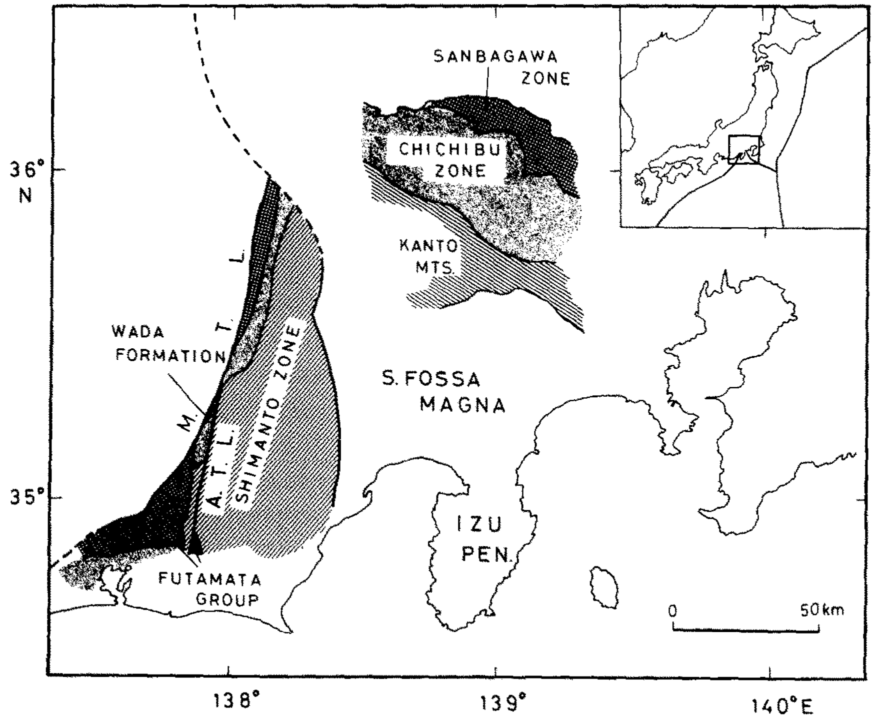


Fig. 12. Distribution of subduction terrains of pre-Miocene age in south-central Honshu (after Geol. Surv. Japan, 1982 and Kimura, 1961); Sanbagawa zone (Mesozoic), Chichibu zone (Paleozoic–early Mesozoic), and Shimanto zone (Cretaceous–early Tertiary). *M.T.L.* and *A.T.L.* are the Median Tectonic Line and Akaishi Tectonic Line, respectively.

pointed out a possibility that the main structure of the Akaishi Tectonic Line formed after the Wada formation of early Miocene age. Although more studies are necessary to determine the amount of the movement along the Akaishi Tectonic Line before or after the Miocene, the evidence cited by Matusda is not necessarily contradictory to our preferred model. Further note that it is not very straighforward to relate directly the bending of subduction terrains to collision episodes. Subduction near the junction with no collision episode may also produce a similar bend of terrains.

Origin of the West Philippine Basin

In our 17 Ma reconstruction (Fig. 6), we notice that the estimated trends of the Palau–Kyushu Ridge and the spreading axis of the Shikoku Basin is more or less parallel to the trend of the Central Basin Ridge. This parallelism and the occurrence of subduction beneath the northern part of the Palau–Kyushu Ridge during 48–40 Ma ago suggests that both of the basins, i.e., the Shikoku and West Philippine basins formed by a similar mechanism, i.e., by back-arc spreading. However, the spreading axis of the basin, i.e., the Central Basin Ridge, is not located close to the inferred volcanic front along the northern part of the Palau–Kyushu Ridge (see Fig. 2c, d). This appears contradictory to the fact that back-arc spreading often occurs close to the volcanic front. However, if back-arc spreading is passive, i.e., caused by the retreat of the trench or continental plate, back-arc basins will be formed along the weakest zones in the back-arc area, which might not be identical to the volcanic front; the Japan Sea formation would be such example.

Another plate in the southwest Pacific?

We noted in the former section that in our 48 Ma reconstruction, there is a difficulty of plate kinematics; the Pacific plate moving to the north with respect to hot-spots has to subduct to the southwest beneath the Philippine Sea. To avoid this difficulty, we propose here another plate subducting beneath the Philippine Sea during 48–43 Ma ago. This plate would be bounded from the Pacific plate by a ridge-transform fault system. A schematic illustration is presented for the configuration of plates in the early Tertiary in the western Pacific region (Fig. 13).

There are three additional pieces of evidence which suggest that there was another plate south of the Pacific plate. First is the dike trend of boninite and related rocks in the Bonin Islands. One of the authors showed that a dike swarm comprising more than 100 dikes run dominantly in a NW–SE direction (Fig. 14, S. Maruyama, unpublished data). According to Nakamura (1977), this dominant trend of dikes should be parallel to the maximum horizontal compressive stress in the region. On the other hand, the extensive paleomagnetic study of Chichi-Jima, the largest island of the Bonin Islands, by Kodama et al. (1983) and Keating et al. (1983) indicates that the island has rotated about 100° in a clockwise sense since its formation. If we

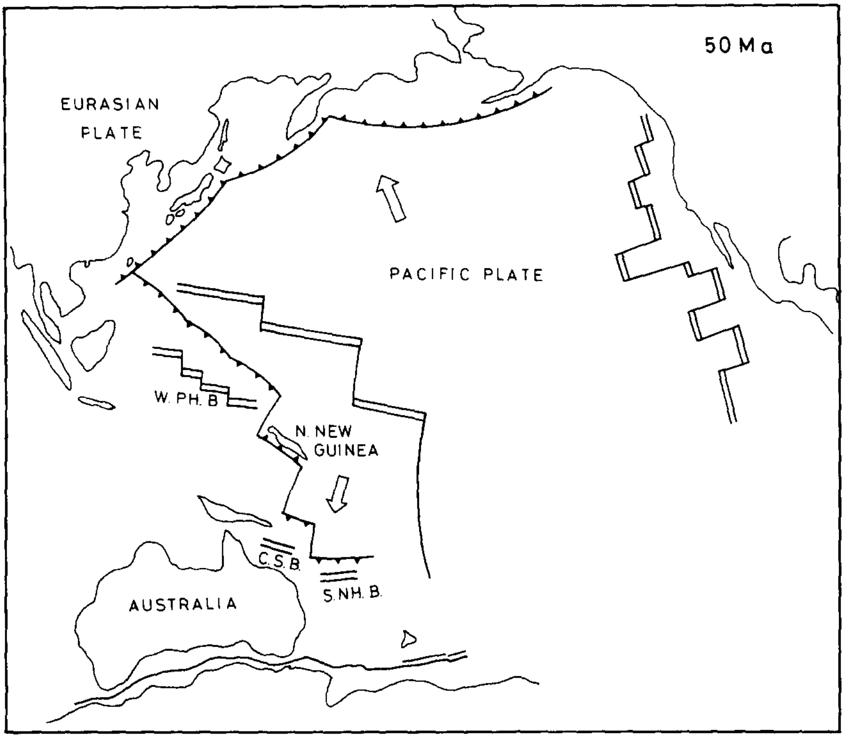


Fig. 13. A hypothesized plate geometry in southwestern Pacific at 50 Ma ago. W.PH.B., C.S.B., and S.NH.B. denotes the West Philippine Basin, Coral Sea Basin and South New Hebrides Basin, respectively. A plate exists north of New Guinea and is subducting to the southwest or south beneath the West Philippine Basin and northeastern margin of Australia.

rotate this island back to 48 Ma ago using this paleomagnetic data, the direction of the maximum horizontal compressive stress would be NE–SW (see the inset of Fig. 14). In our retreating trench model, if the Pacific plate was subducting beneath the Bonin Islands, the relative motion between the Pacific and Philippine Sea plates is in a NNW–SSE direction as is shown in the velocity–space diagram of Fig. 10a. However, if the hypothesized plate was subducting, the direction of the convergence could be NE–SW, which is consistent with the dike trend at 48 Ma ago.

Next, the geology of New Guinea suggests that another plate than the Pacific plate existed during the early Tertiary. There is a suture zone along the medial mountains in central New Guinea, which was a subduction zone during the late Cretaceous to early Miocene (Hamilton, 1979). The northern half of New Guinea was an island arc beneath which the seafloor north of southern New Guinea and Australia had been subducting to the north (Hamilton, 1979). During this period, the relative motion between the Australian and Pacific plates was diverging (Cande and Muther, 1982). This implies that the block which includes northern New Guinea

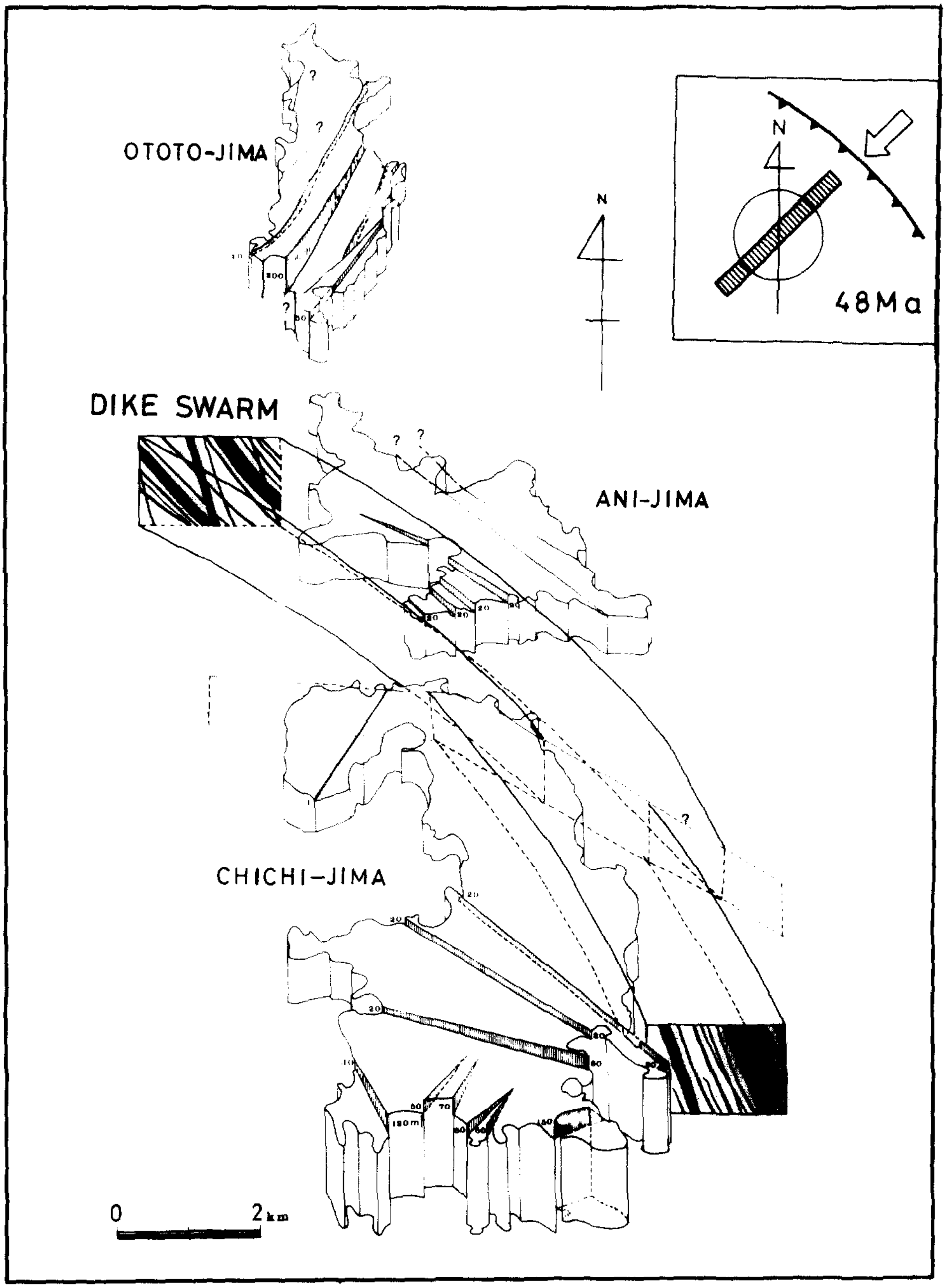


Fig. 14. Distribution of dike swarm in Chichi-Jima and Ani-Jima of the Bonin Islands (after S. Maruyama, unpublished data). The inset shows the direction of dike swarm at 48 Ma ago reconstructed using the paleomagnetic data of the Bonin Islands by Kodama et al. (1983).

is not part of the Pacific plate but part of another plate which existed north of Australia. In addition, the opening of the Coral Sea Basin and the south New Hebrides Basin during Paleogene was roughly in a north–south direction (Weissel and Watts, 1979; Weissel et al., 1981), which suggests subduction of another plate to the south beneath the Australian continental margin during the early Tertiary.

From these we speculate that there was a large plate in the southwestern Pacific during the Paleogene which shared ridge-transform boundary with the Pacific plate (Fig. 13). It is interesting to note that there are some studies which suggest that the Pacific plate was not a single plate during the early Tertiary (Gordon and Cox, 1980; Farrar and Dixon, 1981), although how their studies are related to the plate proposed in this study is not clear and a subject to be studied in the future. The sudden change of the Pacific plate motion at 43 Ma ago is easily explained if we assume this hypothesized plate because it was separated by a ridge-transform system from the Pacific plate. A sudden disappearance of this divergent boundary could have occurred by its subduction beneath Australia. This decrease of ridge-push force from the south can cause a change of the absolute motion of the Pacific plate as was shown by Gordon et al. (1978). The hypothesis proposed here will be described extensively in a separate paper (T. Seno, in prep.) and needs to be substantiated from the geology of the southwestern Pacific region.

CONCLUSIONS

Through the reconstruction of the Philippine Sea back to 48 Ma ago with respect to Eurasia, we have obtained the following results.

The West Philippine Basin formed by a distinct episode of back-arc spreading associated with subduction beneath the northern part of the Palau–Kyushu Ridge. The back-arc spreading which formed the West Philippine, Shikoku and Parece Vela basins resulted from the seaward retreat of the trench; the formation of the Mariana Trough is an exception and likely to be caused by the landward retreat of the upper plate. There would be a plate other than the Pacific plate in the southwestern Pacific during the early Tertiary; this plate was subducting southward beneath the Philippine Sea and Australia. The annihilation of this plate beneath Australia may have caused the change of the geometry of the southern boundary of the Pacific plate and thus the abrupt change of the Pacific plate motion at 43 Ma ago.

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