PALEOGEOGRAPHIC RECONSTRUCTION OF THE PHILIPPINE SEA AT 5 m.y. B.P.

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The Philippine Sea at 5 m.y. B.P. has been reconstructed by the following process. Firstly, it was rotated rigidly relative to the Eurasian plate around the pole of rotation at 45.5° N, 150.2° E with a rotation angle of 6.0° for the past 5 m.y. Secondly, the evolution and deformation along the plate boundaries were incorporated in the rigid rotation. This reconstruction suggests: (1) the Izu Peninsula, which was originally a volcanic island of the Izu-Bonin Arc, collided with central Honshu in a west-northwest direction a few million years B.P.; (2) a TTT(a)-type triple junction east of Honshu has migrated west-northwestward relative to the Eurasian plate; and (3) the subduction zone of the Pacific plate, beneath the central part of the Mariana Arc, has remained fixed relative to Eurasia. Westward motion of the Philippine Sea plate and subduction beneath the eastern Eurasian margin has resulted in the opening of the Mariana Trough.

1. Introduction

The Philippine Sea (Fig. 1) is the largest marginal sea in the western Pacific and it has evolved through successive stages of sea-floor or back-arc spreading of some sort [1-8]. It is tempting to reconstruct the Philippine Sea after its birth on the basis of available data of geophysics and plate tectonics. Although several workers [2,9-11] attempted to reconstruct the Philippine Sea, these works were highly speculative because of limited information about the relative motion of the Philippine Sea with the surrounding plates.

Our main concern here is to reconstruct the Philippine Sea at 5 m.y. B.P. as quantitatively as possible. Since quantitative data on the relative motion of the Philippine Sea to the surrounding plates are now available, as will be discussed in the next section, we first rigidly rotate the Philippine Sea plate with respect to the Eurasian plate from the present to 5 m.y. B.P. Next, the deformation and opening along the plate boundaries is taken into account. This approach is based on the basic assumption in plate tectonics that plates move rigidly as a whole and that the main tectonic evolutions occur along the zones near the plate boundaries. Although the rigid rotation is a simple procedure, it provides useful constraints and information on the evolution of the plate boundaries.

2. Major motion

In order to conduct a rigid rotation of the Philippine Sea at 5 m.y. B.P. as quantitatively as possible.
The Philippine Sea plate with respect to the Eurasian plate, it is necessary to select from the literature the rotation vector or the angular velocity vector between these plates \[9,12-16\]. Some of these vectors give too large or too small a rate of relative plate motion compared with the rate of seismic slip along the Nankai Trough, the northern boundary of the Philippine Sea plate, or show a large discrepancy between the direction of plate motion and the slip direction of shallow thrust-type earthquakes along this part of the boundary.

Seno \[14\], using only the direction of the slip vectors of shallow thrust-type earthquakes along the boundaries of the Philippine Sea plate, obtained an instantaneous rotation vector \((45.5^\circ N, 150.2^\circ E, 1.20^\circ /\text{m.y.})\) between the Philippine Sea and Eurasian plates with reference to model RM1 of Minster et al. \[17\]. This vector gives a convergence rate along the Nankai Trough comparable with the seismic slip rate \[14\]. Thus we use Seno’s \[14\] rotation vector for the purpose of reconstruction. The velocity and direction of the relative motion of the Philippine Sea plate to Eurasia calculated by this rotation vector is shown in Fig. 2.

Before reconstructing the position of the Philippine Sea plate at 5 m.y. B.P. around the pole of rotation of Seno \[14\], it is necessary to ascertain that the Philippine Sea plate has been moving about the same
rotation vector since 5 m.y. B.P. The Nankai Trough developed sufficiently deeply to trap the terrigeneous sediments at 3 m.y. B.P. [18]; thus subduction along the Nankai Trough in the present stage is inferred to have commenced earlier than 3 m.y. B.P. The length of the downgoing slab beneath southwest Japan gives another rough estimate of the time of onset of subduction along the Nankai Trough; Shiono [19] estimated seismologically its length as approximately 150–200 km. The average convergence rate along the Nankai Trough at present is about 3.5–4.5 cm/yr [14]. If this rate of subduction has persisted in the past, the duration of the subduction is inferred to be several million years. Therefore, it is likely that the type of plate boundaries and their configuration around the Philippine Sea plate have been unchanged for about 5 m.y. B.P. Given this condition, the driving mechanism of plate motion given by Forsyth and Uyeda [20] would imply that the pattern of plate motion of the Philippine Sea has been grossly uniform during the time interval concerned. For these reasons, we assume in this study that the Philippine Sea plate has undergone a uniform rotation around the pole of Seno [14] for the past 5 m.y.

Fig. 3 shows the position of the Philippine Sea plate with respect to the Eurasian plate after rigid rotation for the past 5 m.y. On the basis of this figure, we investigate the possible regional tectonic evolution; namely the collision deformation at the northeastern corner of the plate, the migration of the triple junction off Honshu, and the deformation of the Mariana Arc.

3. Plate boundary evolution

3.1. Collision of Izu with central Honshu

The Izu-Bonin Arc joins with central Honshu at the south Fossa Magna region where pre-Miocene and Miocene terrains are convexed northwards. The Izu Peninsula (Fig. 1), which now forms part of Honshu, was originally a volcanic island in the Izu-Bonin Arc and it is called the Izu block [21]. We can see from Fig. 3 that the Izu block collided with central Honshu from an east-southeast direction. The lower density of the Izu block prevented it from subduction and it overrode the trench. Matsuda [21]
inferred the time of collision of the Izu block as early Quaternary from the fact that a deep marine sedimentary trough had persisted between the south Fossa Magna region and the Izu Peninsula until the end of the Upper Pliocene or possibly until the Early Quaternary. The cusp bordered by the Sagami and Suruga Troughs is believed to be the result of the overriding of the buoyant Izu block. We can estimate the time of collision of the Izu block on the basis of the rigid rotation described in the previous section, provided that the shape of the plate boundary between the Sagami and Suruga Troughs is known. If we simply assume that there was no cusp between these troughs (see Fig. 7), the time of the collision is estimated at about 2 m.y. B.P.

There had been no consensus as to the direction and time of the collision of the Izu block with Honshu among earlier investigators. Kobayashi and Nakada [7] proposed that the collision took place from the west-southwest at least before Middle Miocene time, because they associated the collision with the opening of the Shikoku Basin. The time of collision estimated by them seems too early as they did not take into account the relative motion between the Philippine Sea and Honshu after the Middle Miocene. Kaizuka [22] proposed a collision from the south along the axis of the Izu-Bonin Trench. This is based on the idea of the "Izu Bar", which is a sliver of the Izu-Bonin Arc supposedly decoupled from the rest of the Philippine Sea plate. The Izu Bar was supposed to have moved to the north along the Izu-Bonin Trench. If this was the case, the difference in the direction of the motion between the Izu Bar and the Philippine Sea plate had to be accommodated by shear motion and spreading at the boundary of these two plates. Kaizuka [22] proposed that the Nishi-Shichito Fault (Fig. 1) is such a boundary of shear motion. However, no seismic activity is found there and the topography does not seem to indicate a left-lateral shear motion in recent geological times. Further, a crustal extension is necessary to compensate for the westward component of the Philippine Sea plate. Karig and Moore [23] suspected that the basins in the Shichito-Iwojima Ridge were an extensional feature during the Quaternary. However, the width of these basins is at most 25 km [23] and this cannot account the motion which amounts to about 150 km for the past 5 m.y.

Matsuda [2] also supported the idea of the Izu Bar, although he inferred the direction of its motion relative to Honshu as north-northwest, which is slightly different from that proposed by Kaizuka [22]. His inference is based on analysis of the interplate earthquakes of 1923 and 1703 [24,25] along the Sagami Trough. He also referred to the fact that the trend of the maximum-pressure axes in the south Fossa Magna region and Izu Peninsula lies between north and northwest. However, there remains considerable ambiguity about the slip direction of the 1923 Kanto earthquake that ranges from N22°W to N55°W [24, 26–28]. It should also be noted that the trend of the maximum-pressure axes does not necessarily imply a north-northwestward motion of the Izu-Bonin Arc relative to Honshu. This trend in the Izu Peninsula may be due to the effect of bending of the oceanic lithosphere near the subduction zone [29]. In the south Fossa Magna region, it may reflect a change in the crustal stress field caused by large nearby interplate earthquakes.

As a result, we feel that it is difficult to decouple the Izu-Bonin Arc from the rest of the Philippine Sea plate and we believe that the Izu Peninsula has moved west-northwestward with the Philippine Sea plate and collided with central Honshu a few million years ago.

3.2. Triple junction

At the present the Japan and Izu-Bonin Trenches and the Sagami Trough form a TTT(a)-type triple junction. Since McKenzie and Morgan [30] first mentioned this triple junction, several authors [13,14,21,31] have discussed its stability. McKenzie and Morgan [30] noted that this triple junction is not stable and was off northern Japan at 3 m.y. B.P. Although other authors [13,14,21] suggested a possibility of the stability of the junction by assuming a spreading behind the Izu-Bonin Arc, the suspected opening, with a width of 25 km at most [23], is not sufficient to compensate for the westward component of the movement of the Philippine Sea plate as discussed in the former section. Thus, we ignore the opening behind the Izu-Bonin Arc and conclude this triple junction to be unstable. The evolution of the plate boundaries near the triple junction is presented in three stages in Fig. 4a. We can see from this figure that the present feature that the three boundaries of different
trends meet at one point appears to be too coincidental. At the same time, it does not seem plausible that the cusped area of the Eurasian plate bordered by the Japan Trench and the Sagami Trough (Fig. 4a, lower) could be stable. Alternatively, we believe that this triple junction migrates as if it was stable, as shown in Fig. 4b. Such a process would be possible if the dotted area in Fig. 4b disappeared from the earth’s surface along with the westward migration of the Izu-Bonin Trench.

Murauchi and Asanuma [32] found that the elongated rises of the acoustic basement to the west of the dotted area in Fig. 4b (upper) trend linearly in a north-northwesterly direction and are terminated by the Japan Trench. Murauchi and Asanuma [32] and Sugimura [33] considered that this is due to the absorption of the continental crust by subduction at the trench, i.e., due to tectonic erosion. Especially this type of tectonic process is expected during the deformation of plate boundaries in the vicinity of a triple junction as illustrated in Fig. 4b. The area absorbed along the Japan Trench as estimated by Sugimura [33] coincides almost precisely with the dotted area in Fig. 4b (upper).
3.3. Opening process of the Mariana Trough

The Mariana Trough, between the West Mariana Ridge (third arc) and the Mariana Ridge (volcanic frontal arc), is a typical interarc basin of extensional origin [1]. Geometric and kinematic aspects of the opening of the Mariana Trough have been investigated by several authors [34–36]; however, the causative process of opening is not clearly defined. The position of the Mariana Arc at 5 m.y. B.P. may give us a clue to this problem.

Because the Mariana Trough has been opening since about 5 m.y. B.P. [37], almost the whole of it should be closed at 5 m.y. B.P. After removing the crust of the trough which accreted perpendicular to the spreading trends, as proposed by Karig et al. [36], we have reconstructed the Mariana Arc before the onset of spreading (Fig. 7). Fig. 3 shows that the central part of the West Mariana Ridge at 5 m.y. B.P. was located approximately at the central part of the present Mariana Ridge. This means that the latter has hardly moved relative to the Eurasian plate since the opening began. Since, according to Minster and Jordan [38], the Eurasian plate is approximately fixed to the absolute framework of their model AM1-2, the central part of the Mariana Ridge has, therefore, been fixed to this absolute frame. On the other hand, the northern and southern parts of the Mariana Arc must have moved relative to the Eurasian plate, i.e., relative to the absolute frame, to the extent shown by the gap between the West Mariana Ridge at 5 m.y. B.P. and the Mariana Ridge at present (Fig. 3).

Intermediate and deep activity along the Mariana Arc seems to reflect the above differences in the movement of the arc and trench. Fig. 5 shows the profiles of the earthquake foci and epicentral distribution based on U.S. Geological Survey data during the period 1964–1976 [39]. The figure shows significant differences in activity for the three parts of the Mariana Arc. In the central part of the arc, the Wadati-Benioff zone plunges vertically down to a depth of more than 600 km. In contrast, in the northern and southern parts of the arc, the activity is relatively shallow and the dip of the zone’s activity is smaller. This difference in shape may be due to the differences in the movement of the arc and the trench relative to the absolute frame. We suggest that the downgoing slab under the central part of the Mariana

Fig. 5. Map view (left), cross-section (lower-right), and longitudinal section (upper-right) of the distribution of earthquakes in three parts of the Mariana region: (a) north, (b) central, and (c) south. (From T. Eguchi, in preparation, with the permission of the author).
Arc has been anchored to the less mobile upper mantle.

It is also important to notice in Fig. 5b (left) that the downgoing slab under the central part of the Mariana Arc does not exist below the Mariana Trough over most of the trough width. Spreading in the trough was roughly symmetric and confined to an axial zone in the basin [1]. Very recent pillow basalts were dredged from the steep flanks of the axial high in the basin of the central part of the arc [1]. This indicates that, at least in recent geological time, spreading occurred without a slab directly beneath the spreading axis. This seems to preclude the proposed mechanism that spreading may be triggered either by frictional heat generated by the sinking slab and which convected to the surface [40,41] or by hydrodynamic forces generated by secondary flows associated with the sinking of the slab [42]. On the other hand, Uyeda and Kanamori [43] proposed the following mechanism: if the slab is anchored with respect to the upper mantle and the lithosphere behind the arc moves away, back-arc spreading would result. We advocate this as a possible mechanism for the opening of the Mariana Trough. Fig. 6 shows a schematic diagram of the opening process. The slab which went down was fixed horizontally to the absolute frame under the central part of the Mariana Arc at 5 m.y. B.P. and the platelet between the trench and the arc was also trapped, whereas the Philippine Sea plate behind the arc continued to move westward. As a result, a tensile stress field was formed between the Philippine Sea plate and the Mariana platelet resulting in rifting and formation of the Mariana Trough. The northern and southern parts of the Mariana Arc moved westward, probably because the slab under these parts of the arc was not trapped by the upper mantle, thereby increasing the curvature of the arc. This presumably caused an extensional strain parallel to the Mariana platelet [36].

4. Conclusions

On the basis of rigid rotation with respect to the Eurasian plate and by considering the associated possible deformation of the boundaries, we have reconstructed the Philippine Sea at 5 m.y. B.P. Fig. 7 shows the final result. This may correspond to the stage when the Philippine Sea plate started to subduct along the Nankai Trough, Ryukyu Trench and the Philippine Trench after the cessation of spreading in the Shikoku and Parece Vela Basins. The trend of the Japan, Izu-Bonin and Mariana Trenches was straighter than that seen at present. The location of the triple junction was approximately 150 km eastward of the present position. The Izu block was located to the southeast of the Bosso Peninsula of Honshu.

Although quantitative treatments in the reconstruction of the plates for the geological past can pro-

![Fig. 6. Schematic view of the opening process of the Mariana Trough.](image)

![Fig. 7. Reconstructed Philippine Sea plate at 5 m.y. B.P. Dotted area shows the part of plate which has subducted during the past 5-m.y. period.](image)
duce useful constraints on the possible mechanism of tectonic evolutions, more direct data, such as the absolute dating of rock units, are necessary to substantiate them. It is our hope that this study will provide useful as a guide for future studies.

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