Tectonic evolution of the triple junction off central Honshu for the past 1 million years

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Abstract


We discuss several models of the evolution of the trench–trench–trench triple junction off central Honshu during the past 1 m.y. on the basis of plate kinematics, morphology, gravity and seismic reflection profile data available for the area. The study area is characterized by large basins, 7–8 km deep on the inner lower trench slope on the Philippine Sea side and the deep (9 km) Izu-Bonin Trench to the east. Between the basins and the trench, there are 6–7 km-deep basement highs. The triple junction is unstable due to the movement of the Philippine Sea plate at a velocity of 3 cm/yr in WNW direction with respect to Eurasia (Northeast Japan), subparallel to the strike of the Sagami Trough. Generally we can expect the boundary area between the Philippine Sea and Pacific plates to be extended because the Pacific plate is unlikely to follow the retreating Philippine Sea plate due to the obstruction of the southeastern corner of Eurasia. The above peculiar morphology of the junction area could have resulted from this lack of stability. However, there are several possible ways to explain the above morphology.

Our gravity model across the trench–basement high–basin area shows that the basement highs are made of low-density materials (1.8–2 g/cm³). Thus we reject the mantle diapir model which proposes that the basement highs have been formed by diapiric injection of serpentinites between the retreating Philippine Sea plate and the Pacific plate.

The stretched basin model proposes that the basins have been formed by stretching of the Philippine Sea plate wedge. We estimated the extension to be about 10 km at the largest basin. We reconstructed the morphology at 1 Ma by moving the Philippine Sea plate 20 km farther to the east after closing the basins, and thus obtained 8 km depth of the 1 Ma trench, which is similar to that of the present Japan Trench to the north. Although this stretched basin model can explain the formation of the basins and the deep trench, other models are equally possible. For instance, the eduction model explains the origin of the basin by the eduction of the Philippine Sea basement from beneath the basement high, while the accretion model explains the basement highs by the accretion of the Izu–Bonin trench wedge sediments. In both of these models we can reconstruct the 1 Ma trench depth as about 8 km, similar to that of the stretched basin model.

The deformation of the basement of the basins constitutes the best criterion to differentiate between these models. The multi-channel seismic reflection profiles show that the basement of the largest basin is cut by normal faults, in particular at its eastern edge. This suggests that the stretched basin model is most likely. However, the upper part of the sediments shows that the basement high to the east has been recently uplifted. This uplift is probably due to the recent (0.5 Ma) start of accretion of the trench wedge sediments beneath this basement high.

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Introduction

The triple junction off central Honshu, Japan, connects the Japan Trench, the Izu–Bonin Trench and the Sagami Trough. The Pacific plate (PAC) subducts beneath Northeast Japan (NEJ) and the Philippine Sea plate (PHS) along the Japan and Izu–Bonin Trenches, respectively. On the other hand, PHS subducts beneath NEJ along the Sagami Trough (Fig. 1). Thus the triple junction is of trench–trench–trench (a) type (McKenzie and Morgan, 1969). Although the area has been investigated since the development of plate tectonic theory (McKenzie and Morgan, 1969; Sugimura

Fig. 1. Present plate geometry near the Japanese islands. The study area at the triple junction is indicated by the rectangle. The relative plate motions are from NUVEL 1 (Demets et al., 1985) for major plates and from Seno et al. (1987) for the Philippine Sea plate. The boundary between the Eurasian and North American plates is from Nakamura (1983). Bathymetry is from Chase et al. (1970).
1972; Seno, 1977; Matsubara and Seno, 1980; Seno and Maruyama, 1984; Le Pichon and Huchon, 1987; Hamano, 1987), details of its morphology and structure were poorly known until Seabeam and other geophysical surveys were conducted during the French-Japanese Kaiko project in 1984 (Kinoshita et al., 1986; Renard et al., 1987; Ogawa et al., 1989, this vol.; Huchon and Labaume, 1989, this vol.) and by the Hydrographic Department of Maritime Safety Agency of Japan (Kato et al., 1985). Recently a multi-channel seismic reflection survey was conducted during a cruise of Hakuho-maru, University of Tokyo, in 1986 (Taira et al., 1988). The evolution of the area for the past 1 m.y. is discussed in this paper, using the recent data mentioned above and the reconstructions based on the plate kinematic parameters. The study area of this paper is indicated by the rectangle in Fig. 1.

Figure 2 shows the major morpho-tectonic features (Renard et al., 1987) and Fig. 3 shows the bathymetry based on the Seabeam maps of the area (Kaiko I Research Group, 1986; Kato et al., 1985). The triple junction area is marked by the 9 km deep trench and two major basins on the lower inner trench slope on the Philippine Sea side. The trench has a 25 km wide floor near the junction (Fig. 3), underlain by a thick pile of sediments. Such a large trench wedge is not seen anywhere else in the Japan-Izu-Bonin trench system.

On the Philippine Sea side slope, there are two large basins. The North Basin (NB) is located at the mouth of the Boso and Awa canyons (Fig. 2) and has a depth of about 7 km (Fig. 3). The South Basin (SB), having two subsidiary basins in the south and in the north, is separated from NB by a basement high and has a depth of 7–8 km. Seaward of these basins, there are basement highs called North Nose (NN), Central High (CH) and South Nose (SN). These basins on the lower inner trench slope are only present south of 34°30′N and display a marked contrast with respect to the morphology of the northern part of the area. NB has a thick pile of sediments, part of which was transported into the trench through a canyon located between NN and CH. This large amount

Fig. 2. Major tectonic elements in the triple junction area off central Honshu (modified from Renard et al., 1987). PAC—Pacific plate, NEJ—Northeast Japan, PHS—Philippine Sea plate, NB—North Basin, SB—South Basin, NN—North Nose, CH—Central High, SN—South Nose. In the inset, the relative velocity diagram for the major plates is shown using NUVEL 1 (Demets et al., 1985) and Seno et al. (1987). NA—North American plate, EUR—Eurasian plate.
of sediments in the junction area originates from central Honshu through the Boso Canyon in the Sagami Trough (Figs. 1 and 2, Nakamura et al., 1987; Renard et al., 1987). Thus the high rate of sedimentation is one of the characteristics of this trench-trench-trench triple junction.

The origin of the basins on the landward slope and that of the deep trench, the depth of which amounts to 10-10.5 km if the trench fill sediments are removed, remains debatable (e.g., Renard et al., 1987; see also Seno, 1986; Nakamura, 1988; Huchon and Labaume, 1989, this vol.; Ogawa et al., 1989, this vol.). In this paper we try to explain the peculiar morphology of the area, discuss possible kinematic evolution models and assess their validity based on the presently available data. Our major conclusions are as follows. The basins are likely to have been formed by the stretching of the PHS wedge. The subsidence of the basins and the deepening of the trench axis would have occurred.
simultaneously as the PHS wedge slid down on the PAC slab associated with the landward retreat of PHS.

**Plate geometry**

Figure 1 shows the major plates near the Japanese islands. NEJ is now considered to have transferred from being part of the Eurasian plate to being part of the North American plate (NA) by the displacement of the EUR-NA boundary from central Hokkaido to the eastern margin of the Japan Sea (Nakamura, 1983; Kobayashi, 1983; Seno, 1985b). The Sagami Trough is the boundary between NEJ and PHS.

In the Sagami Trough, the deformation front runs from the Awa canyon in the west and shifts to the Boso canyon in the east (see Fig. 2, Nakamura et al., 1987; Renard et al., 1987). In the triple junction area, the basements beneath NB and SB are apparently continuous to the PHS slope in the west. Also CH and SN are seen as part of PHS in the Kaiko seismic reflection profiles (Kaiko I Research Group, 1986; Ogawa et al., 1989, this vol.). Thus the PHS–NEJ boundary runs at the northern edge of NB, although incipient thrusting occurs within the sediments in NB (Ogawa et al., 1989, this vol.). Although the boundary cannot be accurately depicted, it may run farther to the east along the western edge of NN and through the canyon between NN and CH (Fig. 2). However, the possibility that it runs north of NN cannot be ruled out at present (Fig. 2, double broken lines). In the proposed models we take into account both cases.

**Plate motions**

Although there have been a number of solutions for the rotation vector of the present PHS motion (see Seno and Eguchi, 1983; Ranken et al., 1984), it is the most recent solution by Seno et al. (1987) that we use for the present study. The solutions by Ranken et al. (1984) and Huchon (1985) yield an EUR–PHS pole very close to the Sagami Trough, and consequently, a small EUR–PHS velocity at the triple junction (0.8–1.3 cm/yr). This small PHS velocity at the junction does not explain the observed WNW PAC–PHS seismic slip vectors even if we take into account a possible back-arc spreading in the Bonin arc (Seno et al., 1987). Therefore their solutions are less useful for our study. Recently Seno et al. (1987) inverted the seismic slip vectors in the Nankai Ryukyu and Bonin trenches using the NUVEL1 global data set (Demets et al., 1985) and arrived at a solution which satisfies the Caroline–Pacific boundary condition of Ranken et al. (1984), i.e., Mussau Trench convergence and Sorol Trough divergence, within the 1 σ error ellipses of this global solution. We use this recent solution in the present study. The velocity diagram of the major plates at the junction, using their solution, is shown in the inset of Fig. 2.

It is to be noticed that NEJ is presently part of NA. However, because the transition of NEJ from EUR to NA is likely to have occurred only recently, probably at around 0.5 Ma (Seno, 1985b; 1987), and because the triple junction is almost stable if NEJ is part of NA (see the PHS–NA motion in Fig. 2), we ignore this transition in the present study. Therefore, we apply the EUR–PHS–PAC motions in the diagram of Fig. 2 to the NEJ–PHS–PAC motions at the junction for the past 1 m.y. Should we include the above transition, then the actual period treated would extend from 1.5 to 0.5 Ma.

PHS moves WNW (N58°W) at the rate of 3.3 cm/yr with respect to NEJ (Fig. 2). This motion predicts that the triple junction is unstable. As PHS migrates to the west with respect to NEJ, there would appear a gap between PAC and PHS because PAC cannot follow PHS immediately due to the obstruction of the southeastern edge of NEJ (see the inset in the velocity diagram of Fig. 2). The large basins on the lower trench slope at the PHS side and the deep trench at the junction might be a consequence of this lack of stability (Seno, 1986; Renard et al., 1987; Nakamura, 1988). However, a variety of mechanisms is responsible for the formation of those basins and basement highs in the area as shown in the next section.

**Models**

In this section, we propose models for the evolution of the triple junction for the past 1 m.y.
explaining the above morpho-tectonic features. As already mentioned, we treat the case of NEJ being part of EUR, whereby the convergence component of the PHS–EUR motion along the Sagami Trough is very small (Fig. 2), and we do not take into account the three-dimensional shape of PHS beneath NEJ which is discussed by Hamano (1987), Le Pichon and Huchon (1987) and Huchon and Labaume (1989, this vol.). Figure 4 illustrates the proposed models. The following models differ on the point of how the basement highs were formed or to which plate NN belongs.

**Pull-apart and stretched basin models**

In these models, the lower trench slope of PHS is stretched and faulted at the surface by the extension due to the westward movement of PHS, forming NB and SB (Fig. 4a, b). In the pull-apart basin model (Fig. 4a). NN is regarded as part of NEJ; thus the formation of NB directly reflects the relative motion between PHS and NEJ. In the stretched basin model (Fig. 4b), NN is regarded as part of PHS, and thus NB is an intraplate extensional basin. In both of the models, CH and SN are regarded as part of PHS, and SB is formed by intraplate extension within PHS.

**Mantle diapir model**

Because the westward movement of the PAC slab following the retreating PHS is prevented by the existence of NEJ at the junction (Fig. 2, inset),
it may be anticipated that the separation of the PHS/PAC interface has occurred near the junction. Nakamura (1988) proposed that the basement highs (NN, CH and SN) were formed by the rise of a diapir of mafic and ultramafic rocks, which occupied the gap at the PHS/PAC interface (Fig. 4c). These mantle rocks can intrude the supposed gap since the trench depth is well below the mantle geoid (3.25 km depth, Turcotte et al., 1977). In the presence of water dehydrated from the subducted slab, the intruded ultramafic rocks would have transformed to serpentinite. On the Bonin–Mariana lower trench slope, small seamounts made of serpentinite have been found and ultramafic rocks were dredged (Taylor and Smoot, 1984; Hussong and Fryer, 1985; Ishii, 1985). These are believed to intrude as a consequence of the westward retreat of PHS (Nakamura, 1988).

**Eduction model**

In this model, the PHS basement below NB has been educted from beneath NN (Fig. 4d). This model requires NN to be part of NEJ. On the other hand, SB has been formed by the stretching of the PHS wedge as in the pull-apart or stretched basin model. This model implicitly assumes that prior to 1 Ma, PHS was subducting beneath NN. This model was first proposed by Seno (1986).

**Accretion model**

In this model, the basement highs (NN, CH and SN) have been uplifted by accretion of the voluminous trench sediments (Fig. 4e). NB and SB are the forearc basins formed behind the basement highs. This model was proposed onboard during the “Hakuho-maru” cruise KH86-5. The underlying fact was that accretion is currently taking place at the western edge of the Bonin Trench in the junction area (Taira et al., 1988) as will be shown later in the seismic reflection profile.

In the following sections we discuss the viability of the five models, as outlined above, taking into account gravity anomalies, reconstructions and seismic reflection profiles.

**Gravity modeling**

We constructed density structures and calculated gravity anomalies in the E–W cross-sections along Lines 87, 81 and 63 shown in Fig. 3. Lines 87, 81 and 63 cross the center of NB, CH and southern SB, respectively. The calculated gravity anomaly was compared with the observed free-air anomaly (Kaiko I Research Group, 1986). By trial and error, we obtained optimal models for density structures.

We calculated the gravity anomaly from a structure in a two-dimensional space using a line source approximation. A rectangular area of 4' (6.13–6.18) in horizontal length and 1 km in depth is represented by one line source. The upper surface of the subducting PAC slab is derived from the accurate depth determination and focal mechanism study of major earthquakes in the region (Seno and Takano, 1988). The depth of the basement in NB (Line 87, Fig. 5a) is estimated from the multi-channel seismic profiles obtained in KH86-5 on the assumption that the P-wave velocity of the sediments is 2 km/s. The P-wave velocity structure in the Bonin arc across 32°N compiled by Houza and Tamaki (1985) and the relation between P-wave velocity and density (Nafe and Drake, 1963) were used to assign densities in the initial model and then the model was further improved until it fitted the observed anomaly.

Figure 5 shows the obtained density structures. Kinoshita et al. (1986) also arrived at a similar structure in one NW–SE cross-section of the area. We noticed the low density of NN, CH and SN (1.8–2.0 g/cm³). We calculated gravity anomalies by replacing the densities of NN, CH and SN by the 2.7 g/cm³ density of serpentine in the portion represented by the broken lines in Fig. 5. We examined various sizes of diapir as shown in these figures. The positive anomaly above these basement highs becomes too large compared with the observed one, showing that the mantle diapir model is not consistent with the observed gravity anomaly. Also, there are no significant magnetic anomalies associated with these basement highs (Renard et al., 1987). The magnetic anomalies in the area can be explained by the magnetization of the subducted Pacific oceanic crust (Kinoshita et
Fig. 5. Comparison of the calculated gravity anomaly (solid circle) and the observed free-air anomaly (solid line) obtained during the Kaiko Project (Kaiko I Research Group, 1986) along Lines (a) 87, (b) 81 and (c) 63. The density structure used for the calculation is shown below; numbers are in g/cm³. The open circles show the calculated gravity anomaly for the case that the area indicated by the broken line has a density of 2.7 g/cm³ (serpentinite).
al., 1986). We can thus reject the mantle diapir model. However, the other three models are not inconsistent with the low density of the basement highs. In the next section, we compare the remaining three models by reconstructing the morphology at 1 Ma.

**Reconstruction**

We reconstruct the morphology in cross-sections along the above three lines and in a map view. First we present reconstructions in cross-sections by moving the PAC slab and the PHS wedge back to 1 Ma. The westward component of PHS with respect to NEJ is taken as 3 cm/yr (Fig. 2); thus we have to shift the present PHS wedge by 30 km to the east for the reconstruction at 1 Ma. The reconstruction of the PHS wedge is dependent partly on how we reconstruct the PAC slab and partly on the models. The part dependent on the models will be described in each case in the following subsections.

There are various possible ways to reconstruct the PAC slab at 1 Ma. The simplest way is to move back the present PHS/PAC interface to the east by 30 km as a whole (Fig. 6a). In this case a significant offset between the Japan and Izu–Bonin trenches at 1 Ma occurs because we observe no significant offset in axis between these trenches at present. This case is unlikely since it can hardly be expected that at 1 Ma the trench axis was offset by the exact amount which provides its present continuity. The larger width and depth of the Izu–Bonin Trench compared to the Japan Trench is neither explained by this concept. We agree with Nakamura (1988) that the westward movement of PAC following the retreat of PHS is prevented by the NEJ's blocking at the junction, and that the wide and deep trench has been formed by the downwarp of the PHS wedge associated with its sliding along the PAC slab surface. Therefore the next simple assumption would be that the PAC slab did not change its geometry and the PHS wedge has slid down along its upper surface. However, in this case the subsidence of the PHS wedge becomes too large (more than 10 km). Therefore, we use the geometry shown in Fig. 6b. In this case, the dip angle of the PAC slab decreases in order to sustain the base of the PHS lithosphere as PHS retreats westward.
Fig. 6. Illustration of two possible models for the change in geometry of the PHS/PAC interface in a vertical cross-section. PHS has been retreating to the west for the past 1 m.y. The thick and thin lines indicate the geometry at present and at 1 Ma, respectively. a. The geometry is not changed but transferred as a whole to the west. b. As PHS moves to the west, the PAC slab changes its dip to a shallower aspect and sustains the base of the PHS lithosphere. The PHS wedge slides down on the PAC surface. In the inset, the procedure how to retrieve the 1 Ma surface of the PHS wedge is shown.

The eastern wedge of PHS slides down on the PAC surface to fill the gap between PAC and PHS as shown by the arrows in the figure. We assume the thickness of PHS to be 30 km as derived from surface wave studies (e.g., Abe and Kanamori, 1970).

The following reconstruction for each model is based on the PAC/PHS deformation shown in Fig. 6b. The reconstruction of the surface of the PHS wedge can be done as indicated in the inset of Fig. 6b. First, the PAC surface is reconstructed and the PHS wedge shallower than 30 km depth is shifted to the east and raised by the amount that it slides upon the reconstructed PAC slab. In the following subsections, the features of the various models are described. Reconstructions were made for cross-sections along Lines 87, 81 and 63. The results for Line 81 are only shown in the text but not in figures. Owing to its simplicity, we first discuss the reconstruction based on the accretion model.

**Accretion model**

In this model the basement highs, NN, CH and SN, have been uplifted by the accretion of the trench wedge sediments. We have to estimate the size of the accretionary prism beneath these basement highs first. We estimate that the western edge of the prism is located beneath the wall between the basin and the basement high (Fig. 7). The top of the prism is assumed to be located at the terrace on the lower trench slope in Line 87 (Fig. 7a), while it has been placed at an arbitrary level in Lines 81 and 63. The thickness of the prism measured vertically at its eastern edge is assumed to be 2.8 km in Line 81 and 2.0 km in Line 63 (Fig. 7b). Then the prism is removed (thin broken lines in Fig. 7). The PAC slab is reconstructed as described before (thick line in Fig. 7). The prism-removed PHS wedge is shifted to the east by 30 km as a whole but is also raised along the 1 Ma PAC surface as indicated by the arrows. The reconstructed PHS surface is indicated by the thick line in Fig. 7. The depth of the trench axis is reconstructed as 8.6, 8.7 and 8.2 km in Lines 87, 81 and 63, respectively. Obviously this trench depth is dependent on the assumed size of the prism. In the reconstruction based on this model, a bulge, the top of which is 2 km below sea level, appears at the location of the present NB.

**Eduction model**

In this model, NB is formed by the eastward eduction of the PHS basement from beneath NN. Because the origin of SB is exactly the same as in the stretched basin model (see Fig. 4b, d), we will show the reconstructions for Lines 81 and 63 in the next subsection. The depth of the PHS basement beneath NN is estimated by the eastward extrapolation of the basement beneath NB (Fig. 8, thick broken line). Then, after removing the sediments in NB, the PHS wedge is shifted to the east by 30 km and raised along the reconstructed PAC surface. The lateral position of NN is fixed but NN is uplifted vertically in association with the
Fig. 7. Reconstruction of the PHS wedge based on the accretion model, along (a) Line 87 and (b) Line 63. The hatched area depicts the assumed accretionary prism. The broken line indicates the geometry when the prism is removed. This prism-removed PHS wedge is shifted to the east and raised on the 1 Ma PAC surface (thick solid line) as indicated by the arrows.
Eduction

Fig. 8. Reconstruction of the PHS wedge based on the eduction model along Line 87. The basement of NB is extrapolated to the east beneath NN (broken line). This PHS basement is shifted eastward and raised on the 1-Ma PAC surface. The hatched area east of NN is to be eroded between 1 Ma and present.

raised PHS wedge, its top reaching a depth of 2.2 km. NB is just closed by the above 30 km eastward shift of the PHS wedge. Although the top of NN is located only 50 km landward from the trench axis, its depth is not unrealistic because the inner trench slope of the Japan Trench at 2.2 km depth is located only 60 km inside from the trench axis in some areas. The depth of the trench east of NN is reconstructed as 7.6 km. In this reconstruction, the PHS wedge penetrates beneath NN and exists further to the east. Above this portion of PHS, NEJ (seaward extension of NN, hatched area in Fig. 8) must have existed; this portion would have been eroded as PHS retreated westward since 1 Ma.

Pull-apart and stretched basin models

In these models, we have to estimate the amount of stretching necessary for the formation of NB and SB. Since we know the basin geometry, we can estimate the amount of extension. Starting from the shape of the basins as shown by the thick broken lines in Fig. 9, we estimated the values of \( h \), \( d h \), and \( l + dl \) (see the inset of Fig. 9a) in the middle of the basin as shown in Fig. 9. The amount of extension \( dl \) can be calculated by:

\[
h \times l = (h - d h) (l + dl)
\]

Table 1 lists the values of \( dl \) (10, 2 and 5 km for Lines 87, 81 and 63, respectively) together with the estimates of \( d h \), \( h \) and \( l + dl \). Obviously, since the estimates for \( d h \), \( h \) and \( l + dl \) are subject to considerable uncertainty, the above values of \( dl \)

<table>
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<th>Line No.</th>
<th>( h ) (km)</th>
<th>( d h ) (km)</th>
<th>( l + dl ) (km)</th>
<th>( dl ) (km)</th>
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<td>10</td>
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<td>1</td>
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<td>2</td>
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<td>7</td>
<td>2</td>
<td>16.5</td>
<td>5</td>
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</table>

Table 1
Amount of extension needed to form the basins
Fig. 9. Reconstruction of the PHS wedge based on the stretched basin model, along (a) Line 87 and (b) Line 63. The inset in Fig. 9a illustrates stretching of a thin plate. The basin geometry in the profiles is assumed as indicated by the thick broken line. The surface of the PHS wedge and the PAC slab, when the basins are closed, is indicated by the thin broken line. The thick and thin solid lines indicate the geometry at 1 Ma and at present, respectively.
should be taken as an estimate on the order of magnitude.

First, we reconstruct the PAC slab by shifting its 30 km deep surface to the east by 10 and 5 km in Lines 87 and 63, respectively (thin broken line in Fig. 9). We then shift the PHS wedge west of the basin to the east by 10 km to close NB, and to the south, by 5 km to close SB, and thus obtain

Fig. 10. Reconstruction of the morphology in the triple junction area in a map view based on (a) the accretion model, (b) the eduction model and (c) the stretched basin model. The thick solid and thin broken lines show the reconstructed (1 Ma) and present bathymetry, respectively. The solid circles are the locations used to draw the contours of the 1-Ma bathymetry. The hatched area in Fig. 10b is the area which must have been eroded since 1 Ma.
the PHS surface when these basins are closed (Fig. 9, thin broken lines). The basement highs, NN and SN, are fixed at this moment in their lateral positions but shifted vertically along with the change in dip of the PAC slab.

The eastward shift of PHS by 10 km only accounts for one third of the total 30 km shift for the past 1 m.y. Since we regard NN as part of NEJ in the pull-apart basin model, the reconstruction for this model stops at 0.3 Ma. This is unlikely because it cannot explain the deep Izu–Bonin Trench at the junction; the Izu–Bonin Trench must have been originally deeper than the Japan Trench in the triple junction area.

In the stretched basin model, we can continue the reconstruction further back to 1 Ma. In this case, the 1 Ma PAC slab is reconstructed as indicated by the thick line in Fig. 9 by shifting its 30 km deep surface further to the east by 20 and 25 km for Lines 87 and 63, respectively. Then the PHS wedges with closed NB and SB (thin broken line) are shifted to the east by 20 and 25 km, respectively, and raised along the 1 Ma PAC surface. The thick solid line in Fig. 9 shows the reconstruction at 1 Ma based on this model. The reconstruction in Line 81 was done in a similar manner using the value of d/ in Table 1. The depth of the trench axis is reconstructed as 8.2, 8 and 8 km, respectively, along Lines 87, 81 and 63. A bulge, the top of which is 2 km below sea level, appears above the present location of NB.

Reconstruction in a map view

In this subsection, we reconstruct the morphology of the triple junction area in a map view based on the above reconstructions in cross-sections for the eduction, accretion and stretched basin models. Since Lines 81 and 63 are crossing only PHS and PAC, the 1-Ma profiles along these lines are shifted to the south by 22 km in all the models. This corresponds to the N–S component of the PHS–EUR motion. Its E–W component is 30 km for 1 Ma (Fig. 2, inset). In the stretched and accretion models, the profile along Line 87 is similarly shifted to the south by the same distance because in these models NN is also part of PHS. In the eduction model, however, the profile is fixed at the present position because NN is part of NEJ.

Figure 10 shows the reconstruction in a map view for these models. The solid and thin broken lines indicate 1 Ma and present isobaths respectively. The locations for which depths are given from the reconstructions in the three profiles are indicated by the solid circles. The 1 Ma isobaths are drawn by the interpolation of the values at these points.

In all the models, the reconstructed trench axis is located at about 8 km depth on the present outer trench slope. This depth is similar to that of the present Japan Trench. This suggests that the 1 Ma trench axis would have been continuous to the Japan Trench in the north along the present 8 km contour of the outer slope of the Bonin Trench. This also suggests that the WNW PHS–EUR motion has continued for the past 1 Ma and shows that the 1-Ma period used in our reconstruction is reasonable. In all the models, there appears a relatively shallow bulge above the present NB, the top of which reaching a depth of 2–2.5 km below sea level. In the eduction model, there is another bulge above NN (Fig. 10b), which is the uplifted NN (Fig. 8). In Fig. 10, the PHS–NEJ boundary at 1 Ma is indicated by the thick broken line. The eduction model requires that the hatched area in Fig. 10b has been eroded since 1 Ma.

Discussion

We discuss here the three models, i.e., the stretched basin, eduction and accretion models, on the basis of the reconstructions and the multi-channel seismic profiles. Figure 11 shows some of the track lines of the KH86-5 cruise and Fig. 12 shows the obtained profiles along these lines; they are bandpath filtered (10–50Hz), deconvoluted and common depth-point stacked. Figure 13 shows the interpretation of these seismic profiles.

The reconstructions in the former section for all the models give a similar morphology at 1 Ma. However, a major difference exists in the plate boundary geometry between NEJ and PHS; the eduction model requires that the boundary passes between NN and ND and links up with the Izu–Bonin Trench towards the southeast. On the
KH86-5 Seismic Lines

contrary, in the stretched basin and accretion models, it runs north of NB and NN. In the former case, a vast area between the trench axis and NN must have been eroded since 1 Ma (hatched area in Fig. 10b). We can examine whether erosion is taking place at the eastern base of NN by studying the seismic profiles. Line $A-A'$ crosses the trench and the eastern edge of NN in an E-W direction near the canyon between NN and CH (Fig. 11). In profile $A-A'$ (Fig. 12a), we can see that the PAC oceanic basement dips to the west and penetrates beneath NN. Thick trench wedge turbidites overlie this PAC basement and are deformed at the base of NN. The upper turbidite layers dip to the east as they constitute a deep-sea fan here (Fig. 11), called the Mogi Fan (Soh et al., 1988). The dip of the slope of this fan changes abruptly at shotpoint 920, and we infer that incipient thrusting occurs here (Fig. 13a). We can also infer incipient thrusts farther oceanward by a slight disruption of coherent reflections. In the deeper portion, between shotpoints 850 and 1100, we can see numerous diffractions, which are interpreted as indicating corners of thrust sheets forming an accretionary prism (Fig. 13a).

Since it would be difficult to imagine that erosion and accretion occur simultaneously, the above profile and its interpretation seem unfavourable for the eduction model. However, it is quite possible that the accretion began only at 0.5 Ma when vast amounts of turbidite started pouring into the Nankai and Sagami troughs (Taira and Niitsuma, 1985) due to the collision of Izu against Honshu at this time (Koyama, 1986). Noting that our reconstruction actually ranges from 1.5 to 0.5 Ma while the triple junction was unstable, the above evidence for accretion does not necessarily exclude the eduction model because the triple junction has been stable since 0.5 Ma and no significant erosion has occurred.

In all the reconstructions (Fig. 10), there appears a narrow depression south of NB. This is
Fig. 12. Multi-channel seismic reflection profiles along Lines (a) $A-A'$, (b) $B$ shotpoint. Two-way travel time is shown in the vertical axis.
- B' and (c) Line C–C' in Fig. 11. SP denotes
Fig. 12 (continued).
Fig. 13. Interpretation of the seismic profiles in Fig. 12. a. Line A-A' across the Izu-Bonin Trench. The PAC oceanic basement is dipping to the west, and at the base of NN, accretion is currently taking place. (b) Line B-B' and (c) Line C-C' across the North Basin (NB). The basement of NB is cut by normal faults; however, the shallow part of the sediments (above 11 s) shows an uplift of NN with respect to the basement to the west.
not unrealistic because at present we see a similar morphology in the Sagami Trough west of 140.7°E. There are two canyons, the Boso and Awa canyons, and an accretionary bulge in between (Nakamura et al., 1987). Thus we can interpret the narrow depression as the Awa canyon at 1 Ma and the bulge to the north as the accretionary prism formed by the northward subduction of PHS before 1 Ma (Nakamura et al., 1984). Since these features are common to all three models, they are of little help in differentiating between the models.

The basement morphology and the deformation recorded in the sediments in NB would provide the best information to rate the models. In all models, we expect that the basement of NB would subside since 1 Ma along with the westward retreat of PHS (see Fig. 6b). The major difference would exist in the mode of deformation of the basement. In the stretched basin model, the basement would be faulted by grabens or half-grabens (Fig. 4b). In the accretion model, the basement should be more smooth and not faulted, in particular, at the western edge of NN (Fig. 4e). NN would be uplifted with respect to the basement west of it due to the accretion. In the eduction model, we expect that the basement would penetrate beneath NN (Fig. 4d).

Lines B–B’ and C–C’ cross NB and the western edge of NN in a WSW–ENE direction (Fig. 11). In profile C–C’, the basement at shotpoints 4050–4180 looks cut by normal faults at both sides (Figs. 12c and 13c). In profile B–B’, the numerous diffractions at the western edge of NN suggest normal faults here (Figs. 12b and 13b). The deformation of the sediments seen in Lines B–B’ and C–C’, in its deeper part below 11 s (two-way travel time), is consistent with this interpretation of normal faults. The depocenters are located above the basement which appears to be cut by the normal faults. However, the shallower part of the sediments does not show simple sagging in the above depocenters and suggests that the mode of deformation has changed. For example, though the sediments between 10.25 and 11 s in profile C–C’ are still thickest in the eastern part of the basin, it is uplifted at its eastern end with respect to the western part. Furthermore, in the portion shallower than 10.25 s, the depocenter has migrated to the western half of the basin.

In profile B–B’, this depocenter migration cannot be seen because this profile covers only the eastern half of NB. In this profile, an anticlinal structure can be vaguely detected around shotpoint 1900. However, the two-way travel time beneath the terrace is as much as 0.1 s shorter than that of the west of it, and this produces an artificial uplift of the part beneath the terrace. It should also be noticed that the track line changed to the north shortly after shotpoint 1900 and that the basement of NB is known to be dipping to the north (Renard et al., 1987). Thus the antcline is exaggerated. Huchon and Labaume (1989, this vol.) interpreted a similar antcline in one of the Kaiko profiles as an indication of compression and suggest the presence of thrusts dipping to the east. We tend to disagree with their opinion because this apparent antcline was seen in only one Kaiko profile (Line 85) which crosses NB at almost the same location of Line B–B’ and none of the other Kaiko profiles show similar sediment deformation features. Note that the lines in which the antcline appears are crossing the steepest portion of the scarp of the terrace (Kaiko I Research Group, 1986), on which the travel time difference effect would be most pronounced. We believe that the antcline is an artificial one and that the deformation of the sediments in Line B–B’ would not essentially be different from that seen in Line C–C’. This deformation entails the uplift of NN with respect to the area west of it during the deposition of the sediments above 11 s though the sagging around shotpoint 1800 between 10 and 11 s indicates that subsidence due to normal faulting also continued during the sedimentation of this part. We suggest that this uplift of NN has probably been caused by the accretion at the eastern base of NN.

As we have mentioned earlier, the accretion is likely to have started when vast amounts of sediment were transported into the trench. This should also be the time of major sediment supply to NB. We also have suggested that this occurs around 0.5 Ma and coincides with the change of the relative motion between NEJ and PHS from the EUR–PHS motion to the NA–PHS motion. The
component of the crustal separation at the eastern end of NB would have diminished significantly by this change in motion (see Fig. 2). This explains why the subsidence in the eastern half of NB decreased in the upper part of the sediments. Though the deformation of the basement seen in the seismic profiles supports the stretched basin model, we believe that it is valid only for the period before 0.5 Ma. This limited duration, however, should be tested by future deep-sea drilling in NB and by age determination of the sediments.

Conclusions

The basins in the lower trench slope are likely to have been formed by the extension within the PHS wedge associated with the PHS retreat with respect to NEJ. The subsidence of the basins and the deepening of the trench axis would have occurred simultaneously as the PHS wedge slid down on the PAC slab surface. This scenario should, strictly speaking, be applied to the 1-Ma period before 0.5 Ma while NEJ has been part of EUR. Since 0.5 Ma, the relative motion between PHS and NEJ has a larger component of convergence along the Sagami Trough and a smaller component of extension between NN and NB. Consequently the mode of deformation at the triple junction area would have changed. Around this time the importance of the accretion at the trench probably influenced the development of the morphology in the junction area because at this time vast amounts of sediment started to accumulate in the trench and NB. The development and the tectonics of the triple junction area after 0.5 Ma, however, will be fully treated in a separate paper.

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