

## Spatial and temporal evolution of the subducting Pacific plate structure along the western Pacific margin

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[1] Tomographic images of the subducting Pacific plate beneath the Izu-Bonin-Mariana arc illustrate a progression of geometries from shallow dipping to vertical from north to south along the arc. Recent advances in technology and inversion techniques have improved resolution of slab structure beneath the western Pacific island arcs, but reasons for the variation in geometry and morphology are still poorly understood. By comparing high-resolution tomographic images of the western Pacific and updated paleogeographic reconstructions, we are able to link the spatiotemporal evolution of the subducting Pacific plate back to the mid-Miocene. We have reconstructed tectonic motions along the Kurile-Japan-Izu-Bonin-Mariana arc system and the Ryukyu arc to provide an independent, additional interpretation of the subducting Pacific plate using the most current plate motion data. We then investigate the plausibility of our model and three other proposed models based on the interpreted slab structure from tomographic images. The new reconstruction agrees with the basic characteristics of former trench retreat models but illustrates the importance of the collision of the Ogasawara Plateau with the trench in the mid-Miocene and its subsequent effect on the slab structure at depth and the impact of other aseismic ridge collisions along the plate boundary. The combination of evidence in changed physical properties imaged with tomography and the current interpreted slab morphology can be analyzed with the past plate motions to understand subduction zone processes.

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### 1. Introduction

[2] The Izu-Bonin-Mariana arc system, consisting of the Izu-Bonin arc in the north and the Mariana arc in the south, reaches an extent of almost 3000 km from Japan to Palau (Figure 1). The Pacific plate, late Cretaceous in age at the Izu-Bonin trench and early Jurassic in age at the Mariana trench [Müller *et al.*, 1997], is subducting beneath the Philippine Sea plate at a rate that decreases southward along the arc. The Philippine Sea plate is bounded by the Ryukyu arc in the northwest, Japan to the north, Taiwan and the Philippines in the west, and the volcanic islands along the Izu-Bonin-Mariana arc along the eastern margin. The tectonic history of the region and the formation of the Philippine Sea plate have been widely studied using many different methodologies in earth science. Many geophysical research groups have investigated the mantle structure and plate motion dynamics using many different methods including numerical modeling, analogue modeling, empirical modeling, and forward modeling [Hager and O'Connell, 1981;

Kincaid and Olson, 1987; Richards and Engebretson, 1992; Ricard *et al.*, 1993; Griffiths *et al.*, 1995; Lithgow-Bertollini and Richards, 1995; Zhong and Gurnis, 1995; Moresi and Gurnis, 1996; Schellart *et al.*, 2003]. Seismologists have used seismicity and tomographic images to investigate the heterogeneity in the mantle and morphology of the subducted Pacific plate [Chiu *et al.*, 1991; van der Hilst *et al.*, 1991; Fukao *et al.*, 1992; van der Hilst *et al.*, 1993; Gudmundsson and Sambridge, 1998; Widiyantoro *et al.*, 1999, 2000].

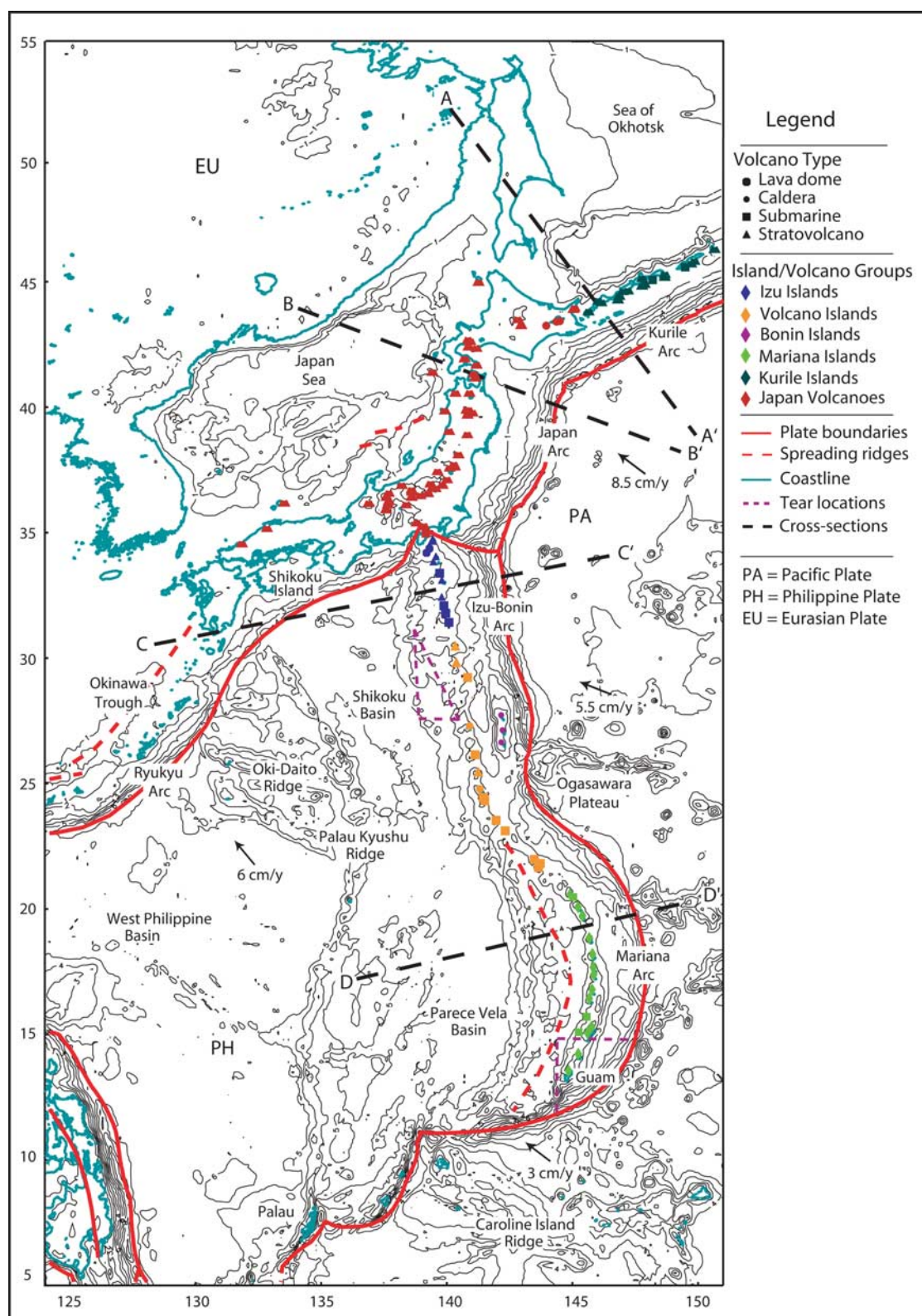
[3] Numerous plate reconstruction models have focused on the location of the Izu-Bonin trench with respect to Japan and spreading of the basins within the Philippine Sea plate, these models are typically nonunique, with poor constraints on plate motion through time due to subduction at the edges of the Philippine Sea plate and the consequent lack of many magnetic anomalies [Uyeda and Ben-Avraham, 1972; Matsuda, 1978; Lewis *et al.*, 1982; Seno and Maruyama, 1984; Celaya and McCabe, 1987; Otsuki, 1990; Seno *et al.*, 1993; Hall *et al.*, 1995a, 1995b; Hall, 2002]. Although it is a challenge, plate reconstructions of the region can be produced and then verified using the current slab morphology and structure interpreted from tomographic images.

### 2. Previous Tectonic Reconstructions

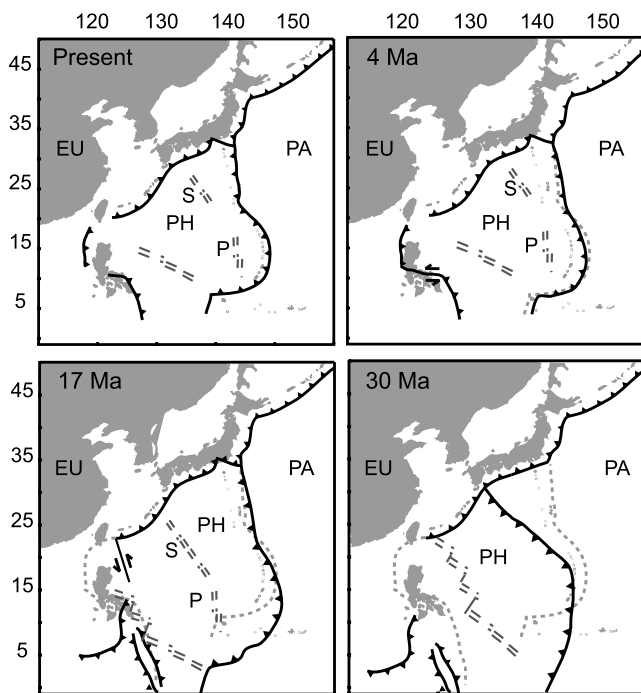
[4] The western Pacific margin has been studied to understand interoceanic convergent margin systems and

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**Figure 1.** Map of the northwest Pacific with ETOPO5 bathymetry with depth contours in kilometers, volcanoes from the Smithsonian Volcano Index, motion vectors of the Pacific and Philippine Sea plates from Zang *et al.* [2002], and cross section locations used in Figure 6.



**Figure 2.** Tectonic reconstruction of the Philippine Sea plate (PH) based on *Seno and Maruyama* [1984]. The black lines with triangles illustrate the trench location at the time located in the upper left corner, dashed lines are the present plate boundary, and double dashed lines represent extinct spreading ridge axes. PA, Pacific plate; PH, Philippine Sea plate; EU, Eurasian plate; S, Shikoku Basin; P, Parece Vela Basin.

subduction zone processes. The formation of the island arcs and marginal basins along the Kurile-Japan-Izu-Bonin-Mariana system and the surrounding tectonic regime are diverse and complex. *Molnar and Atwater* [1978] explained back-arc basins as being formed behind subduction zones where older slabs are subducting; the retreat of the trench line due to the gravitation pull force on the slab creates back-arc spreading. Arc formation, arc migration, and back-arc extension are generally linked to trench retreat and changes in plate motion. With these processes in mind, the motion of the Izu-Bonin and Mariana arcs have been modeled back in time by incorporating magnetic isochrons, geologic data, GPS, earthquake slip vectors, radiometric dating, and paleolatitude data. The result of combining these data sets is a paleogeographic plate motion model based on interpreted Euler poles for the motion of the Philippine Sea plate, Pacific plate, Australian plate, and North American plate (Japan), relative to the Eurasian plate.

[5] The tectonic history of the Philippine Sea is a disputed topic, which includes three broad categories of models that all focus on the trench-trench-trench triple junction location of the Izu-Bonin, Japan, and Ryukyu arcs. Initial models suggested the triple junction had remained fixed relative to Japan resulting in only a small degree of rotation of the Philippine Sea plate [*Uyeda and Ben-Avraham*, 1972; *Matsuda*, 1978; *Lewis et al.*, 1982]. Others argued that the Philippine Sea plate has rotated clockwise since the mid-Eocene, and therefore the triple junction migrated from the

southwest to the northeast with a westward change in motion in the late Miocene [*Seno and Maruyama*, 1984; *Seno et al.*, 1993; *Hall et al.*, 1995a; *Hall*, 2002]. A further model claims the triple junction initially moved northeast with a component of clockwise rotation but at 25 Ma changed direction and then moved 500 km westward along the coast of Japan [*Otsuki*, 1990]. In this paper, we compare models describing the motion of the eastern margin Philippine Sea plate retreating with respect to the location of the triple junction of the Philippine Sea, Pacific, and Eurasian plates [*Seno and Maruyama*, 1984; *Seno et al.*, 1993; *Hall et al.*, 1995a, 1995b; *Hall*, 2002], an opposing view of the triple junction advancing westward with time [*Otsuki*, 1990], and compare them to our own reconstruction.

## 2.1. Trench Retreat-Type Reconstructions

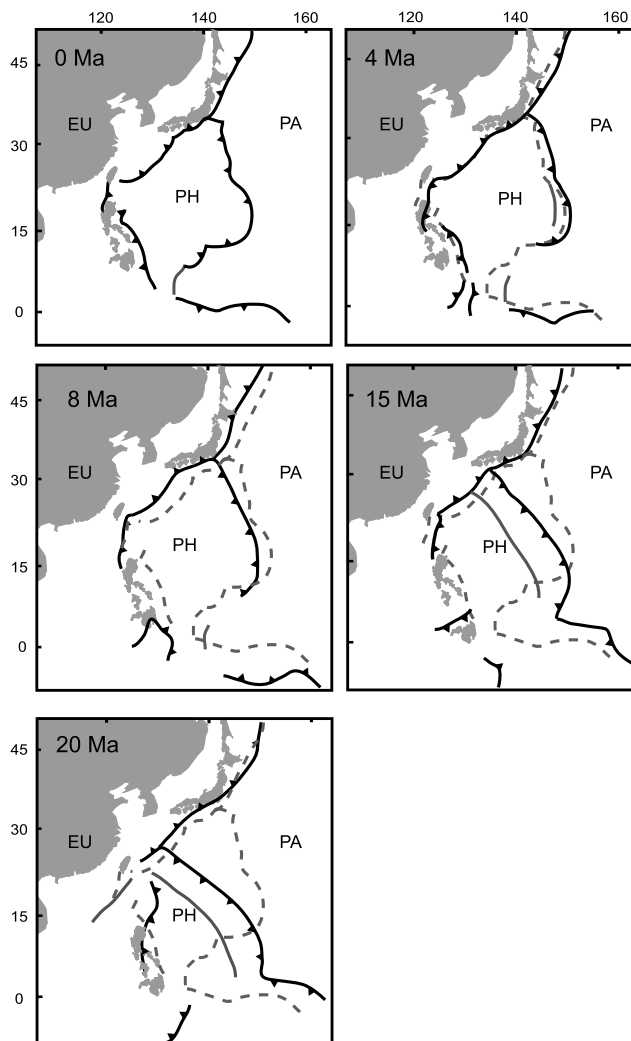
[6] The two retreating trench models presented are based on paleomagnetic data from the islands along the arcs surrounding the Philippine Sea plate, results from the Ocean Drilling Program (ODP) [*Haston and Fueller*, 1991; *Koyama et al.*, 1992] and back-arc spreading calculations. One of the first tectonic reconstructions of the Philippine Sea plate modeled the plate motion back to 48 Ma and speculated on the change in motion of the Pacific plate at 43 Ma, then was later revised to include NUVEL-1 data [*Seno and Maruyama*, 1984; *Seno et al.*, 1993]. In Figure 2 we present their reconstructions from the present back to 30 Ma.

[7] *Seno and Maruyama* [1984] describe the most important aspect of their reconstruction at 30 Ma as interpreting the position of the triple junction when the Shikoku and Parece Vela basins begin opening. They place the triple junction to be southeast of Kyushu at 30 Ma before the Izu-Bonin arc begins to quickly migrate eastward along the Nankai Trough due to the opening of the basins (Figure 2).

[8] For the last 17 Myr the shape of the Philippine Sea plate was reconstructed using on shore geologic data from Japan and paleomagnetic data from drill cores [*Seno and Maruyama*, 1984]. The Izu-Bonin trench at 17 Ma was calculated to be at its most easterly position based on the location of the Miocene volcanic arc in central Japan (Figure 2). Limited K-Ar ages of intrusive and extrusive rocks from central Honshu dated between 10 and 20 Ma were used to estimate the position of the volcanic front in the Miocene. This model also includes the deformation of the Japan Islands and the opening of the Sea of Japan, which are important factors in reconstructing the area. Back-arc spreading events that formed the West Philippine, Shikoku, and Parece Vela basins were thought to have caused the oceanward retreat of the Izu-Bonin trench 100 km east of the present location.

[9] The reconstruction at 4 Ma (Figure 2) is also primarily based on the distribution of extrusive rocks in central Honshu and the location of the present Philippine-Pacific Euler pole [*Seno and Maruyama*, 1984]. The volcanic front onshore Japan at 4 Ma was estimated to be approximately 20 km east of its present location, therefore the triple junction was estimated to be 70 km east of its present position due to the right-lateral offset of the Japan Trench from the Izu-Bonin trench. It was assumed the Izu-Bonin trench motion changed direction and started moving landward some time between 10 and 4 Ma based on the





**Figure 3.** Series of images based on the reconstruction of Southeast Asia from Hall [2002]. Black lines with triangles are subduction zones locations at time indicated in upper left corner, dashed lines illustrate current plate boundaries, and solid lines are active spreading centers.

cessation of Miocene volcanism (10 Ma) and turbidite deposition near the Nankai Trough (4–5 Ma).

[10] Hall *et al.* [1995a, 1995b], Macpherson and Hall [2001], and Hall [2002] have proposed another trench retreat style reconstruction that concentrates on the Philippine Sea plate motion and its relationship with the Caroline and Australian plates rather than with the trench-trench-trench triple junction and its relationship to Japan. Their initial model was based on that of Seno and Maruyama [1984], but additional paleomagnetic data from drill cores and geologic data from the southern portion of the Philippine Sea plate were used to portray early development of the Philippine Sea. The marine magnetic anomalies and geological data of the west Philippine Sea and the eastern Indonesian islands were interpreted to not only reflect the deformation at the southern plate edge, but the motion of the whole plate unlike the Seno and Maruyama [1984] model. The latest reconstruction of the Philippine Sea plate was published as part of a large-scale

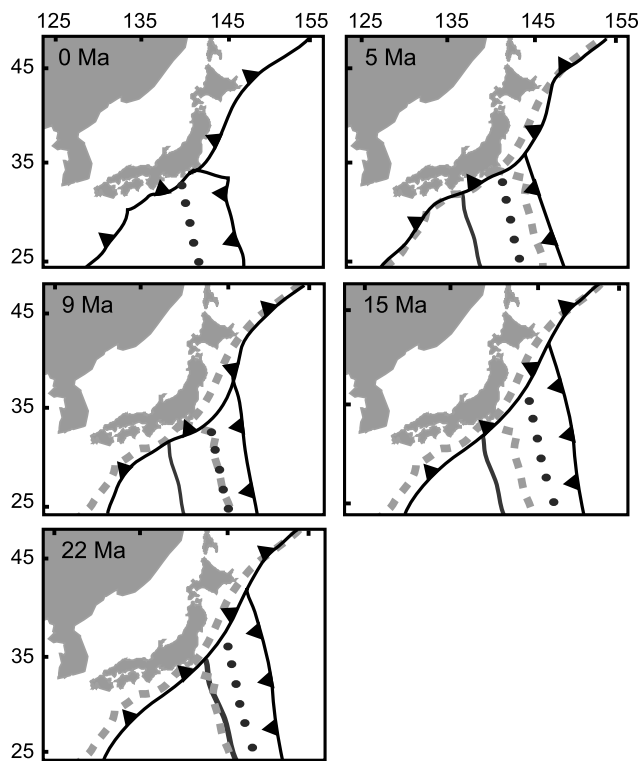
reconstruction of Southeast Asia with a focus on important periods where plate boundaries and motions changed: 45, 25, and 5 Ma [Hall, 2002]. We present the main characteristics of this model for the western Pacific region back to 20 Ma from his series of 1 Myr incremental figures (Figure 3).

[11] The models of the most recent tectonic history by Seno and Maruyama [1984], Hall *et al.* [1995a, 1995b], and Hall [2002] are similar, but Hall's models of the Philippine Sea plate display no rotation between 25 and 40 Ma but include a fast clockwise rotation of the whole plate from 25 to 10 Ma. Geological evidence of the Indian Ocean lithosphere subducting beneath the southern Philippine Sea plate in eastern Indonesia was the basis for the lack of rotation between 40 and 25 Ma [Hall *et al.*, 1995a], and whole plate rotation was based upon anomaly skewness data and seamount studies in the Shikoku basin. Hall [2002] suggests a major plate reorganization occurred in the late Miocene to early Oligocene when the Ontong Java Plateau collided with the Melanesian Arc. At this time the eastern edge of the Philippine Sea plate became a rapid intraoceanic subduction zone and spreading of the Parece Vela and Shikoku basins propagated to form one large marginal basin [Hall, 2002]. A second major change in plate motion at 5 Ma led to subduction of the Philippine Sea plate beneath the Philippines and initiation of back-arc spreading in the Marianas, but the causes of these changes were not fully explained. Their models show a slight advance of the Izu-Bonin trench after 5 Ma, but it is not as significant as illustrated in the Seno and Maruyama [1984] model (Figures 2 and 3).

## 2.2. Advancing Trench Reconstructions

[12] The previous models were based on trench retreat and back-arc spreading theories. Although they are more widely accepted and referenced, there is another model that describes a significantly different interpretation of the paleogeographic location of the Izu-Bonin arc (Figure 4). The Otsuki [1990] model is based on paleomagnetic data from Japan, the fan-shaped opening of the Japan Sea around 15 Ma [Otofuji and Matsuda, 1983; Hayashida and Ito, 1984; Otofuji and Matsuda, 1984; Otofuji *et al.*, 1985; Otofuji and Matsuda, 1987; Toshio and Hamano, 1988], and his proposed “laws of convergence rate of plates” [Otsuki, 1989].

[13] From paleomagnetic declination and skewness of magnetic anomalies on the Philippine Sea plate, Otsuki [1990] proposed that significant clockwise rotation of the Philippine Sea plate occurred between 40 and 25.5 Ma, which is in direct opposition to Hall *et al.* [1995a, 1995b] and Hall [2002]. It was interpreted that the clockwise rotation took place after spreading in the West Philippine Basin, but before the back-arc opening of the Shikoku Basin. Before the opening of the Sea of Japan at 15 Ma, the Izu-Bonin trench was north of the Japanese Islands and the paleo-Ryukyu arc was located along the eastern boundary of the Japan (Figure 4). From 25 Ma to the present, the Izu-Bonin arc is described as advancing landward 500 km with a southwest component down the proto-Japan trench. One important point that Otsuki [1990] mentions is that the large values for total rotation at Guam and the Bonin islands may be due to the affects of the buoyant subduction of the Caroline Ridge and the Ogasawara Plateau [Otsuki, 1990].



**Figure 4.** Series of figures based on the paleogeographic maps from *Otsuki* [1990]. Black lines with triangles are subduction zones at time indicated, the dotted line represents current plate boundaries, the solid lines are spreading centers, and dots indicate the position of the Izu-Bonin volcanic arc.

[14] The trench advance and retreat models discussed are very different, but the one important feature that both the models have in common is a change in direction of motion of the Izu-Bonin arc relative to Japan in the late Tertiary. A few important elements are missing from the previous models; the effect of buoyant aseismic ridges on the down-going plate, specifically the Ogasawara Plateau and the Caroline Islands Ridge, the recent motion of the Ryukyu, Kurile, and Japan arcs, and the stability of a trench-trench-trench triple junction. All of these features are important factors in the recent plate motion history of the western

Pacific margin and must be considered in paleogeographic reconstructions.

### 3. Paleogeographic Reconstruction

[15] We have reconstructed the motion of the plates in the western Pacific for the past 25 Myr using updated Euler vectors determined by earthquake slip vectors, GPS observed velocities, and data from the NUVEL-1 and -1A global plate motion models [Zang *et al.*, 2002] in PlatyPlusPlus software. The new Euler pole for the current PA-PH boundary is slightly different from the previous calculation [Seno *et al.*, 1993] due to adjustment of the Pacific-Caroline plate vector from new interpretation of slip vectors (Table 1). New results for the Philippine Sea plate motion are constrained by geological and geophysical data along the plate boundaries and take into account the deformation within the plate and along its boundaries [Zang *et al.*, 2002]. The new tectonic reconstruction of the western Pacific is slightly different to those previously published, but confirms the basic characteristics presented previously in the trench retreat style models [Seno and Maruyama, 1984; Seno *et al.*, 1993; Hall *et al.*, 1995a, 1995b; Hall, 2002]. Important results from the model are the Izu-Bonin arc exhibits a rapid clockwise rotation from the Oligocene but changes in direction at 8 Ma; distinct collision events of the Ogasawara Plateau and Caroline Island Ridge at the trench; and the presence of back-arc extension in the Mariana arc since the late Miocene.

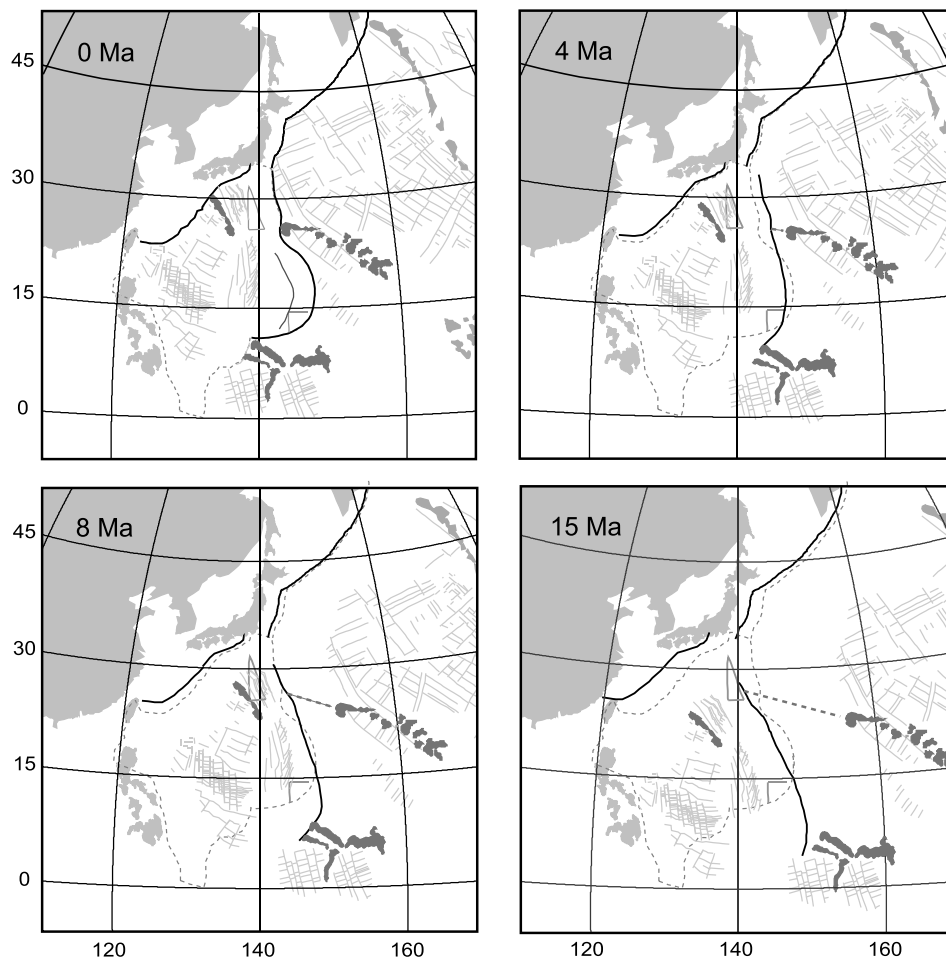
#### 3.1. Mariana Arc

[16] The pronounced arcuate shape of the Mariana arc has been explained as the result of the collision of the Caroline Island Ridge at the southern most end of the arc and the Ogasawara Plateau at the northern end [Vogt, 1973; Vogt *et al.*, 1976; McCabe and Uyeda, 1983; Hsui and Youngquist, 1985]. The shape of subduction zones and specifically the curvature of the Mariana arc can be attributed to “pinning” of the arc as aseismic ridges collide with the trench and resist subduction. Previous tectonic reconstructions have not included the timing or effects of the collision of oceanic plateaus and aseismic ridges, but both the position and motion of the Caroline Island Ridge and the Ogasawara Plateau have been incorporated. Our reconstruction shows both pinning of the southern cusp of the Mariana arc by the Caroline Island Ridge and the impact of the Ogasawara

**Table 1.** Total Rotation Vectors Used in Paleogeographic Reconstruction<sup>a</sup>

Plate Pair	Begin, Ma	End, Ma	Latitude, °N	Longitude, °E	Rotation Angle, deg	References
EU-PA	0	10	70	287	9.4	Engelbreton <i>et al.</i> [1985]
EU-PA	0	20	68	283	14.7	Engelbreton <i>et al.</i> [1985]
EU-PA	0	37	72	295	26.5	Engelbreton <i>et al.</i> [1985]
EU-PA	0	40	73	294	27.7	Engelbreton <i>et al.</i> [1985]
PA-PH	0	3	46.67	158.9	3.105	Zang <i>et al.</i> [2002]
PA-PH	0	8	48.23	156.97	8.68	Seno <i>et al.</i> [1993]
PA-PH	0	25	15	160	27.25	Hall <i>et al.</i> [1995b]
PA-PH	0	40	10	150	43.6	Hall <i>et al.</i> [1995b]
NA-PA	0	10.6	65.38	133.58	−2.44	Lawver <i>et al.</i> [1990]
NA-PA	0	19.7	68.92	136.74	−4.97	Lawver <i>et al.</i> [1990]
NA-PA	0	33.3	65.44	136.95	−7.51	Lawver <i>et al.</i> [1990]

<sup>a</sup>For motion of the second-listed plate with respect to the first-listed plate with positive rotations anticlockwise when viewed from above the surface of the Earth. EU, Eurasian plate; PA, Pacific plate; PH, Philippines Sea plate; and NA, North American plate.



**Figure 5.** Paleogeographic reconstruction of the western Pacific from the mid-Miocene based on new GPS based Euler poles. Black lines are interpreted paleoplate boundaries, dotted lines are current plate boundaries, thin light grey lines are magnetic anomalies, dark grey objects are aseismic ridges/oceanic plateaus with dotted dark grey lines are projected extension of the Marcus-Necker ridge, and thick grey lines represent the current position of slab tears.

Plateau as it reaches the trench at the junction of the Izu-Bonin and Mariana arcs (Figure 5). The collision of the Caroline Island Ridge has effectively dragged the southern end of the arc westward to create the initial bowing at about 13 Ma, which is consistent with variable strike of paleomagnetic lineations recorded along the Mariana arc [McCabe, 1984]. Back-arc spreading appears to begin between 6 and 8 Ma, which is in agreement with previous estimates of spreading initiation [Bibee *et al.*, 1980; Hussong and Uyeda, 1981; Eguchi, 1984; Hsui and Youngquist, 1985; Fryer, 1995] but prior to estimates by Hall *et al.* [1995a, 1995b]. The general motion of the Mariana arc has been slightly northward over the past 17 Myr with most of the motion due to back-arc spreading and the development of the arcuate shape due to the collision of the Caroline Island Ridge (Figure 5).

### 3.2. Izu-Bonin Arc

[17] Trench migration of the Izu-Bonin arc to the northeast during the Oligocene and Miocene similar to the previous trench retreat style reconstructions [Seno and Maruyama, 1984; Seno *et al.*, 1993; Hall *et al.*, 1995a,

1995b; Hall, 2002] has been verified in our reconstruction (Figures 2, 3, and 5). The trench retreat occurs at a slower rate compared to the previous models and the subsequent change in arc motion occurs slightly later. Figure 5 illustrates that the Izu-Bonin arc motion changes direction from the clockwise rotation taking place for the past ~43 Myr to the trench advance at approximately 8 Ma.

[18] Previous studies have estimated the collision of the Ogasawara Plateau with the Izu-Bonin trench to occur in the mid-Miocene [Hsui and Youngquist, 1985; Okamura *et al.*, 1992; Miura *et al.*, 2004], but the new reconstruction illustrates the collision at approximately 1 Ma. However, both the curvature and spreading in the Mariana back arc is present before the existing Ogasawara Plateau reaches the paleogeographic position of the trench. This discrepancy could be due to the unknown original size of the Marcus-Necker ridge, which the Ogasawara Plateau is part of. To account for timing of the onset the deformation of the Mariana arc, it appears that an extension of Marcus-Necker ridge has previously been subducted. It is proposed that the initial collision of the oceanic plateau (or aseismic ridge) occurred at 8 Ma and may be the cause of the slowed (and



subsequent change in) trench retreat velocity of the Izu-Bonin arc.

### 3.3. Ryukyu Arc

[19] Along the northwestern margin of the Philippine Sea the plate is currently subducting beneath Eurasia at the Ryukyu arc at a rate of about 6 cm/yr [Zang *et al.*, 2002]. The new reconstruction illustrates the slight asymmetric trench retreat of the Ryukyu arc and the change in motion of the Philippine Sea plate at 8 Ma (Figure 5). Behind the arc the Okinawa Trough has been spreading asymmetrically since the late Miocene, with opening occurring faster in the southwest than the northeast [Fournier *et al.*, 2001]. Paleomagnetic declinations indicate that there has been approximately 27° of counterclockwise rotation of the Ryukyu arc with respect to the Eurasian continent since the late Miocene [Kodama and Nakayama, 1993]. As proposed by Schellart *et al.* [2002] the recent irregular extension in the back-arc region can be explained by asymmetrical rollback of the Philippine Sea plate where the retreat rate increases from northeast to southwest. The asymmetry could be the result of buoyant ridges (Palau Kyushu Ridge and Oki-Daito Ridge) in the northeastern part of the Philippine Sea plate colliding with the trench (Figure 1).

### 3.4. Japan-Kurile Arc

[20] To the north of the Izu-Bonin-Mariana arc system the reconstruction shows the slow spreading of the Japan Sea with a slow clockwise component from the mid-Miocene to the present and the continuous retreat of the Japan trench (Figure 5). The slow rotation is consistent with studies on the bending of the Japanese Islands [Otofuji and Matsuda, 1983; Seno and Maruyama, 1984; Celaya and McCabe, 1987; Otofuji and Matsuda, 1987]. The Kurile arc slowly retreats asymmetrically about a hinge located near Kamchatka (and the cusp at the Emperor Seamount Chain), which is consistent with previous findings [Vogt, 1973; Katsumata *et al.*, 2003; Schellart *et al.*, 2003]. The wedge shape geometry of the back-arc basins behind the Kurile Trench can be explained by this asymmetric opening (Figure 5).

## 4. Four-Dimensional Reconstruction

### 4.1. Previous Tomographic Images

[21] Previous studies have used tomographic inversions to characterize the geometry of the subducting plate along the western Pacific margin [van der Hilst *et al.*, 1991; Fukao *et al.*, 1992; Zhao *et al.*, 1992; van der Hilst *et al.*, 1993, 1997; Castle and Creager, 1998, 1999; Deal and Nolet, 1999; Widiyantoro *et al.*, 1999; Lebedev and Nolet, 2003; Miller *et al.*, 2004, 2005]. Images from the earlier studies had lower resolution [Zhou and Clayton, 1990; van der Hilst *et al.*, 1991, 1993] or focused primarily on regional-scale heterogeneities [Zhao *et al.*, 1990, 1994; Castle and Creager, 1998, 1999]. As technology improves, the resolution and gradients in tomographic inversion are also improving, which allows us to interpret the images with greater detail. One recent advance in inversion methodology is the application of three-dimensional (3-D) ray tracing to global arrival time data sets [Koketsu and Sekine, 1998; Gorbatov *et al.*, 2000; Widiyantoro *et al.*, 2000], which accounts for the bending of the ray path as it encounters 3-D

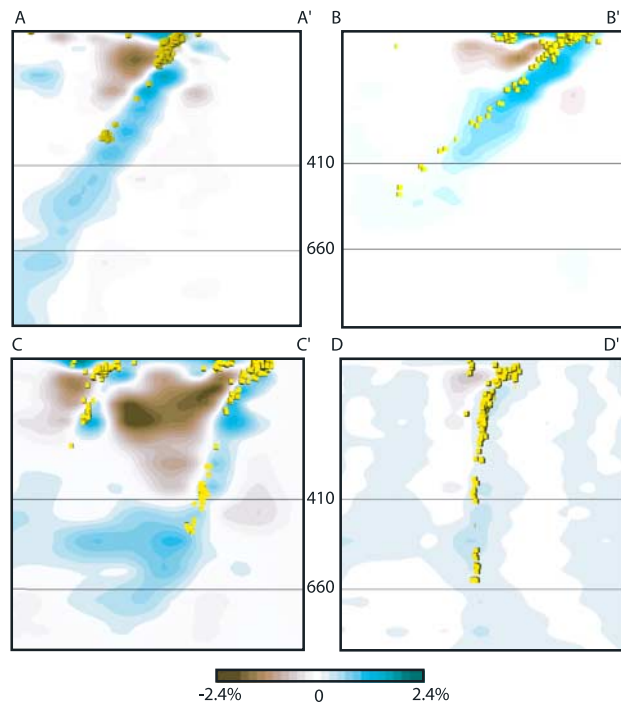
velocity structures by searching iteratively for the minimum travel time ray path connecting source and receiver. This algorithm provides a more accurate treatment of the rays, which results in improved resolution of wave speed gradients and positioning of heterogeneities, particularly the strong variations in velocities along subduction zones [Widiyantoro *et al.*, 2000].

[22] van der Hilst and Seno [1993] used the interpreted structure of the slab beneath the western Pacific margin from *P* wave tomographic images combined with a paleogeographic reconstruction of the Philippine Sea plate to understand the relationship of plate motion and slab geometry. From tomographic images the morphology of the subducting slab was interpreted to have a shallow dip beneath the northern Izu-Bonin arc, to lay stagnant on the 660 km discontinuity beneath southern Izu-Bonin, and then transition to a near vertical dipping slab beneath the Marianas. van der Hilst and Seno [1993] proposed that the slab on top of the 660 km discontinuity was the result of the rapid rollback of the Izu-Bonin trench while beneath the Mariana arc the slab penetrates into the lower mantle due to the relatively stationary position of the trench. We expand on these ideas of a multidisciplinary approach of spatial and temporal analysis of subduction zone processes by incorporating the new reconstruction and new detailed tomographic images to unravel the development of the slab structure in the western Pacific, specifically the Izu-Bonin and Mariana arcs.

### 4.2. Tomographic Images

[23] Shear wave speed and *P* wave data were inverted using a 3-D ray tracing scheme, and the resulting images are used to illustrate the variation in slab geometry along the arc [Miller *et al.*, 2005]. The resolution of gradients and variation in wave speed have been improved in these images by including the trajectory of seismic ray propagation between source and receiver through the three-dimensional structure of the Earth [Gorbatov and Kennett, 2003]. Resolution calculations are shown by Gorbatov and Kennett [2003] and ray path density for the model region are illustrated and discussed by Miller *et al.* [2005] and Gorbatov and Kennett [2003]. The prior discussion and figures in these papers demonstrate that images of the subducted Pacific plate can be recovered along its complete extension and there is very consistent and high ray density in areas where subduction related structures may be expected.

[24] We present a series of cross sections of the *P* wave model perpendicular to the trench (as shown in Figure 1) with seismicity [Engdahl *et al.*, 1998] to confirm the previously identified dramatic change in the dip of the Pacific slab subducting beneath the Kurile, Japan, Izu-Bonin, and Mariana arcs in Figure 6. Our images of the geometry of the slab along the western Pacific plate margin is similar to previous results of 1-D *P* wave models and shear velocity perturbation models that use a variety of reference velocity models [Li and Romanowicz, 1996; van der Hilst *et al.*, 1997; Widiyantoro, 1997; Deal and Nolet, 1999; Lebedev and Nolet, 2003] as well as joint inversions [Kennett *et al.*, 1998; Widiyantoro *et al.*, 1999; Kennett and Gorbatov, 2004]. For example, Lebedev and Nolet [2003, Figure 18] present cross sections through a shear velocity



**Figure 6.** Cross sections of the  $P$  wave perturbation model referenced to ak135 [Kennett *et al.*, 1995] along traverses illustrated in Figure 1. Cross sections A-A' and B-B' illustrate the relatively shallow dip of the subducting Pacific plate beneath the Japan and Kurile arcs, C-C' illustrates the slab laying on the 660 km discontinuity beneath the Izu-Bonin arc and the Philippine Sea plate subducting along the Ryukyu arc, and D-D' depicts the steeply dipping slab beneath the Mariana arc. Earthquake hypocenters from the Engdahl *et al.* [1998] catalogue are plotted along the slices.

tomographic image that illustrate the locations of observed high-velocity anomalies consistent with high-resolution  $P$  wave imaging. The cross sections through a 1-D  $P$  wave inversion shown by Deal and Nolet [1999, Plate 1] are also in agreement with the more recent 3-D ray tracing inversions that we present in Figures 6 and 7. Surface wave studies can be more useful in defining low-velocity regions, like back arcs, but in this study we are focusing on the high-velocity features that define the subducting Pacific plate morphology.

[25] Comparison of tomographic images using different parameterizations, reference models, and arrival time data is beyond the scope of this paper (general differences in image characteristics are reviewed by Fukao *et al.* [2001]), but the images we present appear to resolve more details of the heterogeneity within the mantle along the western Pacific convergent margin than some other prior studies. The resolution of anomalous velocity structures diminishes from north to south along the western Pacific margin due to the sparse number of seismic stations on the Mariana Islands (Figures 6 and 7). Despite the lack of seismic stations in the southern region of the western Pacific the high-velocity anomalies are resolved for structures larger than 50–100 km. The position and morphology of the subducting Pacific plate is imaged in both the  $P$  wave and shear wave speed

inversions, which have been produced by similar, yet different inversion algorithms.

[26] Depth slices at 204 km, 456 km, and 660 km through both the shear wave speed and  $P$  wave tomographic images for the western Pacific illustrate the position and geometry of the subducting Pacific plate in the mantle at depth (Figure 7). The past position of the trench has been interpreted by assuming dip angle (and the distance) between the slab at depth and the position of the trench is similar to the current dip for each of the Kurile, Japan, Izu-Bonin, and Mariana arcs (Figure 6). We have interpreted the past plate boundaries of the Pacific plate along the entire arc system from the Kurile arc to the Mariana arc based on the depth slices in Figure 7. These past trench positions at certain depths can then be translated into a range of ages along the arc system by defining average convergence rates of 5 cm/yr for the subduction of the Pacific plate beneath Izu-Bonin-Mariana arc and 8.5 cm/yr beneath Japan–Kurile arc [Zang *et al.*, 2002]. The interpreted position of the paleoboundaries at 2.4 Ma, 5 Ma, and 10 Ma for all the individual arcs were then combined to approximate the trench location at each of these time periods in Figure 8. Figure 8 shows the progression and change in geometry of the western Pacific convergent margin since the late Miocene.

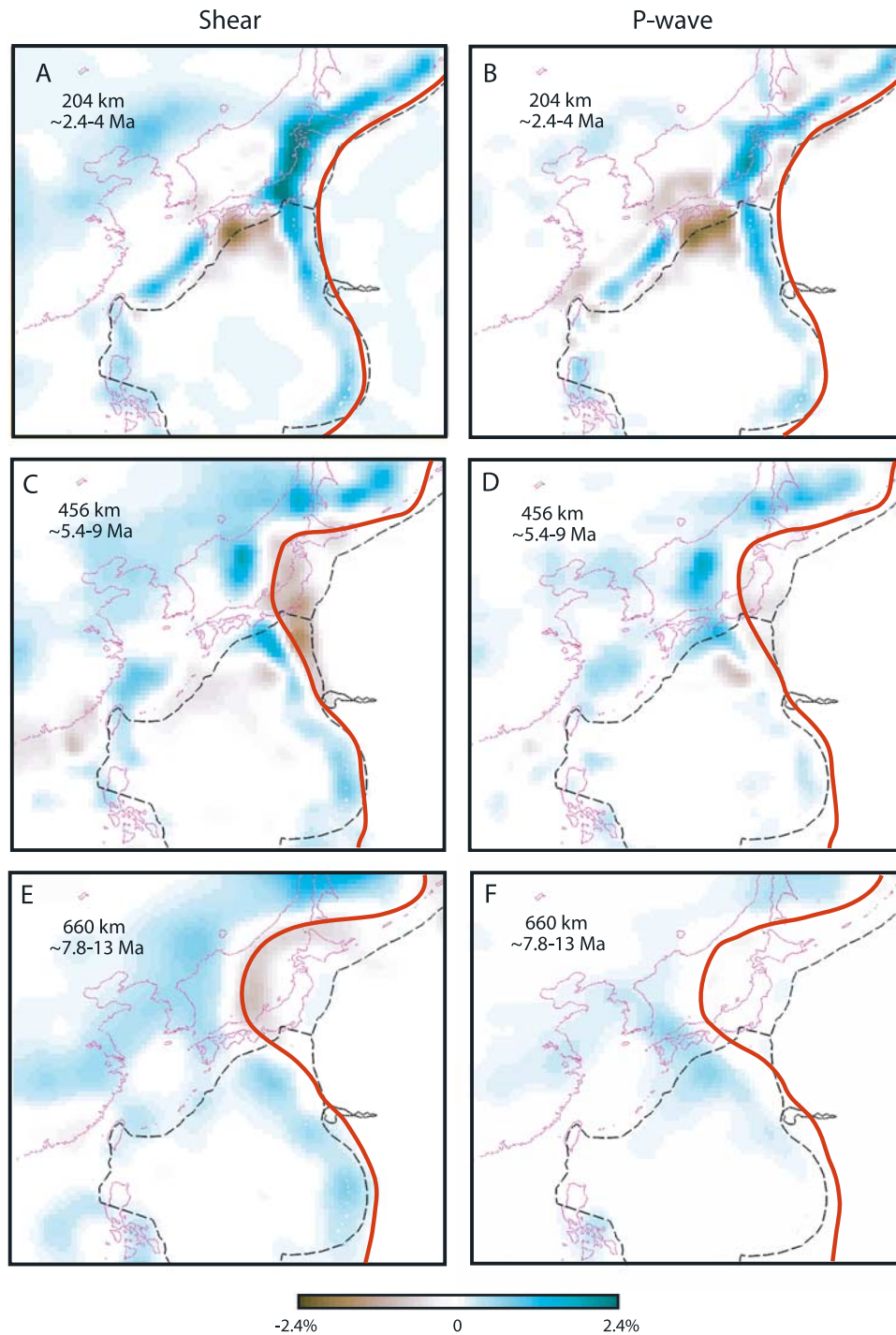
#### 4.3. Izu-Bonin Arc

[27] The amplitude and resolution of the fast velocity perturbations beneath the Izu-Bonin arc are quite strong, which allows for clear interpretation of the past trench location. The progression of the Izu-Bonin arc position from approximately 4 Ma (Figure 7a) to 16 Ma (Figure 7f) is illustrated by the interpreted past position of trench from depth slices of shear wave tomography. The tomographic images confirm that the trench (and position of the slab) was further eastward between 4 and 8 Ma than it is at the present. Prior to 8 Ma the trench was west of its current location and had a more northwest-southeast orientation. This evolution in plate boundary position confirms the likelihood of the trench retreat models and specifically the new paleogeographic reconstruction presented.

#### 4.4. Mariana Arc

[28] The amplitude of the anomalies beneath the Mariana arc is less intense than other areas due to fewer seismic stations, but the position of the slab can still be interpreted from the tomographic images (Figure 6, D-D'). The interpreted change in position of the trench back in time has a smaller range than the Izu-Bonin and Japan arcs, but the development of the curvature of the arc can be seen at depth (Figure 7a–7f). The position of the trench has remained relatively stationary from 4 to 16 Ma, but has become more arcuate shaped over time, similar to the model presented in the new reconstruction. The less significant migration of the Marianas trench could be due to “anchoring” of the subducted Pacific plate in the lower mantle [Seno and Maruyama, 1984; Carlson and Mortera-Gutierrez, 1990; van der Hilst and Seno, 1993]. The limited movement of the slab beneath the Mariana arc could allow for the subducted lithosphere to accumulate in the transition zone and then finally penetrate into the lower mantle causing the slab to be “anchored” [van der Hilst and Seno, 1993]. The idea of a





**Figure 7.** Depth slices of the shear wave speed and  $P$  wave inversions illustrating the inferred past position of the trench along the western Pacific margin with the current position of the Ogasawara Plateau and the Asian coastline in purple for reference. The dashed black line indicates the current plate boundaries, and red lines indicate the interpreted position of the trench at the specified time/depth. The time range is based on the maximum and minimum age of the slab at that depth along the western Pacific margin.

slab with a steep dip that extends below the transition zone was initially based on hypocenter locations and early tomographic images. Higher resolution tomography has confirmed this type of slab morphology [van der Hilst *et al.*, 1991; Fukao *et al.*, 1992; van der Hilst and Seno, 1993; Widiyantoro *et al.*, 1999; Gorbatov and Kennett, 2003; Miller *et al.*, 2004, 2005] and the new trench retreat style

reconstruction and images validate these ideas, but how the slab developed into its current geometry is still an unanswered question.

#### 4.5. Ryukyu Arc

[29] Tomographic images of the mantle beneath the Ryukyu arc can resolve the slab depth to approximately

300 km and the seismicity in the region is present down to a maximum depth of 300 km (Figure 7b). The relatively shallow extent of the Philippine slab beneath the Ryukyu arc could be evidence against the continued subduction of the plate (and associated subduction zone) that is presented in the tectonic reconstructions by *Hall et al.* [1995a, 1995b], *Hall* [2002], and *Seno and Maruyama* [1984] and shown in Figures 2 and 3.

#### 4.6. Japan-Kurile Arc

[30] Strong anomalies outline the Pacific slab subducting beneath the Japan and Kurile arcs and appear to be continuous to approximately 700 km depth (Figure 7e). The position of the trench appears to have been retreating over for at least the past 12 Myr, which is in agreement with the new reconstruction (Figure 5). Another interesting feature is the curved shape of the interpreted trench location along the north central Japanese islands and the complex morphology of the slab that can be interpreted from these images. A strong linear feature striking NW-SE at 660 km depth appears to be a former plate boundary. Although the Pacific plate has been subducting at a moderate velocity along the northwestern margin (8.5 cm/yr) it has not been a simple process.

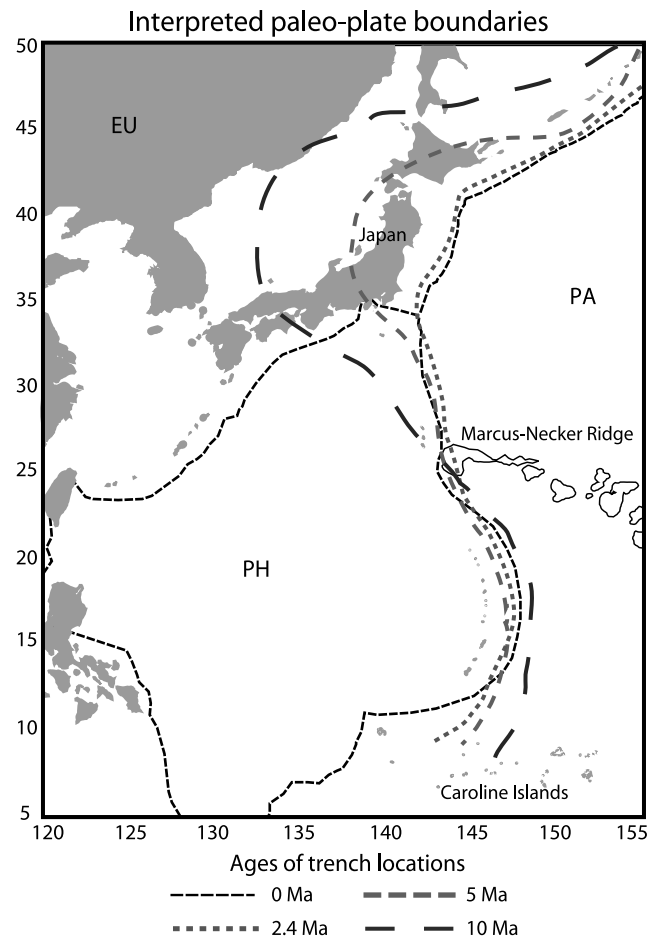
### 5. Discussion

[31] The interpreted past positions of the convergent margin and the velocities of the plates can be coupled to slab morphology interpreted from tomographic images. Plate motions can explain anomalies and features imaged in the mantle and in bathymetry, but plausibility of the proposed plate orientation must also be considered.

[32] All of the previous proposed tectonic models have focused on the position of the trench-trench-trench triple junction back in time. The current state of the Boso triple junction is considered stable, but this may not have always been the case. If the convergence rates of the three plates have altered since the Miocene then the triple junction could be unstable, but even if it has maintained its stability it could migrate along the boundary of the Eurasian plate. Therefore the evolution of the triple junction rotating clockwise along the Eurasian plate boundary may be possible, but other plate configurations could have also evolved into the present state.

[33] The plate boundaries near the trench-trench-trench triple junction of Japan in Figure 5 have been left unconnected because the position and nature of the boundary is still unclear. There is little evidence that the Pacific-Philippine subduction zone quickly retreated to the northeast and therefore subducted beneath the Ryukyu Arc, as presented in the models proposed by *Hall et al.* [1995a, 1995b], *Hall* [2002], and *Seno and Maruyama* [1984]. The northeast portion of the Philippine Sea plate beneath Eurasia can only be imaged down to 300 km (Figures 6 and 7), which can be attributed to it being a relatively young subduction zone. Therefore an alternative tectonic model must be considered.

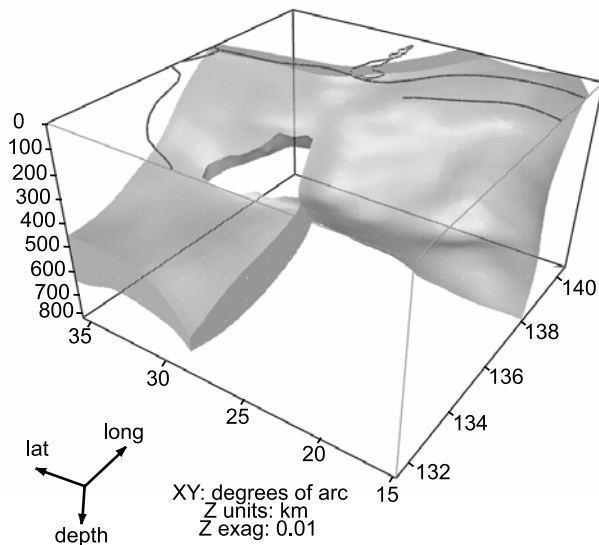
[34] *Hibbard and Karig* [1990] proposed that the Japan triple junction was generated when the Shikoku Basin initially collided with southwest Japan at 15 Ma. The northern edge of the Shikoku Basin (and the Philippine Sea plate) was a transform boundary, which was then



**Figure 8.** Map of the western Pacific margin with the interpreted positions of paleoplate boundaries illustrated as a series of dotted lines based on the tomography images in Figure 7.

subducted beneath the Eurasian plate at Shikoku Island (Figure 1). The collision of the transform boundary in the Miocene is evident in widespread uplift of the Shimanto accretionary prism, probable initiation of the central Japan collision zone, and widespread magmatism around 14 Ma, and an abrupt change in the stress field of southwest Japan [*Hibbard and Karig*, 1990]. This model could explain the short subducted slab beneath Ryukyu and withdraws the need for the triple junction to be sweeping along the western boundary of the Philippine Sea plate since the Oligocene. The morphology of the Philippine Sea plate beneath southwest Japan is highly complex, which may also be accounted for by the subduction of a spreading basin and a transform boundary in this region (Figures 7 and 8).

[35] The evolution of the Japan and Kurile arcs does not appear to be a simple process and must be included in evaluation of the evolution of the full margin of the Pacific plate. The tomographic images show a strong linear feature that we interpret as a paleoplate boundary at a depth of 660 km (Figures 7e and 7f). Previous reconstruction models of the Philippine Sea plate neglected the complex nature of the evolution of the Japanese islands, including the opening of the Japan Sea around 15 Ma, and the possibility of an



**Figure 9.** Interpreted three-dimensional model of the morphology and geometry of the subducting Pacific plate beneath the Izu-Bonin-Mariana arc. The absent block illustrates the location of the slab tear, the current plate boundaries and position of the Ogasawara Plateau are draped on the top of the image.

alternative plate configuration to the trench-trench-trench triple junction that is present today.

[36] *Schellart and Lister* [2004] mention that simple westward migration of the overriding Philippine Sea plate cannot explain the opening of the Parece Vela basin nor the opening of the Mariana back-arc basin. The shapes of the Palau-Kyushu and Izu-Bonin-Mariana ridges are too dissimilar, therefore the lateral discontinuity between the two must be accounted for by a variation in trench migration velocities along the arc, which is shown in the new tectonic reconstruction. The plate motions of the western Pacific are much more complicated for a simple convergent rate variation. Changes in direction of motion such as the change to a primarily westward motion of the Izu-Bonin arc illustrated in the reconstruction and the tomography (Figures 5, 7, and 8) are one of the factors to consider. Another factor is the collision and subsequent subduction of bathymetric features, like the Marcus-Necker ridge.

[37] The new tomographic images have also been used to model the slab morphology, which includes several tears in the subducting Pacific plate beneath southern Izu-Bonin and the southern Marianas [*Miller et al.*, 2004, 2005]. The three-dimensional visualization models of the complex slab morphology of the Izu-Bonin-Mariana arc based on the *P* wave tomographic image shown in Figure 9. This interpreted three-dimensional model, based on tomographic images, illustrates a subhorizontal tear in the slab beneath the southern Izu-Bonin arc from distinct changes in physical properties in the mantle. *Miller et al.* [2004, 2005] proposed that the Ogasawara Plateau collision and subsequent subduction are related to the distortion and heterogeneity in the Pacific plate at depth. Using the new reconstruction with the three-dimensional visual model it can be inferred that the initiation of the oceanic plateau subducting at approximately 8 Ma and the resulting complex slab morphology are related.

We calculated the maximum convergence velocity for the relative motion of the Pacific and Philippine plates for the center of the tear ( $139^{\circ}\text{E}$ ,  $29^{\circ}\text{N}$ ) from the stage poles for motion in the periods 0–3 Ma and 3–8 Ma (the later is a rotation of  $5.58^{\circ}$  around  $49.02^{\circ}\text{N}$   $155.75^{\circ}\text{E}$ ) using the methods outlined by *Cox and Hart* [1986]. The maximum velocity of 4.58 cm/yr (0–3 Ma) and 4.99 cm/yr (3–8 Ma) occurred along a bearing of  $300^{\circ}$  and  $298^{\circ}$ , respectively, assuming that the trench location did not change over this period and that there was no acceleration/deceleration of the plates. Therefore, if we assume a convergence rate of 5 cm/yr along the Izu-Bonin arc and the average depth of the tear at 350 km, the age of the slab at the tear can be estimated to be approximately 8 Ma, which correlates to the time in the change in plate motion in the reconstruction (Figure 5).

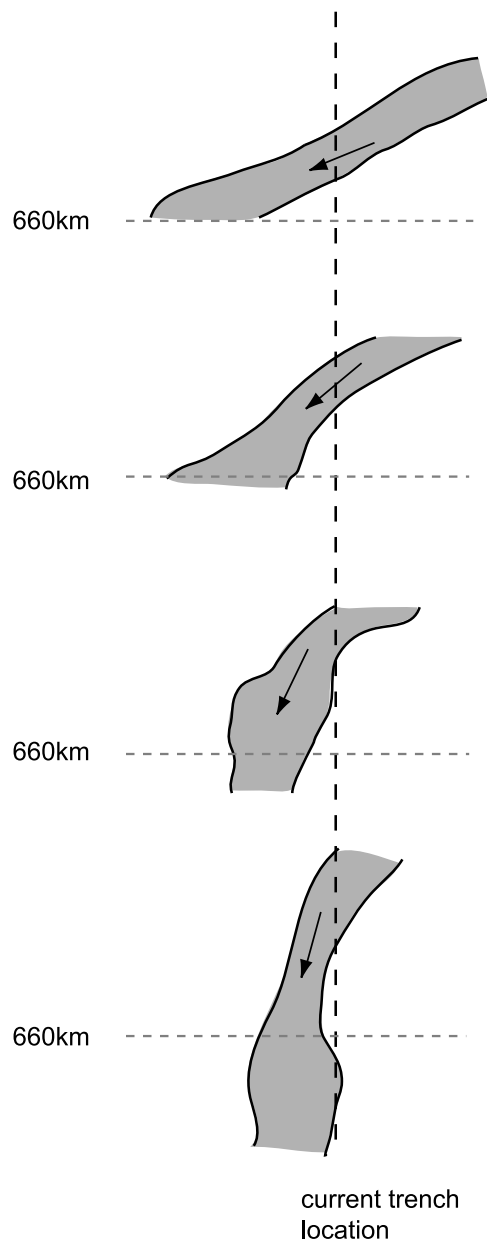
[38] As the Mariana arc curvature developed after the collision of Marcus-Necker Ridge and the Caroline Island Ridge, the slab continued to penetrate into the lower mantle. Its sustained vertical geometry over the past 16 Myr is evidenced by the relatively static position of the trench (Figures 5–9). The continued near vertical orientation of the Pacific plate has also caused deformation in the slab, which is evident in the “crumpled” morphology in Figure 9. The slab appears to buckle and become distorted as it is subducted beneath the Mariana arc. Although it appears that the slab has remained relatively stationary since the mid-Miocene from tomographic images and tectonic reconstructions (Figures 5–9), it is unlikely that it initially subducted vertically. Therefore the slab beneath the Mariana arc must have developed into its current geometry. A possible process that explains the progression of the current slab geometry is trench advance (Figure 10). On the basis of experiments and interpretation of seismic tomography it has been suggested that as the trench migration slows or advances, the angle of subduction becomes steeper, until it reaches near vertical and then the slab penetrates through the transition zone into the lower mantle [*Kincaid and Olson*, 1987; *van der Hilst et al.*, 1991, 1993; *Griffiths et al.*, 1995; *Christensen*, 1996; *Olbertz et al.*, 1997].

[39] As seen in tomographic images and interpreted three-dimensional models, subducting slabs have very complex morphology and continue to deform in the mantle, therefore there are limitations to these reconstructions. Understanding the limitations of reconstruction models when plates are assumed to be rigid and nondeformable must be noted.

## 6. Conclusions

[40] Improved high-resolution tomographic images have enhanced the understanding of the morphology of subducting slabs and the complex effects of plate motions at convergent boundaries. The subducted plate morphology along the western Pacific margin interpreted from tomographic images has been compared with a new tectonic reconstruction to provide evidence to use in evaluating possible tectonic models and the four-dimensional evolution of the slab morphology. Our reconstruction does not include deformation of the plate and subducting slab, in order to allow direct comparison to previous models, but our results have shown that deformation is an important factor in understanding tectonic processes at convergent margins. We have found that subducting oceanic plateaus and sea-





**Figure 10.** Schematic drawing of the evolution of the slab morphology beneath the Mariana arc prior to the Miocene. As the trench advances, the slab dip becomes steeper until the subducted oceanic lithosphere accumulates in the transition zone and finally penetrates into the lower mantle as the slab dip nears vertical.

mounts have had dramatic effects on the motion of the plates and the slab structure at depth. Our reconstruction shows the Izu-Bonin arc direction of motion changed around 8 Ma, which corresponds to the collision of the Marcus–Necker Ridge with the arc. The models also illustrate the Mariana arc progressively becoming more arcuate in shape as the cusps became pinned by the Caroline Island Ridge and the Ogasawara Plateau during the late Miocene.

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