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Plate Convergence and Long-Term Crustal Deformation in Central Japan

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Abstract. Surveys by continuous Global Positioning System in and around Japan revealed that the Amurian Plate collides with the North American Plate in central Japan by ~2 cm/yr. Long-term crustal deformation seems to be influenced mainly by this collision although subduction of oceanic plates governs short-term elastic deformation over the arc. Here we study the long-term deformation field by carefully removing the short-term signals inferred from a-priori plate convergence vectors and coupling strengths predicted by a thermal model. The obtained field shows that the change in velocities occurs along the longitude 135°~137°E, and there exist a relatively rigid block and zones accommodating strains. Characteristic compressional deformation is found northwest of Izu due possibly to the collision of the Izu-Bonin arc with Honshu. Plate convergence rate along the Nankai-Suruga Trough is considerably smaller in eastern parts, due partly to the transition from the Amurian to the North American Plate of the landward side, and partly to the motion of the Izu Microplate relative to the Philippine Sea Plate. This accounts for longer recurrence intervals of interplate earthquakes in the Suruga Trough where the Tokai earthquake is anticipated to occur.

1. Introduction

Southwest Japan (SWJ) is the southeastern edge of the Amurian Plate (AM), a relatively small plate covering northern China, southeast Russia and the Korean Peninsula (Figure 1). It moves by ~1 cm/yr toward ESE relative to the Eurasian Plate (EU) and its current movement was determined with continuous Global Positioning System (GPS) data by *Heki et al.* [1999]. *Seno et al.* [1996] suggested that northeast Japan (NEJ) is on the Okhotsk Plate (OK), another microplate that covers the Sea of Okhotsk and Kamchatka. However, currently available slip direction data including those along the eastern margin of the Japan Sea do not require NEJ detached from the North American Plate (NA) [*Heki et al.*, 1999].

Recently, *Miyazaki and Heki* [2001] analyzed data of the Japanese nationwide GPS array (GPS Earth Observation Network, GEONET), and concluded that intraplate crustal deformation in SWJ is composed of (1) short-term (shorter than interplate thrust event recurrence intervals) deformation due to the elastic loading by the Philippine Sea Plate (PH) slab at the Nankai Trough, and (2) long-term (largely plastic) deformation due to its collision with NA (NEJ). It was not straightforward to separate them since they are not orthogonal to each other (the AM-PH and AM-NA convergence directions differ by only ~20 degrees in central Japan). In such a case, simple inversion of the distribution of slip deficits (backslip vectors) [*Savage,* 1983] at the trough may give a wrong answer; the long-term deformation may be partly misunderstood as the short-term one. To avoid this, *Miyazaki and Heki* [2001] modeled the elastic component by introducing a thermal model [*Hyndman et al.,* 1995] for coupling strength at depth and by modeling backslip vectors as the product of the AM-PH relative velocity and the coupling strength. They found that the differences between the observed and calculated velocities are characterized by N-S extension and E-W shortening, and considered they represent the long-term deformation due to the AM-NA collision.

Here we extend this method to central Japan, the very

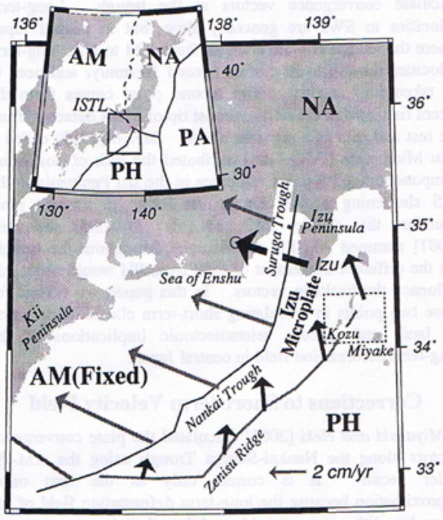

Figure 1. Plate tectonic setting of the Japanese Islands (inset), where AM, NA, PA, PH, and ISTL shows the Amurian, North American, Pacific, and the Philippine Sea Plates, and the Itoigawa-Shizuoka Tectonic Line, respectively. Light and dark gray arrows show AM-IMP (Izu Microplate) and IMP-PH relative velocities, respectively, predicted by the Euler vectors estimated in this study. Black arrow shows the GPS velocity at Izu with respect to AM. The area in the dotted square indicates the region of the 2000 summer volcano-seismic activity in the northern Izu Islands [*Kaidzu et al.*, 2000].

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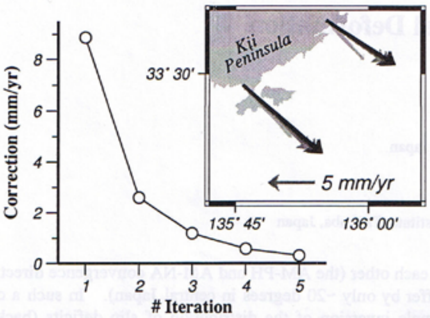

Figure 2. Convergence of the long-term velocity field as indicated by the root-mean-square of the correction to the backslip vectors of fault segments in the Nankai-Suruga Trough in each iteration loop. Upper right panel shows the change of the long-term velocities at two GPS sites at the southernmost Kii Peninsula during the iteration (arrows become darker as the iteration proceeds).

region of the AM-NA collision. There we need to take account of the deformation (1) within the landward plate, and (2) within the subducting oceanic plate. The first point becomes important where the overriding lithosphere has a significant long-term velocity relative to the prescribed plate, since we use relative rotation (Euler) vectors of plate pairs to calculate convergence vectors at the trough. Long-term velocities in SWJ are generally slow, but in central Japan where the landward plate changes from AM to NA, long-term velocities relative to AM often exceed 10 mm/yr and need to be taken into account. The second point comes from the recent finding that the northernmost tip of PH is detached from the rest and acts as a separate block. *Sagiya* [1999] called it "Izu Microplate (IMP)," and attributed the lack of northward component of GPS point velocities in the Izu Peninsula to the N-S shortening across the Zenisu Ridge, a nascent plate boundary that divides IMP and PH. *Miyazaki and Heki* [2001] assumed AM-PH convergence throughout the trough, but the different movement of IMP from PH would obviously influence the backslip vectors. In this paper, we correct for these two points in calculating short-term elastic deformation on land, and discuss seismotectonic implications of the long-term deformation field in central Japan.

2. Corrections to Short-term Velocity Field

Miyazaki and Heki [2001] calculated the plate convergence vectors along the Nankai-Suruga Trough using the AM-PH Euler vector. It is correct only as the first order approximation because the long-term deformation field of the overriding lithosphere would modulate the plate convergence vectors at the trough. Long-term westward velocity with respect to AM increases as we go east across the diffuse AM-NA boundary (Figure 9b in *Miyazaki and Heki* [2001]), which makes the subduction direction (rate) deflect clockwise (get smaller). This will reduce the westward component of the short-term velocities on the overriding plate due to the plate coupling. We would hence overestimate this westward component by failing to take account of the existence of the long-term velocities. The overestimated short-term westward velocity would then make us underestimate the long-term westward velocity to be obtained by subtracting the short-term velocities from the observed ones. After all, this lets us underestimate the long-term velocities.

In this paper we use the same geometry of fault segments along the trough as *Miyazaki and Heki* [2001]. In the present study, we made a minor modification to reduce the overlap between the three pairs of plate segments, namely, 13-14, 14-15, and 4-5 (the numbers follow those in Figure 7 of *Miyazaki and Heki* [2001]); we shortened the width of the segments 14, 15 and 5 by 10 km, 10 km and 5 km, respectively (see Figure 5). GPS velocity data are the same as *Miyazaki and Heki* [2001]. A-priori backslip vectors were calculated using the AM-PH (IMP) Euler vectors and thermally predicted coupling strengths. Elastic half space is assumed in calculating the crustal response to the dislocation at depth. Since the thermal model [*Hyndman et al.,* 1995] is based on heat flow data in the western Nankai Trough, there is some ambiguity in extrapolating it eastward. For example, coupling becomes zero at the depth of 35 km in their model, and making it 25 km in the Suruga Bay fault segments alters the short-term velocity (and hence the long-term velocity) on land by up to ~2 mm/yr. We need to keep it in mind that uncertainty of this magnitude may be present in our results.

To make short- and long-term velocity fields consistent, we repeated the following procedure, (1) calculate short-term velocities using initial a-priori backslip vectors, (2) obtain the long-term velocities as the differences between the short-term and the observed velocities, (3) obtain the correction to the backslip vector as the average of the long-term velocities of GPS points within the surface projection of each fault segment, (4) go back to (1) and apply the correction to the a-priori backslip vectors. In (3), for several fault segments whose surface projections do not include any GPS points (e.g. offshore fault segments), we used the average corrections of their landward neighbors. Figure 2 shows that 5 iterations seem enough to let the residual (long-term) field converge.

Mazzotti et al. [1999] inferred shortening directions and rates at several points along the Zenisu Ridge (Figure 1), a submarine range that bounds IMP (or "Zenisu west-Izu block") from PH, and constrained the IMP-PH Euler pole near the western tip of their boundary, off the Kii Peninsula, by using these data. In this study, we estimated IMP-PH Euler vector using the same constraints as in Table 1 of *Mazzotti et al.* [1999] except for the two GPS data giving IMP's velocity. We substituted them for the average residual velocity of seven GPS points in southern Izu (the average coordinate is 34.7°N, 138.9°E) obtained in this study, i.e. $V_e=-38.9\ (11.9) \pm 2.0$ mm/yr, $V_n=12.9\ (-22.5) \pm 2.0$ mm/yr, with respect to AM (PH). Since this velocity changes slightly during the iterative refinement of the long-term velocity field, non-linear least-squares estimation of the IMP-PH Euler vector was done at each iteration step using the refined GPS velocity of Izu. The finally estimated pole position (33.3°N, 135.5°E) was close to, and the rate (3.96 ± 0.87 deg/Myr) did not differ significantly from *Mazzotti et al.* [1999]. In calculating a-priori backslip vectors, the AM-IMP Euler vector was used instead of the AM-PH vector for the segments 5, 14 and 29 (136°~137°E) and those to the east. It is not critical where we divide the fault segments into IMP and PH, because the IMP-PH Euler pole is near this boundary and they move little mutually there. In Figure 1 we show IMP-PH relative velocities along the Zenisu Ridge and the GPS site velocity in the Izu Peninsula used to obtain the Euler vector.

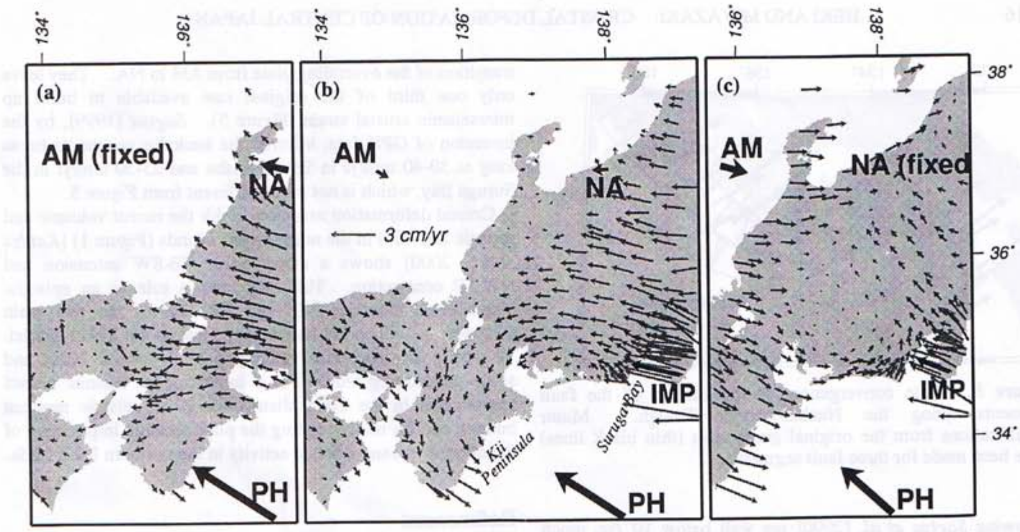

Figure 3. Long-term velocity fields of central Japan in the frames fixed to AM (a), EU (b), and NA (c). Thin gray arrows and thick black arrows show observed velocities and those predicted by Euler vectors.

3. Long-term Velocity Field

Figure 3 shows long-term velocities of the GPS points viewed from the three plates, namely AM, EU, and NA. They have uncertainties of ~0.5-0.6 mm/yr due to the dispersion of daily solutions, and additional frame definition errors, the largest of which is ~0.7-0.8 mm/yr for the AM frame (see *Miyazaki and Heki* [2001]). The one with respect to AM (Figure 3a) is fairly similar to the earlier version (Figure 9b in *Miyazaki and Heki* [2001]); the AM-NA boundary lies at 135°~137°E where we can see crustal shortening in the convergence direction as well as southward crustal expulsion.

In Figure 3c (NA frame), we see that the points east of the AM-NA boundary are generally stationary, except for the northwestward vectors of up to 10 mm/yr in a region northwest of Izu. The Izu Peninsula has a light continental crust and cannot subduct at the trough. It causes strain partitioning such that the northward component of PH is accommodated by shortening along the Zenisu Ridge resulting in the detachment of IMP from the rest of PH. On the other hand, westward movement of Izu is accommodated by the subduction at the Suruga Trough, as seen in the recurrence of large thrust events there. Mechanisms of crustal earthquakes [*Ukawa,* 1991] show that principal stress axes in northern Izu align with the NA-PH convergence (i.e. NW-SE) in spite of the IMP's instantaneous westward subduction there. The long-term velocity northwest of Izu is also northwestward rather than westward, and would be driven by the strong compressional stress in the NA-PH convergence direction there.

In Figure 4 GPS points are given colors so that vivid points show sites with small velocities relative to AM, NA, and IMP. When short-term elastic deformation is removed, most parts of central Japan seem fairly stationary relative to either AM or NA, with their boundary recognized as the red-green contrast at ~136.5°E, much westerly than the Itoigawa-Shizuoka Tectonic Line (ISTL, Figure 1), formerly considered to bound NEJ from SWJ. In the northern part, the boundary coincides with the Niigata-Kobe Tectonic Zone (NKTZ) newly defined by *Sagiya et al.* [2000]. To the south, the boundary departs from NKTZ and extends to the Ise Bay, but this portion of boundary does not necessarily mean that the deformation concentrates there. In Figure 3b are drawn long-term velocities in a frame fixed to EU, which has a velocity midway between AM and NA there and offers a "neutral" platform for the velocity field. There we can recognize that an area to the south of NKTZ, extending from the Suruga Bay to the eastern half of the Kii Peninsula behaves as a block with relatively small deformation (strain rates in this block calculated

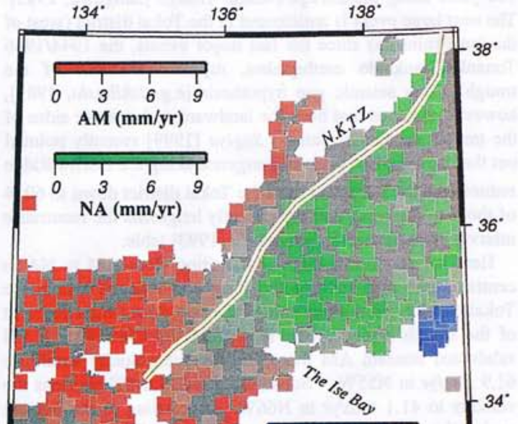

Figure 4. One of red, green and blue colors was given to each GPS point to show which plate best explains its long-term velocity vector. Vivid colors show that the points move little with respect to that plate (numbers in the scale indicate velocities relative to that plate). Niigata-Kobe Tectonic Zone [*Sagiya et al.,* 2000] is shown by a yellow broad line.

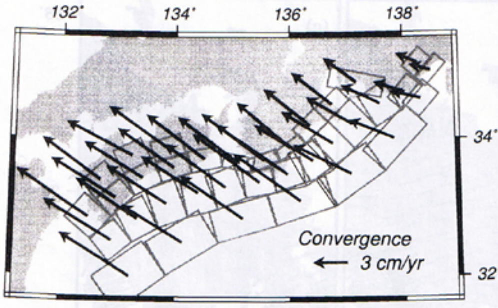

Figure 5. Plate convergences at the centers of the fault segments along the Nankai-Suruga Trough. Minor modifications from the original geometries (thin black lines) have been made for three fault segments.

following *Sagiya et al.* [2000] are well below 10^{-7}/yr, much smaller than those along NKTZ), although the AM-NA "boundary" runs through it (Figure 4). Its southwestern /northeastern parts move similarly to AM/NA, and the whole block rotates counterclockwise, possibly driven by the torque generated by the "non-head-on" collision of AM with NA. The northwestward collision of Izu might exert additional torque. The color contrast between NA and AM, south of NKTZ (Figure 4) would be an "apparent" boundary emerged by neglecting the existence of this block.

4. Discussion

Magnitude 8 class interplate thrust events are known to have recurred during the last 1,500 years with an average interval of 120 years along the Suruga-Nankai Trough [*Sangawa*, 1993]. The next large event is anticipated in the Tokai district (west of the Izu Peninsula) since the last major events, the 1944/1946 Tonankai/Nankaido earthquakes, ruptured the rest of the trough. This seismic gap hypothesis [e.g. *Ishibashi*, 1981], however, assumes that both the landward and oceanic sides of the trough are single plates. *Sagiya* [1999] recently pointed out that the incipient plate convergence along the Zenisu Ridge reduces the backslip vectors at the Tokai district down to 60 % of those to the west, and significantly lengthens the recurrence interval there as seen in *Sangawa*'s [1993] table.

Here we emphasize that the transition from AM to NA in central Japan also reduces the plate convergence rate at the Tokai district. Let us examine the easternmost fault segment of the trough whose center is at (35.0°N, 138.5°E). If PH subducted beneath AM there, the relative velocity would be 61.9 mm/yr in N55W. Substituting IMP for PH shortens the velocity to 41.1 mm/yr in N66W. According to the present study, the long-term velocity of the overriding lithosphere relative to AM is 22.4 mm/yr in N61W there. This further reduces the convergence rate to 18.8 mm/yr in N72W, only one third as long as the original AM-PH convergence. In a word, the strain partitioning in PH (relative movement between IMP and PH) reduces the plate convergence rate at the Tokai district by one third, and another one third is reduced by the transition of the overriding plate from AM to NA. They leave only one third of the original rate available to build up interseismic crustal strain (Figure 5). *Sagiya* [1999], by the inversion of GPS data, inferred the backslip vectors to be as long as 30-40 mm/yr in Sea of Enshu and 25-30 mm/yr in the Suruga Bay, which is not much different from Figure 5.

Crustal deformation associated with the recent volcanic and seismic activities in the northern Izu Islands (Figure 1) [*Kaidzu et al.*, 2000] shows a meter order NE-SW extension and NW-SE contraction. This may have a role as an episodic convergence between IMP and PH, one of the two main processes to reduce the convergence rate at the Tokai district. To clarify the long-term velocity field in central Japan and strain partitioning within PH is important for seismic hazard assessments in the Tokai district based on seismic moment budget, and for understanding the plate tectonic implication of the current volcano-seismic activity in the northern Izu islands.

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