

# Izu detachment hypothesis: A proposal of a unified cause for the Miyake-Kozu event and the Tokai slow event

Tetsuzo Seno

Earthquake Research Institute, University of Tokyo, Japan

(Received June 21, 2004; Revised January 29, 2005; Accepted April 6, 2005)

Based on the fact that interseismic deformation of collision zones is generally described by slip along a detachment at depth, I attempt to interpret the deformation of the Izu collision zone in terms of a detachment model. The systematic deviation of the GPS velocities of the Izu Peninsula (Nov. 1998–June 2000) from the Philippine Sea–Eurasian relative plate motions is fitted by the slip on the detachment at a depth of 15–20 km with a rate of 3 cm/yr. On June 26, 2000, seismo-magmatic activity that started near Miyakejima expanded NW by 20 km close to Kozushima in association with dike intrusion over a few months. The horizontal movements associated with this event, however, spread over wide areas in central Honshu. Simple dike intrusion models cannot explain these movements. To explain these, I hypothesize that a 20 cm of rapid slip occurred on the detachment at the time of this event. The abnormal crustal movements in the Tokai–central Honshu–Kanto region then started after the event. I propose that they represent delayed diffusive transfer of the slip on the detachment over surrounding low viscosity layers, such as nearby rupture zones of great earthquakes.

**Key words:** Izu Peninsula, detachment, collision, Miyakejima, Kozushima, Tokai, diffusion.

## 1. Introduction

Since the middle of 2000, two spectacular tectonic events have occurred in and south of central Honshu, Japan. The first one is the seismo-magmatic activity associated with the eruption of Miyakejima in the Izu islands starting on June 26, 2000. The Izu islands, consisting of Miyakejima, Niijima, Kozushima, and smaller islands, are volcanic islands in the Izu-Bonin backarc formed by the subduction of the Pacific plate (PA) beneath the Philippine Sea plate (PHS) (Fig. 1). Miyakejima is an active basaltic stratovolcano located at the volcanic front, and Niijima and Kozushima are rhyolitic volcanoes further landward. The magma source first arose beneath the east coast of Miyakejima and migrated to the west coast within several hours (Ukawa *et al.*, 2000). An intense earthquake swarm then started and migrated 20 km to the northwest near Kozushima during the next week and continued over the following two months, in association with the occurrence of several  $M \sim 6$  earthquakes (Sakai *et al.*, 2001). Based on the island displacements detected by GPS (Kaidzu *et al.*, 2000), it has been inferred that dike intrusion amounting to a volume of  $\sim 1 \text{ km}^3$  occurred in the crust between Miyakejima and Kozushima associated with this seismic swarm (Yamaoka, 2000; Nishimura *et al.*, 2001; Ito and Yoshioka, 2002; Furuya *et al.*, 2003). On the other hand, Miyakejima itself erupted first on July 8, 2000 and intermittent phreatic eruptions and caldera formation occurred until the end of August, although emission of an enormous amount of volcanic gas has been continuing since then. I call the above dike

intrusion activity between Miyakejima and Kozushima the Miyake-Kozu event hereinafter.

Although the dike intrusion produced horizontal crustal movements amounting to tens of cm near the Izu islands (Kaidzu *et al.*, 2000), horizontal displacements with a ramp time-function during the event are wide-spread over central Japan (Fig. 2; Geographical Survey Institute, 2003). Figure 3 shows examples at four GPS stations in central Honshu (See Fig. 1 for locations), showing that ramp-shaped horizontal displacements continued for almost three months ( $\sim 85$  days). Because the horizontal movements amounting to 3 cm in the Izu Peninsula (Fig. 2) cannot be explained by the dike intrusion alone, Yamaoka (2000) and Nishimura *et al.* (2001) assumed a creep dislocation source at the northern end of the dike whose moment corresponds to  $M_w$  6.6–7.0. Recently, Yamaoka *et al.* (2005) postulated a huge deflation source beneath the dike to explain the widespread crustal movements.

The second event is the anomalous crustal movement in central Honshu that started after the Miyake-Kozu event (Geographical Survey Institute, 2003; Fig. 4). The horizontal displacements of the GPS stations shown in Fig. 4 are those from which the secular trends before June 2000 have been removed (Geographical Survey Institute, 2003). Ozawa *et al.* (2002) noted that the anomalous deformation became evident at least by January 2001 and attributed this event to a slow slip at the PHS subduction boundary near Lake Hamana because the deformation is large in this area. In Japan, this is called the Tokai slow slip event and has been attracting much attention because the area with the slow slip obtained by Ozawa *et al.* (2002) is located at the deeper extension of or overlaps the deeper portion of the rupture zone expected for the Tokai great earthquake

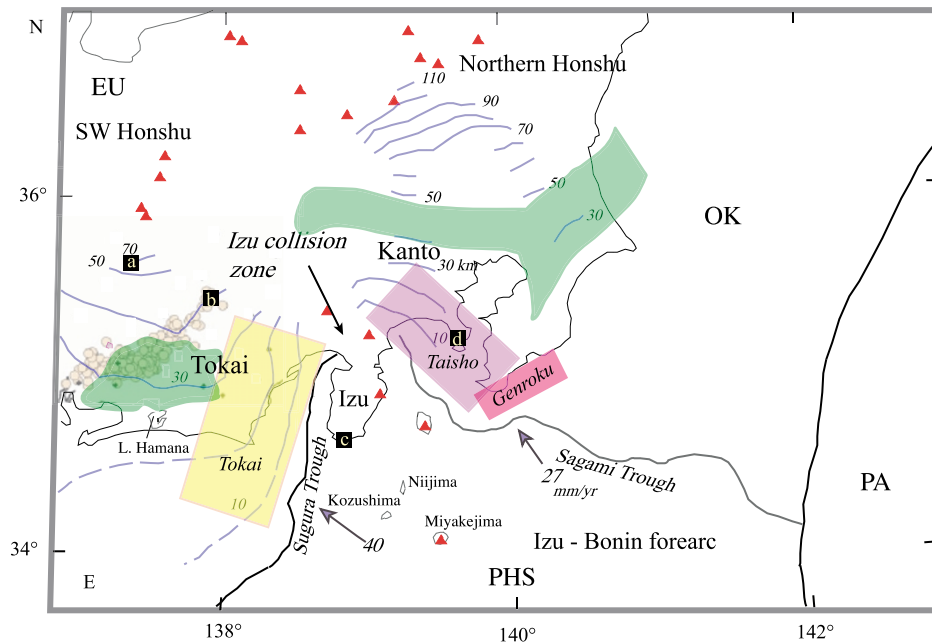


Fig. 1. Tectonic elements in central Honshu-Izu islands region. The Philippine Sea plate (PHS) is subducting along the Sagami and Suruga Troughs, with velocities of 27 mm/yr and 40 mm/yr, respectively (Seno *et al.*, 1993, 1996). OK, EU, and PA denote the Okhotsk, Eurasian, and Pacific plates. The Izu Peninsula is colliding with central Honshu. The contours colored by blue show the upper surface of the intraslab seismicity (Noguchi and Sekiguchi, 2001). The fault planes are those of the Taisho and Genroku Kanto earthquakes (Kasahara *et al.*, 1973) and the Tokai earthquake (Ishibashi, 1981). Low-frequency tremors (brown circles) is from Obara (2002). The possibly serpentinized wedge mantle revealed by the seismic tomography (Kamiya and Kobayashi, 2000, 2005) is shaded by green. The red triangles indicate active volcanoes. The GPS stations whose data are shown in Fig. 3 are indicated by the solid squares: (a) Tsukechi, (b) Minami-shinano, (c) Minami-izu2, and (d) Miura2.

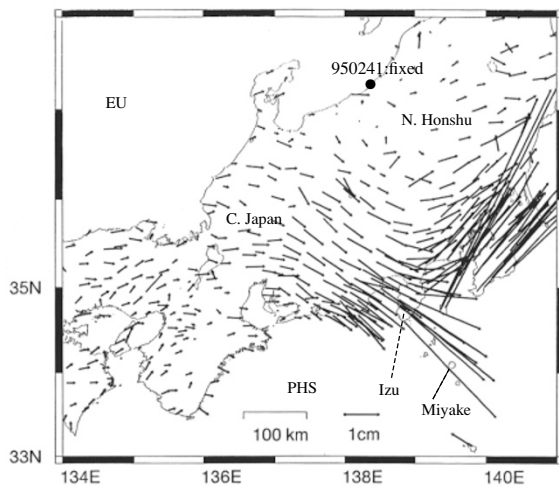


Fig. 2. Horizontal displacements associated with the Miyake-Kozu event (Geographical Survey Institute, 2003); the Ohgata (950241) station is fixed. Displacements are seen over a wide area in central Honshu, not only in the Izu and Boso Peninsulas.

(Fig. 1, Ishibashi, 1981; Matsumura, 1997). I call the anomalous crustal movements shown in Fig. 4 the Tokai slow event.

The peculiar thing here is that the region where the anomalous crustal movements have been seen (Fig. 4) is much wider than the slip area that Ozawa *et al.* (2002) estimated. Comparing Figs. 2 and 4, I notice that the region where the anomalous crustal movements have occurred al-

most coincides with the region over which the horizontal crustal movements associated with the Miyake-Kozu event were evident. It is also noted that the Tokai slow event occurred just after the Miyake-Kozu event; Ozawa *et al.* (2002) inverted the slip history at the plate boundary to estimate slip onset in October, 2000. These suggest a close causal relationship between the Miyake-Kozu and Tokai slow events. In this paper, I try to resolve the above observations and present a unified cause for these two events, by proposing a horizontal detachment existing beneath the western part of the Izu Peninsula. Some implications of the proposed hypothesis for the tectonics in the Izu collision zone are also discussed.

## 2. Detachment beneath the Izu Peninsula

Seno (2005) showed that crustal deformation in collision zones is generally described by the detachment model, whereas that in the subduction zone by the back-slip model of Savage (1983). This is probably due to the lack of dehydration of the subducting slab in collision zones (Seno, 2005). If this is true, the deformation of the Izu collision zone (Fig. 1) would be described also by the detachment model. Recently, Ishibashi and Itani (2004) noticed that the GPS velocities of the western 2/3 of the Izu Peninsula, during Nov. 1998–June 2000, with respect to the Eurasian plate are deviated from the PHS–Eurasian relative plate motions (Seno *et al.*, 1993) systematically. The deviation vectors are directed to S20°E and their magnitudes can be fitted by the function  $a * \exp(-bx^2)$ , where  $a = 2.6$  cm/yr and  $b = 1.2 \times 10^{-4}/\text{km}^2$  (Figs. 5(a) and (b)).

This function shape implies that internal strains occur in

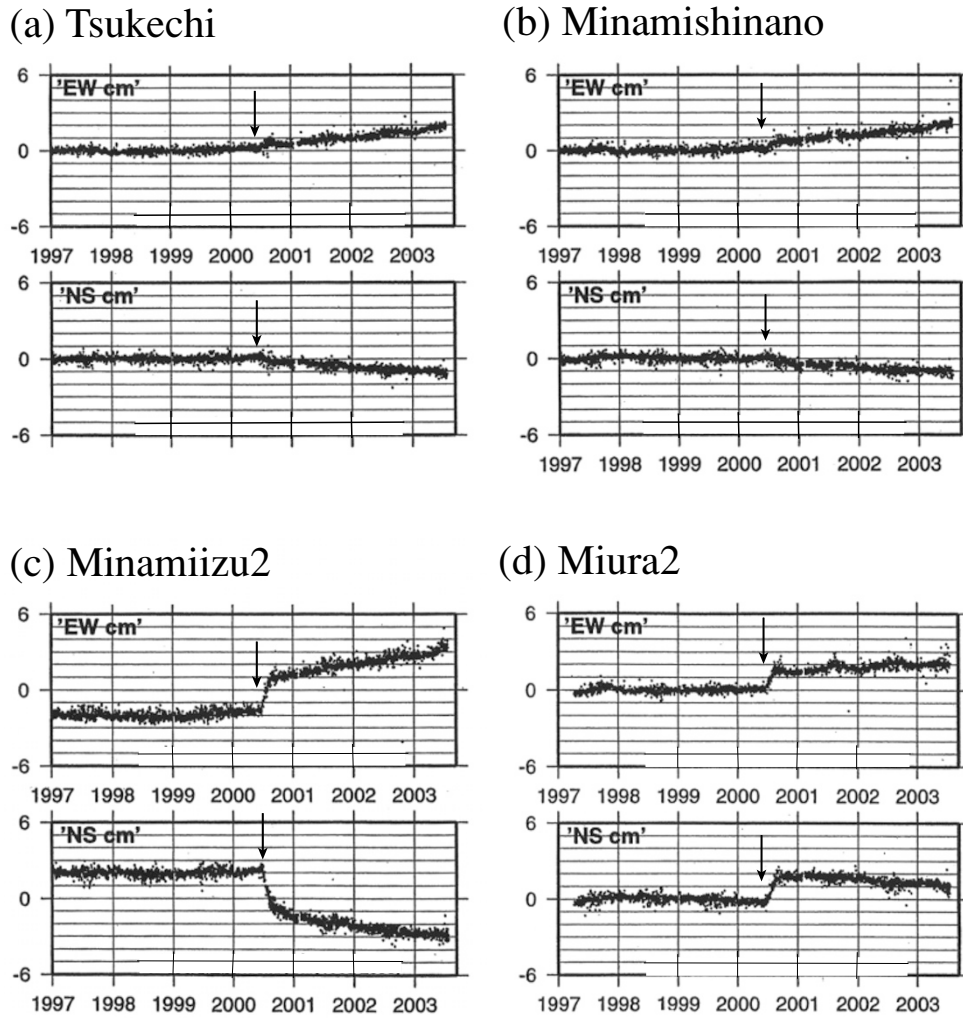


Fig. 3. GPS time series before and after the Miyake-Kozu event (Geographical Survey Institute, 2003). The locations of the stations are indicated in Fig. 1. Ramp function displacements are seen even in Tsukechi and Minami-shinano stations, a few hundred km away from the Izu islands.

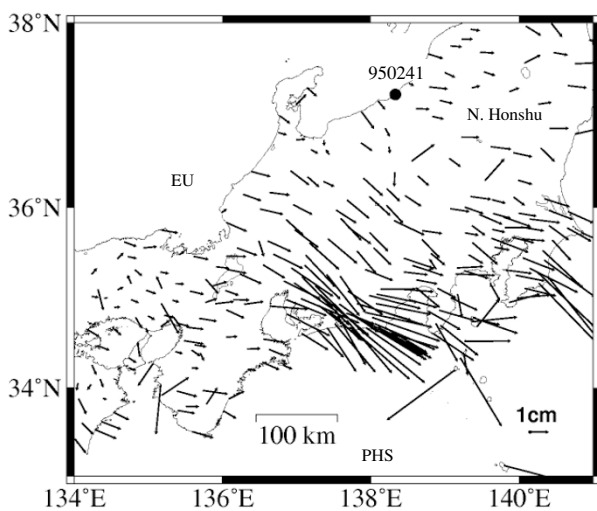


Fig. 4. Non-stationary horizontal displacements in central Honshu between March 27, 2001 and May 29, 2004 (Geographical Survey Institute, <http://cais.gsi.go.jp/tokai/sabun/index.html>). The Ohgata station (950241) is fixed. The displacements are seen in a wide area of central Honshu, which almost coincides with the area deformed at the time of the Miyake-Kozu event.

the Izu Peninsula, probably due to the collision (Ishibashi and Itani, 2004), suggesting that the Izu Peninsula is not a rigid microplate as asserted by Hashimoto and Jackson (1993), Sagiya (1999), and Mazzotti *et al.* (2001). I assume a horizontal detachment surface beneath the area where the horizontal movements deviate from the PHS–Eurasian motion, to explain the discrepancy. This surface is the top surface of the PHS underthrusting horizontally beneath the western part of the Izu Peninsula, and dips to the north from the northern neck of the peninsula near the solid line in Fig. 5(a). I am assuming that there is a PHS slab north of the Izu collision zone at depth (Seno and Yamasaki, 2003; Seno, 2005).

The function can be fitted by the slip on this detachment with a rate of 3 cm/yr at a depth of 15–20 km (Fig. 5(c)) that corresponds to the Conrad discontinuity in this area (Asano *et al.*, 1985); the calculation is conducted in 2-dimensional space using Okada’s (1985) code. The southern edge of the detachment is located about 20 km south from the southern tip of the Izu Peninsula.

Figure 6 shows a schematic cartoon (viewed from above and south) illustrating the deformation expected from the motion on the detachment beneath the Izu Peninsula. The

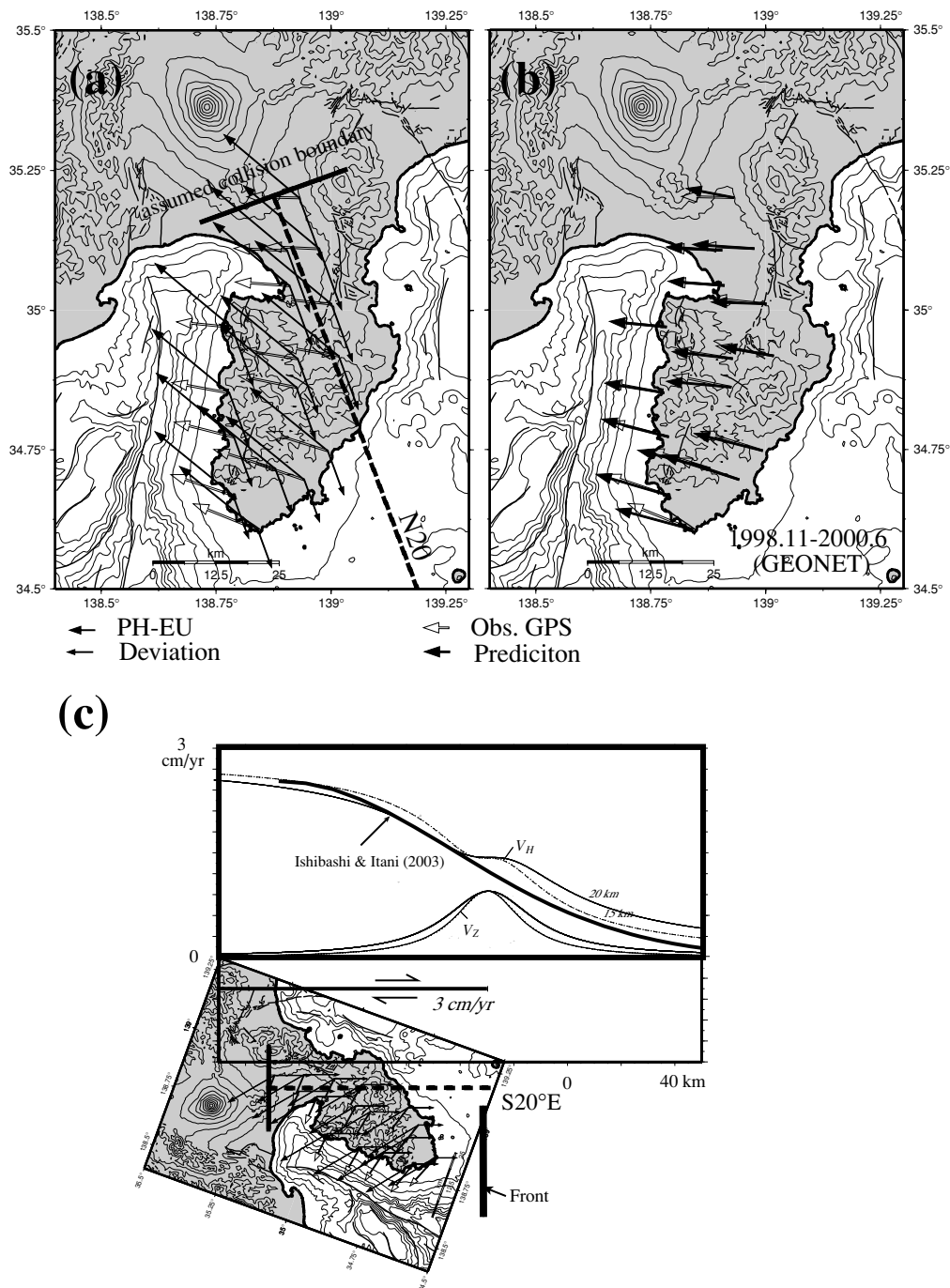


Fig. 5. (a) Deviation of the GPS velocities in the Izu Peninsula from the Philippine Sea–Eurasian plate motions (Ishibashi and Itani, 2004). The deviation is directed in S20°E and its amount can be fitted by the function  $a * \exp(-bx^2)$ , where  $a = 2.6$  cm/yr and  $b = 1.2 \times 10^{-4}/\text{km}^2$ . (b) Comparison of the predicted velocities from the function and the observed GPS velocities (Ishibashi and Itani, 2004). (c) Deviation of the horizontal velocities of Izu Peninsula predicted by the function  $a * \exp(-bx^2)$  is fitted by the surface displacements due to the slip on the detachment beneath the Izu Peninsula at depths of 15 and 20 km with a slip rate of 3 cm/yr, that are calculated by Okada's (1985) code.

detachment extends below the presently non-volcanically active area. I call the slab of the crust above the detachment “the detachment zone”. The zone of the volcanic activity, i.e., near the volcanic front, constitutes a transitional shear zone, between the detachment zone and the Izu-Bonin forearc. Shear strains and stresses are expected to be large in this zone. At the northern edge of the detachment zone, extensional strains are expected because the detachment surface sinks deeper to the north. Extensional strains have been in fact detected in this area near Mt. Fuji by wavelet analysis

of the GPS data (Miyashita *et al.*, 2003).

The  $\sigma_{H \max}$  in the shear zone would be directed NW-SE; in contrast, in the detachment zone, the  $\sigma_{H \max}$  would be directed in NNW-SSE (Fig. 6). Thus the boundary between the shear zone and the detachment zone is marked by a sudden change in the  $\sigma_{H \max}$  direction. This is seen as a sudden change in strike of earthquake faults and active faults such as those associated with the 1930 Kita-Izu and 1978 Izu-Oshima-kinkai earthquakes (Matsuda, 1972; Shimazaki and Somerville, 1979). This abrupt change in  $\sigma_{H \max}$  di-

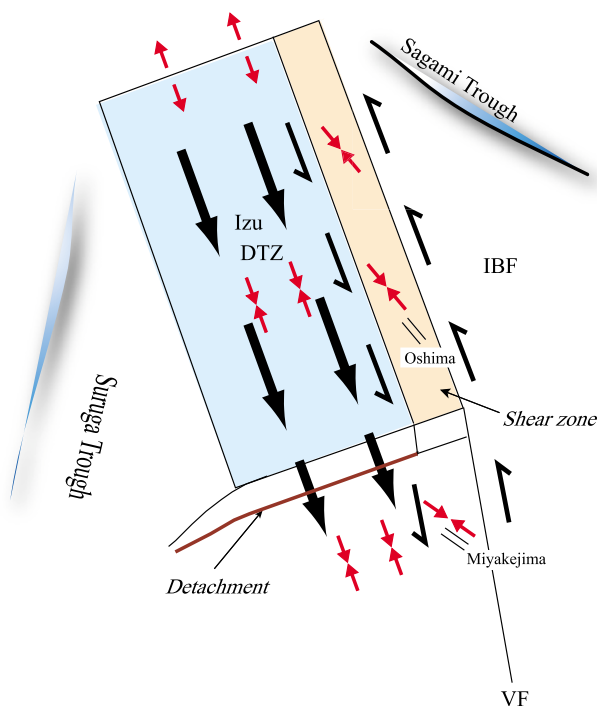


Fig. 6. Schematic cartoon illustrating the deformation near the Izu Peninsula by movement on the detachment viewed from the south and above. The vertical section of the DTZ (the detachment zone) is also shown. Other abbreviations of the symbols are: IBF, Izu-Bonin forearc; VF, volcanic front. The large arrows represent motion of DTZ, and the small opposing arrows represent horizontal stresses. The low viscosity zone near the volcanic front constitutes a shear zone between DTZ and IBF. A sudden extrusion of the detachment zone would have caused stresses in agreement with those seen during the Miyake-Kozu dike intrusion.

rection extending from north to south in the Izu Peninsula has been also noticed by Tsukahara and Ikeda (1991) using focal mechanisms and in-situ stress measurements. This is difficult to explain by bending or collision (Nakamura *et al.*, 1984; Ukawa, 1991) because these predict smooth stress trajectories. On the contrary, Ida (1991) explained such a sudden change in stress regime by introducing the western and eastern Izu blocks; the western one is accommodating a simple shear due to differential subduction along the Suruga Trough, and the eastern one accommodating a pure shear due to collision in the north and subduction in the east along the Sagami Trough. Similar block models have been proposed by Somerville (1978) and Koyama and Umino (1991). It is, however, difficult to explain by these models why the abrupt change in  $\sigma_{H \max}$  direction continues further to the south near the Izu islands (Fukuyama *et al.*, 2001).

In the model presented here, the region south of the detachment zone would be affected by the extrusion of the zone to the south due to the slip on the detachment. The region due south of the detachment zone would then suffer compression, and that near the volcanic front would constitute a sinistral shear zone, similar to the transitional shear zone to the north (Fig. 6). The boundary between the shear zone and the zone affected by the extrusion would be marked by the sudden change in the focal mechanisms, similar to the region to the north; this is in fact seen in many smaller earthquakes between Niijima and Shikine-

jima (Fukuyama *et al.*, 2001).

The geometry of the eastern boundary of the detachment zone is difficult to depict at present because of paucity of data. The seismicity in cross-sections perpendicular to the Suruga Trough by Noguchi (1996) and Aoki (2003) shows that there is a horizontal band of seismicity beneath the Izu Peninsula extending from the PHS slab in the Tokai district. If this represents the bottom of the detachment zone, the zone may decrease its thickness toward the Suruga Trough (Fig. 6).

### 3. The 2000 Miyake-Kozu Event

For the Miyake-Kozu event, Yamaoka (2000) inferred a dike intrusion with 2.5 m opening in a 1.5–15 km depth range over a length of 20 km between Miyakejima and Kozushima. Nishimura *et al.* (2001) and Ito and Yoshioka (2002) estimated a slightly larger volume of intrusion. These models of dike intrusion cannot explain the movements in central Honshu (Fig. 2). I show this using Yamaoka's (2000) model as an example. Figure 7(a) shows the displacement vectors due to the dike intrusion only. The displacements in the Izu Peninsula are directed northward and those in central Honshu are very small. In order to explain the southeastward movements of the GPS stations in the Izu Peninsula amounting to 3 cm, Yamaoka (2000) and Nishimura *et al.* (2001) assumed a creep dislocation source east of Kozushima at the northern end of the dike intrusion zone, whose moment corresponds to  $M_w$  6.6–7. Figure 7(b) shows displacement vectors when the dislocation source of Yamaoka (2000) is added to the dike intrusion. Even if this point source is added, it is difficult to explain the horizontal movements over the Tokai district because the calculated vectors are directed to the west.

Recently, Yamaoka *et al.* (2005) revised the creep dislocation + dike model using a least squares method. They also presented a new model with a deflation source beneath the mid-point of the dike at a depth of 20 km. In this model, the dike extends at depths between 5 and 15 km in a length of 20 km with 10 m opening (intrusion of 2 km<sup>3</sup>). The deflation source below has a volume of 1.5 km<sup>3</sup>. They preferred this deflation + dike model, because there is no evidence for a large creep dislocation near Kozushima. The deflation + dike model seems to have the following defects, however. It predicts symmetric horizontal displacements against a horizontal line along the dike. The observed displacements in Kii Peninsula, SW. Japan, apparently are not symmetric to those in N. Kanto located opposite this line. Furthermore, the amount of intrusion in the dike is predicted to become very large, because the deformation due to deflation counteracts the deformation due to dike intrusion. In addition, I have never known a case where such a single huge magma chamber has existed beneath the middle of a dike.

Based on the belief that the detachment beneath the Izu Peninsula had been active before the Miyake-Kozu event, I hypothesize that a rapid larger slip occurred on the detachment during the Miyake-Kozu event. To explain the horizontal movements of the Izu Peninsula, it is assumed that the upper block slipped by 20 cm in the S60°E direction during 85 days over a horizontal rectangular plane at

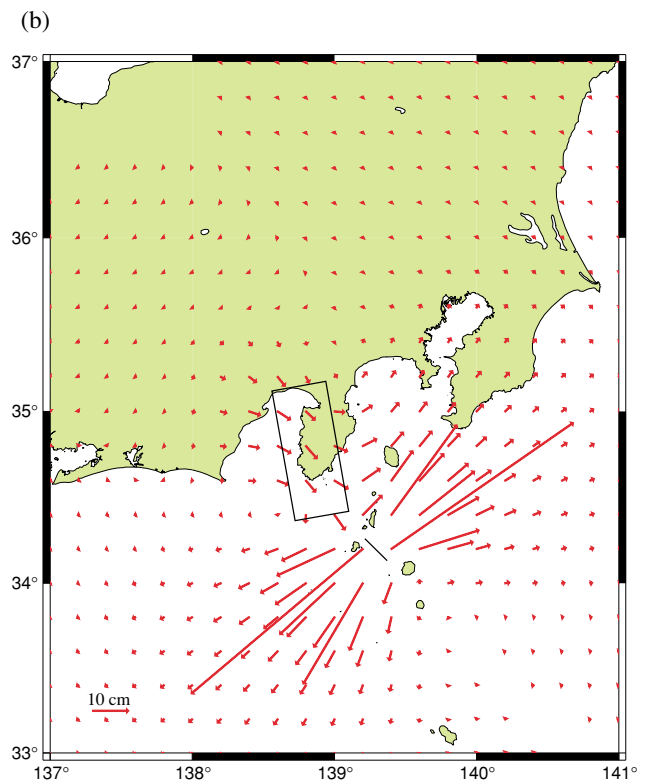
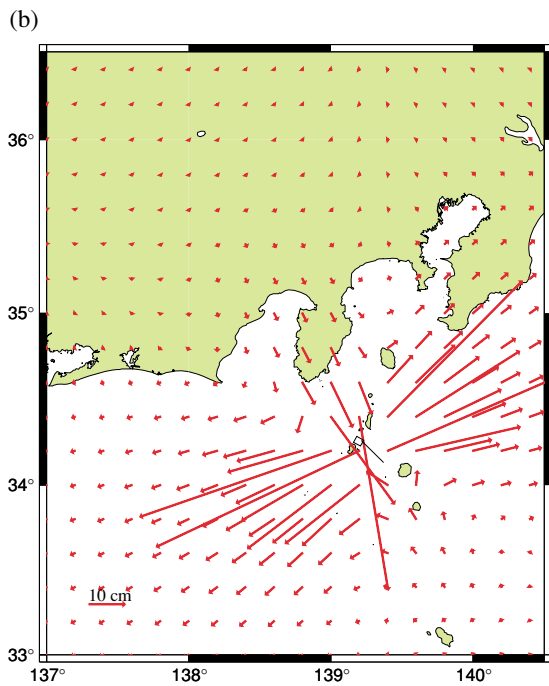
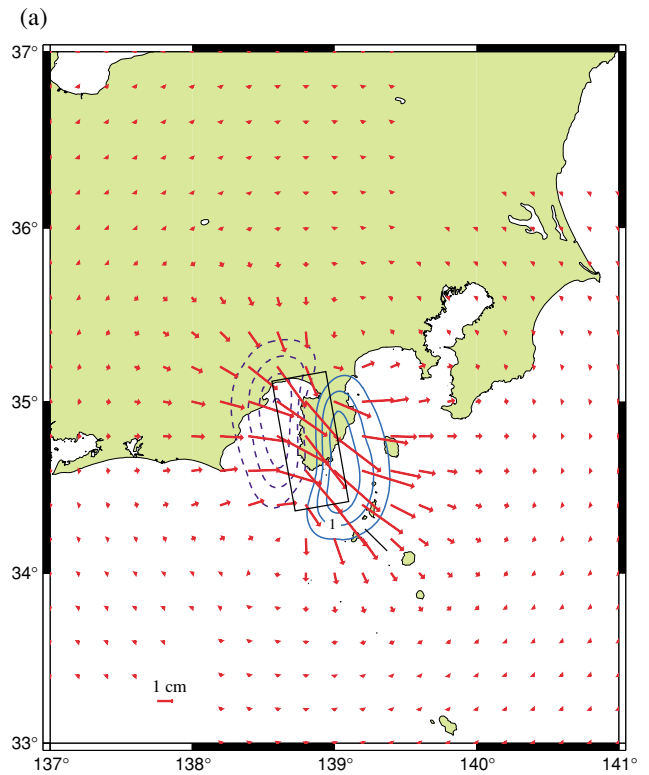
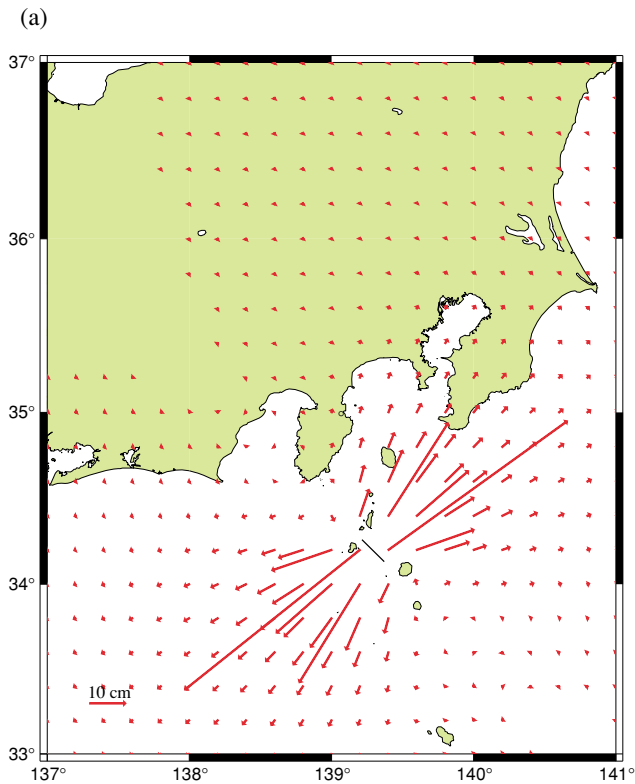


Fig. 7. (a) Horizontal displacements predicted from the dike intrusion model of Yamaoka (2000). Calculation is conducted using the code by Okada (1985). No displacement occurs in central Honshu behind the Tokai district. (b) Horizontal displacements predicted from the dike intrusion plus the point creep dislocation of Yamaoka (2000). The location of the dislocation is indicated by the square. The displacement vectors in Tokai are predicted to be directed S-SW, which are not observed.

Fig. 8. (a) Horizontal and vertical displacements predicted from the slip on the detachment beneath the Izu Peninsula. The contour interval for the vertical displacements is 0.5 cm. A slip of 20 cm in the direction of S60°E at a depth of 20 km is assigned on the horizontal rectangular plane with a width of 35 km and a length of 85 km, and the deformation is calculated using Okada's (1985) code. (b) Deformation caused by the dike intrusion of Yamaoka (2000) is added to that shown in (a). The general pattern of the calculated displacements explains that associated with the Miyake-Kozu event (Fig. 2), although the magnitudes of the calculated displacements are still small in central Honshu.

a depth of 20 km; surface horizontal and vertical movements due to this slip calculated using Okada's (1985) code are shown with the fault geometry in Fig. 8(a). Because steady slip had been occurring on the detachment prior to

this event, this slip at the time of the Miyake-Kozu event is not elastic rebound, but acceleration of the steady slip. The rapid southeastward extrusion of the Izu Peninsula has caused uplift amounting to 0.5–1 cm in Kozushima and Niijima, which is negligible compared to the amount of uplift due to the dike intrusion (Yamaoka *et al.*, 2005; Furuya *et al.*, 2003). It would have produced a sinistral shear east of Kozushima by the extrusion of the detachment zone to the south. Because this stress is conformable to the dike intrusion, it might have triggered the Miyake-Kozu event. Figure 8(b) shows the horizontal movements calculated from both the slip on the detachment and the dike intrusion by Yamaoka (2000), which explains the overall pattern of the observed horizontal movements in central Honshu revealed by GPS (Fig. 2).

#### 4. The Tokai Slow Event

The so-called abnormal crustal deformation in the Tokai district (Fig. 4, Geographical Survey Institute, 2003) started within a half year after the Miyake-Kozu event (Ozawa *et al.*, 2002). Apparently, the crustal deformation extends over much wider areas in central Honshu than the Tokai district. The GPS velocities have been derived by fixing the Ohgata station (950241) in NE Honshu (Fig. 4). The deformation is dependent on the way in which the fixed point is selected. However, there is evidence to suggest that the general southeastward displacements of central Honshu shown in Fig. 4 are likely to be true. First, they are the deviation from the stationary secular movements before the Miyake-Kozu event; the secular ones showed a WNE contraction pattern as expected from the plate subduction (Geographical Survey Institute, 2003). The southward displacements are therefore probably not affected by the manner in which the reference point is selected. Second, if the southeastward motion of central Honshu were not present, those stations in the northern margin of central Honshu, including the Ohgata station, should move to the northwest with respect to central Honshu. This seems unlikely.

I therefore believe that the abnormal movements in the Tokai–central Honshu–Kanto region shown in Fig. 4 are real. Figure 1 shows that the Izu detachment is surrounded by rupture zones of great earthquakes. A great earthquake in the Tokai district is expected to occur in the near future because 150 years have passed since the last event in 1854. It is 80 years since the last Taisho Kanto earthquake in 1923. The rupture zones of these earthquakes are likely to behave as low viscosity zones (Fig. 9), if the pore fluid pressure has to rise close to the lithostatic to reduce the effective normal stress of the fault prior to the occurrence of an earthquake. This elevation of the pore fluid pressure may occur in the barrier portions that occupy most of the rupture zone (Seno, 2003).

Further landward of the rupture zones, the wedge mantle is likely to be serpentinized. Kamiya and Kobayashi (2000, 2005) detected high  $V_p/V_s$  zones above the PHS slab in the 30–45 km depth range (Fig. 1) using seismic tomography and inferred that these zones are serpentinized by the dehydration from the subducting PHS slab (see also Seno and Yamasaki, 2003). These zones may also act as low viscosity layers if dehydration of the serpentine occurs by some

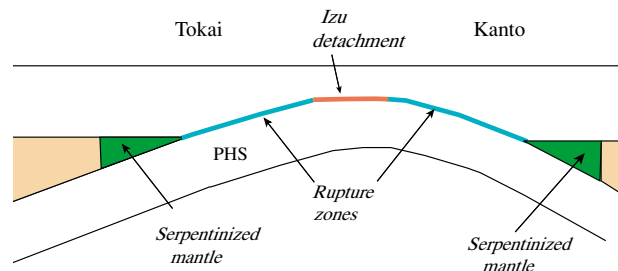


Fig. 9. Schematic cross-section in the Tokai-Izu-Kanto region in the E-W direction. The rupture zones of the Tokai and Kanto earthquakes are likely to have elevated pore fluid pressure. The serpentinized mantle wedges exist further landward of the rupture zones (green color, Kamiya and Kobayashi, 2000, 2005). These constitute low viscosity layers surrounding the Izu detachment, compared to the normal wedge mantle (yellow color). The sudden slip on the detachment during the Miyake-Kozu event would have been transferred to the nearby regions by diffusion through these viscous layers.

agents (Raleigh and Paterson, 1965).

Let us assume that there is a thin low viscosity zone beneath a plate as seen in Fig. 9. If the portion of the plate over the detachment moves suddenly in a horizontal direction, such a movement propagates into neighboring portions of the plate through viscous relaxation of the layer (Elsasser, 1967; Bott and Dean, 1973). I propose that this is the origin of the horizontal movements observed in the Tokai–central Honshu–Kanto region (the Tokai slow event); that is, they represent delayed transfer of the slip on the detachment beneath the Izu Peninsula, that occurred at the time of the Miyake-Kozu event, over the nearby low viscosity layers. At the time of the slip on the detachment, displacements occurred over a wide area in central Honshu (Fig. 2). These could also be sources of disturbance that would propagate by diffusion to nearby areas, even if they are minor. This would explain why the area of deformation in Fig. 2 almost coincides with the area of deformation in Fig. 4.

In a 1-dimensional case, the propagation of the above motion is described by a diffusion equation (Elsasser, 1967). Lehner *et al.* (1981) presented equations describing the 2-dimensional case, where a plate with a constant thickness is floating over a viscous layer of a constant thickness. Heki *et al.* (1993) solved similar equations to describe crustal deformation due to episodic dike intrusion at the spreading axis in Iceland. To model the anomalous crustal deformation after the Miyake-Kozu event, Takahashi and Seno (2005) solved these equations using the finite difference method. They assumed that the plate and the viscous layer have thicknesses of 30 km and 20 m, respectively, put a ramp-shaped displacement of 20 cm on the detachment with a rise time of 85 days during the Miyake-Kozu event, and determined the diffusion coefficient matching the arrival times of horizontal displacements in the Tokai district. The viscosity of the viscous layers was determined to be  $10^{13}$ – $10^{15}$  Pa s from the diffusion coefficient. Figure 10 shows the distribution of the calculated horizontal movements for 3.5 years after March 27, 2001 (See Takahashi and Seno (2005) for details). The overall pattern is similar to that observed (Fig. 4).

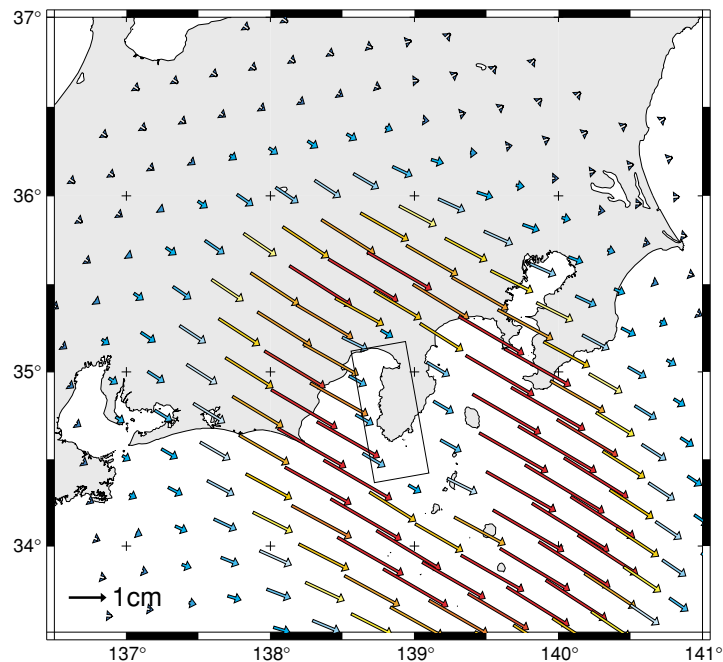


Fig. 10. Calculated horizontal surface displacements (colored arrows) propagated through the low viscosity zones beneath central Honshu from the source at the detachment beneath the Izu Peninsula using a 2-dimensional diffusion model (Takahashi and Seno, 2005). Only displacements for 3.5 years after March 27, 2001 are plotted to compare with those in Fig. 4. The 20 cm of slip is given at the detachment by a ramp function with duration of 85 days, as an initial condition. The displacements in the south are artificial ones due to the simple 2-dimensional geometry of the calculation.

## 5. Discussion

The suggested presence of a detachment beneath the Izu Peninsula has some implications for seismicity and tectonics in the Tokai–Kanto region surrounding the Izu collision zone. I will discuss some of these here.

The detachment hypothesis might help to resolve some enigmas about the tectonics in and near the Izu Peninsula. Sugimura (1972) proposed that the PHS–Eurasian collision boundary is located in the northern neck of the Izu Peninsula. However, there is no conspicuous active geological structure representing a plate boundary in this region. On the other hand, a few incipient thrust zones trending NE–SW have been suggested south of the Izu Peninsula by seismic reflection surveys (e.g., Le Pichon *et al.*, 1987; Taira *et al.*, 1992). Fujii (1977) also inferred that slip occurred on the NE striking thrust dipping to the NW in depths between 12 and 22 km south of the Izu Peninsula at the time of the 1974 Izu-hanto-oki earthquake. These thrust zones may connect the detachment with the surface.

Koyama and Umino (1991) showed that NW striking strips of crust in E. Izu have been rotated in a counter-clockwise sense during the Quaternary based on the paleomagnetism data. This block rotation, that is difficult to explain by pure shear expected from collision in the NW direction, can be explained by the sinistral shear motion between the Izu-Bonin forearc and the detachment zone.

Koyama (1992) cited many examples of simultaneous activation of volcanoes and active faults located in the shear zone within the past 20 ka. If the motion on the detachment produces a shear over the whole or part of the zone, it would be easier to understand this coeval activity. Recent examples of such synchronicity include the dike intrusion and strike-slip earthquakes that occurred in 1930 and 1980

in the NE corner of the Izu Peninsula.

Near the northern end of the shear zone, several historical M 7 shallow earthquakes have recurred (Ishibashi, 2004). In the same place, crustal deformation amounting to 20 cm occurred at the time of the 1923 Kanto earthquake (Miyabe, 1931; Fujii and Nakane, 1978) in association with activity on a buried subsidiary fault. Ishibashi (2004) attributed these fault motions to the activity at the West Sagami Bay Fracture (WSBF), which is a fracture between the inner and outer Izu-Bonin arcs. However, the seismic intensity distributions and tsunami generation are different from one event to another event (Ishibashi, 2004), and the crustal deformation caused by the subsidiary fault of the 1923 earthquake is difficult to explain by the motion on the vertical WSBF. It would be easier to understand them if they are representing activities at various portions of the shear zone including its base and side-walls.

If the seaward slow rebound of the upper Eurasian plate margin as seen by the abnormal horizontal motion is caused by delayed slip over the viscous layers after the Miyake-Kozu event, these movements would have loaded the asperities inside the rupture zone of the Tokai earthquake. I guess, therefore, that this movement will promote the occurrence of the Tokai earthquake in the future. However, because the details of connection of the detachment zone to the plate boundary in the Tokai district are not known, effects on the Tokai earthquake await further study.

## 6. Conclusions

I conclude that there is a detachment beneath the western 2/3 of the Izu Peninsula. This is concordant with the GPS velocities observed during the period before the Miyake-Kozu event (Ishibashi and Itani, 2004). I also propose that at



the time of the Miyake-Kozu event, there was 20 cm of slip on the detachment in the S60°E direction, which explains the horizontal crustal movements over central Honshu. The so-called abnormal crustal movements in the Tokai–central Honshu–Kanto regions started within a half year after the Miyake-Kozu event (Geographical Survey Institute, 2003; Ozawa *et al.*, 2002). I further propose that they represent delayed diffusive transfer of the slip on the detachment associated with the Miyake-Kozu event to the surrounding regions. The rupture zones of great earthquakes and serpentinized mantle wedges west and east of the Izu Peninsula would have acted as low viscosity guides to diffuse the slip effectively.

The proposal of a detachment beneath the Izu Peninsula and the sinistral shear zone between the zone above the detachment and the Izu-Bonin forearc has important implications for the tectonics in the region at the northwestern corner of the PHS. I have discussed some of them, such as the missing plate boundaries in the north of the Izu Peninsula, the block rotations of NE. Izu, the simultaneous seismic and volcanic activities within the shear zone, and the historical earthquakes near the WSBF. The detailed analyses of these and other possible subjects are left open for future studies.

**Acknowledgments.** I thank Kosuke Heki and an anonymous reviewer for their review of the manuscript. I thank Yoji Kobayashi, Naoyuki Fujii and Kana Takahashi for discussion, and Katsuhiko Ishibashi and Koshun Yamaoka for providing me preprints of their papers.

## References

- Aoki, H., Configuration of the PHS plate beneath Tokai areas and a few characteristics of plate motion, *Abstr. Seism. Soc. Jpn.*, C036, 2003 (in Japanese).
- Asano, S., K. Wada, T. Yoshii, M. Hayakawa, Y. Misawa, T. Moriya, T. Kanazawa, H. Murakami, F. Suzuki, R. Kubota, and K. Suyehiro, Crustal structure in the Northern Part of the Philippine Sea Plate as derived from seismic observations of Hatoyama-Off Izu Peninsula explosions, *J. Phys. Earth*, **33**, 173–189, 1985.
- Bott, M. H. P. and D. S. Dean, Stress diffusion from plate boundaries, *Nature*, **243**, 339–341, 1973.
- Elsasser, W. M., Convection and stress propagation in the upper mantle, in *The Application of Modern Physics to the Earth and Planetary Interiors*, edited by S. K. Runcorn, pp. 223–246, John Wiley, New York, 1967.
- Fujii, Y., Creep dislocation propagation along the East-off-Izu Tectonic Line, Japan, around the year of 1930 and 1976, *Jisin*, **30**, 389–400, 1977 (in Japanese).
- Fujii, Y. and K. Nakane, The 1930 Kita-Izu earthquake and related crustal movements in the northern part of the Izu Peninsula, Japan, during pre- and post-seismic period, *J. Geod. Soc. Jpn.*, **24**, 59–68, 1978 (in Japanese).
- Fukuyama, E., A. Kubo, H. Kawai, and K. Nonomura, Seismic remote monitoring of stress field, *Earth Planets Space*, **53**, 1021–1026, 2001.
- Furuya, M., S. Okubo, R. Miyajima, I. Meilano, W. Sun, Y. Tanaka, and T. Miyazaki, Mass budget of the magma flow in the 2000 volcano-seismic activity at Izu-island, Japan, *Earth Planets Space*, **55**, 375–385, 2003.
- Geographical Survey Institute, Crustal movements in the Tokai district, *Rep. Corrd. Comm. Earthquake Predict.*, **69**, 303–393, 2003.
- Hashimoto, M. and D. D. Jackson, Plate tectonics and crustal deformation around the Japanese Island, *J. Geophys. Res.*, **98**, 16149–16166, 1993.
- Heki, K., G. R. Foulger, B. R. Julian, and C.-H. Jahn, Plate dynamics near divergent boundaries: Geophysical implications of postdrifting crustal deformation in NE Iceland, *J. Geophys. Res.*, **98**, 14279–14297, 1993.
- Ida, Y., Interpretation of seismic and volcanic activities in the Izu block in relation to collision tectonics, *J. Phys. Earth*, **39**, 421–440, 1991.
- Ishibashi, K., Specification of a soon-to-occur seismic faulting in the Tokai district, central Japan, based upon seismotectonics, *Earthquake Prediction—An International Review, Maurice Ewing Series*, **4**, 297–332, 1981.
- Ishibashi, K., Seismotectonic modeling of the repeating M 7-class disastrous Odawara earthquake in the Izu collision zone, central Japan, *Earth Planets Space*, **56**, 843–858, 2004.
- Ishibashi, K. and Y. Itani, Explanation of the westward motion of the Izu Peninsula by collision—An interpretation of GPS velocity vectors, *Jisin*, **56**, 387–390, 2004 (in Japanese).
- Ito, T. and S. Yoshioka, A dike intrusion model in and around Miyakejima, Niiijima and Kozushima in 2000, *Tectonophysics*, **359**, 171–187, 2002.
- Kaidzu, M., T. Nishimura, M. Murakami, S. Ozawa, T. Sagiya, H. Yurai, and T. Imakiire, Detection and monitoring of ongoing aseismic slip in the Tokai region, central Japan, *Earth Planets Space*, **52**, ix–xviii, 2000.
- Kamiya, S. and Y. Kobayashi, Seismological evidence for the existence of serpentinized wedge mantle, *Geophys. Res. Lett.*, **27**, 819–822, 2000.
- Kamiya, S. and Y. Kobayashi, Seismological evidence for the existence of serpentinized wedge mantle in the Tokai district, 2005 (in preparation).
- Kasahara, K., J. Yamada, and M. Ando, Crustal movements in the southern Kanto district, and a related working hypothesis, *Publications for the 50th Anniversary of the Great Kanto Earthquake*, 1923, Earthquake Research Institute, University of Tokyo, 103–116, 1973 (in Japanese).
- Koyama, M., Possibilities of simultaneous occurrence of volcanic eruptions and earthquakes in the northern margin of the Philippine Sea plate, *Earth Monthly Suppl.*, **5**, 137–144, 1992 (in Japanese).
- Koyama, M. and S. Umino, Why does the Higashi-Izu monogenetic volcano group exist in the Izu Peninsula?: relationships between late Quaternary volcanism and tectonics in the northern tip of the Izu-Bonin arc, *J. Phys. Earth*, **39**, 391–420, 1991.
- Le Pichon, X. *et al.*, The eastern and western ends of Nankai Troughs: results of Box 5 and Box 7 Kaiko survey, *Earth Planet. Sci. Lett.*, **83**, 199–213, 1987.
- Lehner, F. K., V. C. Li, and J. R. Rice, Stress diffusion along rupturing plate boundaries, *J. Geophys. Res.*, **86**, 6155–6169, 1981.
- Matsuda, T., Surface faults associated with Kita-Izu earthquake of 1930 in Izu Peninsula, Japan, in *Izu Peninsula*, edited by M. Hoshino and T. Aoki, pp. 73–93, Tokai Univ. Press, 1972 (in Japanese).
- Matsumura, S., Focal zone of a future Tokai earthquake inferred from the seismicity pattern around the plate interface, *Tectonophysics*, **273**, 271–291, 1997.
- Mazzotti, S., P. Henry, and X. Le Pichon, Transient and permanent deformation of central Japan estimated by GPS 2. Strain partitioning and arc-arc collision, *Earth Planet. Sci. Lett.*, **184**, 445–469, 2001.
- Miyabe, N., On the vertical earth movement in Kwanto districts, *Bull. Earthq. Res. Inst.*, **9**, 1–20, 1931.
- Miyashita, K., J. Li, and K. Vijaykumar, Tectonic model, explaining the secular crustal deformation in the Kanto-Tokai region, *Abstr. Seism. Soc. Jpn.*, C0034, 2003 (in Japanese).
- Nakamura, K., K. Shimazaki, and N. Yonekura, Subduction, bending and education. Present and Quaternary tectonics of the northern border of the Philippine Sea plate, *Bull. Soc. Geol. France*, **26**, 221–243, 1984.
- Nishimura, T., S. Ozawa, M. Murakami, T. Sagiya, T. Tada, M. Kaidzu, and M. Ukawa, Crustal deformation caused by magma migration in the northern Izu Islands, Japan, *Geophys. Res. Lett.*, **19**, 3745–3748, 2001.
- Noguchi, S., Geometry of the Philippine Sea slab and the convergent tectonics in the Tokai District, Japan, *Jisin*, **49**, 295–325, 1996 (in Japanese).
- Noguchi, S. and S. Sekiguchi, Subduction and deformation of the Philippine Sea and Pacific plates beneath the Kanto region, *The Earth Monthly*, **23**, 733–741, 2001 (in Japanese).
- Obara, K., Nonvolcanic deep tremor associated with subduction in southwest Japan, *Science*, **296**, 1679–1681, 2002.
- Okada Y., Surface deformation due to shear and tensile faults in a half-space, *Bull. Seism. Soc. Am.*, **75**, 1135–1154, 1985.
- Ozawa, S., M. Murakami, M. Kaidzu, T. Tada, T. Sagiya, Y. Hatanaka, H. Yurai, and T. Nishimura, Detection and monitoring of ongoing aseismic slip in the Tokai region, central Japan, *Science*, **298**, 1009–1021, 2002.
- Raleigh, C. B. and M. S. Paterson, Experimental deformation of serpentine and its tectonic implications, *J. Geophys. Res.*, **70**, 3965–3985, 1965.
- Sagiya, T., Interplate coupling in the Tokai District, Central Japan, deduced from continuous GPS data, *Geophys. Res. Lett.*, **26**, 2315–2318, 1999.
- Sakai, S., T. Yamada, S. Ide, M. Mochizuki, H. Shiobara, T. Urabe, N. Hirata, M. Shinohara, T. Kanazawa, A. Nishizawa, G. Fujie, and H. Mikada, Magma migration from the point of view of seismic activity in the volcanism of Miyake-jima island in 2000, *J. Geogr.*, **110**, 145–155, 2001 (in Japanese).
- Savage, J. C., A dislocation model of strain accumulation and release at a subduction zone, *J. Geophys. Res.*, **88**, 4984–4996, 1983.

- Seno, T., Fractal asperities, invasion of barriers, and interplate earthquakes, *Earth Planets Space*, **55**, 649–665, 2003.
- Seno, T., Collision vs. subduction: the importance of slab dehydration, in *The Seismogenic Zone of Subduction Thrust Faults*, edited by T. Dixon and J. C. Moore, Columbia Univ. Press, 2005 (in press).
- Seno, T. and T. Yamasaki, Low-frequency tremors, intraslab and interplate earthquakes in Southwest Japan—from a viewpoint of slab dehydration, *Geophys. Res. Lett.*, **30**(22), doi:10.1029/2003GL018349, 2003.
- Seno, T., S. Stein, and A. E. Gripp, A model for the motion of the Philippine Sea plate consistent with NUVEL-1 and geological data, *J. Geophys. Res.*, **98**, 17941–17948, 1993.
- Seno, T., T. Sakurai, and S. Stein, Can the Okhotsk plate be discriminated from the North American plate?, *J. Geophys. Res.*, **101**, 11305–11315, 1996.
- Shimazaki, K. and P. Somerville, Static and dynamic parameters of the Izu-Oshima, Japan Earthquake of January 14, 1978, *Bull. Seism. Soc. Am.*, **69**, 1343–1378, 1979.
- Somerville, P., The accommodation of plate collision by deformation in the Izu block, Japan, *Bull. Earthq. Res. Inst.*, **53**, 629–648, 1978.
- Sugimura, A., Plate boundaries around Japan, *Kagaku*, **42**, 192–202, 1972 (in Japanese).
- Taira, A., K. T. Pickering, B. F. Windley, and W. Soh, Accretion of Japanese island arcs and implications for the origin of Archean greenstone belts, *Tectonics*, **11**, 1224–1244, 1992.
- Takahashi, K. and T. Seno, Simulation of diffusion of crustal deformation caused by disturbances arising at plate boundaries: a case of the detachment beneath the Izu Peninsula, Japan, *Earth Planets Space*, **57**, this issue, 935–941, 2005.
- Tsukahara, H. and R. Ikeda, Crustal stress orientation pattern in the central part of Honshu, Japan—stress provinces and their origins, *J. Geol. Soc. Jpn.*, **97**, 461–474, 1991 (in Japanese).
- Ukawa, M., Collision and fan-shaped compressional stress pattern in the Izu block at the northern edge of the Philippine Sea plate, *J. Geophys. Res.*, **96**, 713–728, 1991.
- Ukawa, M., E. Fujita, E. Yamamoto, Y. Okada, and M. Kikuchi, The 2000 Miyakejima eruption; Crustal deformation and earthquakes observed by the NIED Miyakejima observation network, *Earth Planets Space*, **52**, xix–xxvi, 2000.
- Yamaoka, K., What are occurring beneath the Miyake and Koju islands?, *Kagaku*, **70**, 926–935, 2000 (in Japanese).
- Yamaoka, K., T. Kudo, M. Kawamura, F. Kimata, and N. Fujii, Long-lasting dike intrusion in the 2000 eruption of Miyakejima volcano—Where did the magma come from?, *Bull. Volcanol.*, **67**, 231–242, 2005.

---

T. Seno (e-mail: [seno@eri.u-tokyo.ac.jp](mailto:seno@eri.u-tokyo.ac.jp))