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Transient crustal movement in the northern Izu–Bonin arc starting in 2004: A large slow slip event or a slow back-arc rifting event?

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ABSTRACT

The Izu–Bonin arc lies along the convergent boundary where the Pacific Plate subducts beneath the Philippine Sea Plate. Horizontal velocities of continuous Global Navigation Satellite System stations on the Izu Islands move eastward by up to ~1 cm/year relative to the stable part of the Philippine Sea Plate suggesting active back-arc rifting behind the northern part of the arc. Here, we report that such eastward movements transiently accelerated in the middle of 2004 resulting in ~3 cm extra movements in 3 years. We compare three different mechanisms possibly responsible for this transient movement, i.e. (1) postseismic movement of the 2004 September earthquake sequence off the Kii Peninsula far to the west, (2) a temporary activation of the back-arc rifting to the west dynamically triggered by seismic waves from a nearby earthquake, and (3) a large slow slip event in the Izu–Bonin Trench to the east. By comparing crustal movements in different regions, the first possibility can be shown unlikely. It is difficult to rule out the second possibility, but current evidence support the third possibility, i.e. a large slow slip event with moment magnitude of ~7.5 may have occurred there.

1. Introduction

The Pacific (PA) and Philippine Sea (PH) Plates are subducting beneath Northeast and Southwest Japan arcs at the Japan Trench and the Nankai Trough, respectively. Southward extension of the Japan Trench is the Izu–Bonin and the Mariana Trenches, where PA subducts beneath PH (Fig. 1a). In the northernmost part of the Izu–Bonin arc, the movement of PA relative to PH is ~49 mm/yr toward N84 W (Argus et al., 2010). In convergent plate boundaries, plate interfaces are often locked and move episodically as interplate earthquakes (including afterslips), and slow slip events (SSE). No historical magnitude 8 class interplate thrust earthquakes are known in the northern Izu–Bonin arc. We do not exactly know how the two plates converge there owing to the lack of appropriate geodetic observations.

Back-arc of the northern Izu–Bonin Arc (the Izu Islands) is considered to be in the initial rifting stage (e.g. Tamaki, 1985). In fact, a chain of topography suggesting active E-W rifting with width of ~30 km have been identified to the west of the Izu volcanic arc (Taylor et al., 1991). In the southern Izu–Bonin Arc (beneath the Bonin Islands), such back-arc spreading does not occur. Further to the south, however, mature active back-arc spreading occurs in the Mariana Arc (Fig. 1c).

The active back-arc spreading in the Mariana Trough has been directly measured by Global Navigation Satellite System (GNSS) as eastward movements of the Mariana Islands relative to the stable part of PH (SPH) (Kato et al., 2003). Likewise, Nishimura (2011) showed that the GNSS stations in the Izu Islands are moving eastward relative to SPH by 2–9 mm/year, and attributed it to the active back-arc rifting behind the Izu arc. In divergent plate boundaries on land, rifting episodes lasting for years occur and are often followed by post-rifting relaxation (e.g. Heki et al., 1993; Wright et al., 2012). However, behaviors of back-arc spreading/rifting have been poorly known due to the lack of geodetic observations near submarine rift axes.

In this study, we report that transient eastward crustal movement of the Izu Islands relative to SPH started in middle 2004 and lasted for a few years. We propose several geophysical mechanisms, such as postseismic movement of a large earthquake, temporary activation of back-arc rifting, and an independent silent earthquake, as candidates responsible for the event. Then we discuss which one best explains the observations.

2. GNSS data in PH

2.1. Secular velocity

First, we confirm the secular eastward movements of the Izu Islands relative to SPH as reported by Nishimura (2011), in three steps, i.e.

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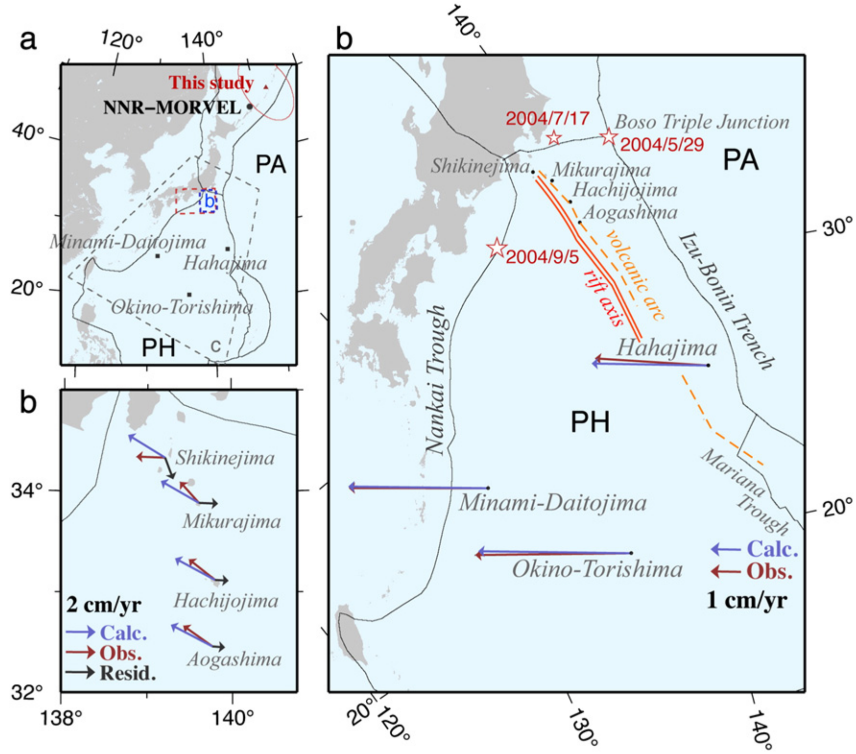

Fig. 1. (a) Plate boundaries in and around Japan. Black circle and red triangle (with 95% confidence ellipse) show the PH Euler poles of the NNR-MORVEL (Argus et al., 2010) and from the present study, respectively. The region shown with blue and gray dashed lines are shown in (b) and (c), respectively. A red rectangle indicates the region shown in Fig. 4a. (b) Map of the northern part of the Izu–Bonin arc (Izu Islands). Here the observed pre-2004 velocities of the four GNSS stations are compared with those calculated using the Euler vector of the stable part of PH (SPH). Residual (black arrows) show eastward direction suggesting the active back-arc rifting. (c) Observed velocity vectors of three GNSS stations in SPH, Minami–Daitojima, Okino–Torishima, and Hahajima, are used to define the reference frame fixed to SPH. The Mercator's projection pole is taken at the Euler pole (48.5 N 152.6E) of SPH so that its movement is expressed as the leftward movements. Blue arrows show velocities calculated using the Euler pole and the rotation rate estimated using these three velocity vectors. Stars show the epicenters of the three earthquakes in middle 2004 (May 29, Jul. 17 and Sep. 5–6) discussed in this study.

1) defining the SPH Euler vector using GNSS stations there, 2) calculating velocities at GNSS stations in the Izu Islands using the estimated Euler vector, and 3) deriving the movements of the Izu Islands with respect to SPH as the differences between the observed and calculated velocities. For this purpose, we use velocities before the start of the transient movement in the middle of 2004 (referred to as "pre-2004" velocities in this paper).

Fig. 1c shows that the velocities of three stations on SPH, Minami–Daitojima, Okino–Torishima, and Hahajima, in the F3 solution (Nakagawa et al., 2009) can be expressed as the clockwise rotation around the Euler pole at (48.5 N 152.6E) of ~0.899 deg./Ma, which is close to the NNR-MORVEL values (46.02 N 148.64E, 0.910 deg./Ma) (Argus et al., 2010). Hahajima, Bonin Islands, is located only ~100 km from the trench, but its velocity suggests that the island is fixed to SPH to a large extent (back-arc rifting does not occur behind the Bonin Islands).

Fig. 1b shows that the observed pre-2004 velocities of four stations in the Izu Islands (Aogashima, Hachijojima, Mikurajima, and Shikinejima) deviate significantly from calculated vectors. The three southern islands (Aogashima, Hachijojima, Mikurajima) show eastward residual velocities (black arrows) of ~1 cm/year. These islands are on the eastern flank of the rift axis, and their residual velocities would reflect E-W tensile strain coming from the back-arc rifting to the west of these islands (red double line in Fig. 1c). This is consistent with the earlier work by Nishimura (2011). In Shikinejima, the northernmost of the four islands, the residual velocity has eastward component coming from the back-arc rifting, but it is somewhat smaller (~0.5 cm/yr) than the other three islands. It also has significant southward component (~1.5 cm/yr), which is due to the north–south compression caused by the collision of the northernmost PH with the Honshu Island (Nishimura, 2011).

2.2. Eastward acceleration of the Izu Islands in 2004

Fig. 2 shows time series of four GNSS stations in the Izu Islands (see Fig. 1b and a for locations). They are expressed in the kinematic reference frame fixed to SPH defined using the pre-2004 velocities of three stations in SPH (Fig.1c). Because SPH is fixed, these stations show persistent eastward velocity (positive trend) throughout the period. In order to avoid the influence of the large-scale intrusion episode that started in 2000 summer of a dike connecting the Kozushima and Miyakejima (Ozawa et al., 2004), the data only after 2001 were used for the two northern stations (Shikinejima and Mikurajima) (Fig. 2b). This intrusion episode, whose duration is indicated as a blue line, did not influence the secular eastward movements of the two southern stations (Hachijojima and Aogashima) (Fig. 2c). Data after the 2011 Tohoku-oki earthquake are not used because large postseismic signals prevail throughout the country. Although a local earthquake swarm in 2002 August at Hachijojima (JMA, 2003) caused a step-like displacement of the Hachijojima GNSS station, its post-rifting transient movement was insignificant (Fig. 2c).

Fig. 2b, c clearly shows that the eastward movements have accelerated significantly in middle 2004. The excessive movement (departure from the extrapolation of the pre-2004 trend) u is a function of Δt, the time after the onset of the event, and can be expressed as

$$u = A \log\left(1 + \Delta t/\tau\right) \quad (1)$$

We used 0.05 year for the time constant τ, for all stations and components, and estimated A for individual stations and components. This time constant τ has been inferred by minimizing the post-fit residuals of the east component time series of Mikurajima. The transient movement

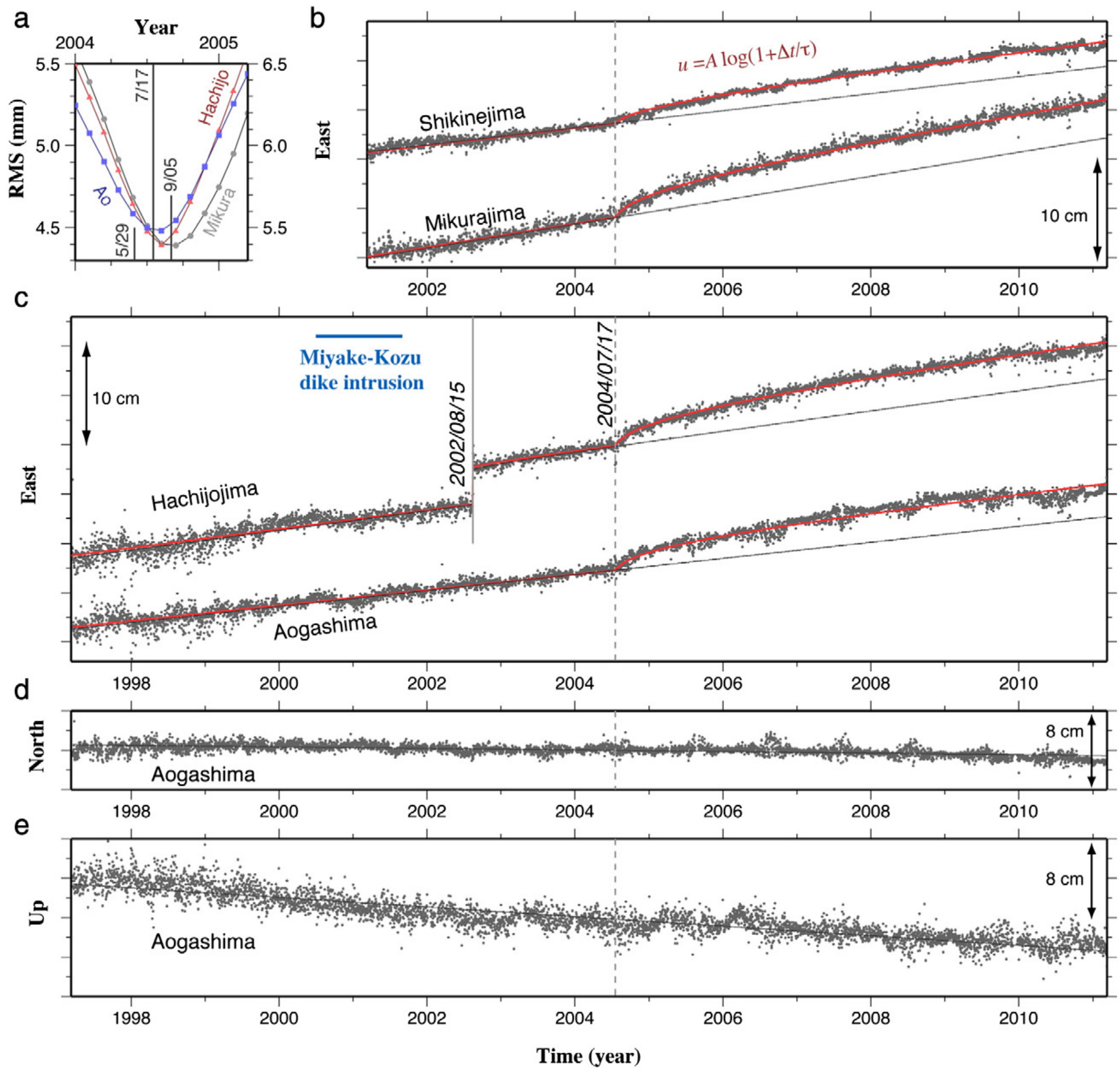

Fig. 2. Time series of four stations in the Izu Islands (see Figs. 1 and 4 for positions) relative to SPH until 2011 March. Eastward acceleration started in the middle of 2004 (b,c). In (a), we compared the root mean squares (RMS) of post-fit residuals of the east component time series (Mikurajima, Hachijojima, and Aogashima) for different onset times of the acceleration, and the three vertical lines show occurrences of three nearby earthquakes in 2004 (epicenters shown in Fig. 1c). We also show that the north (d) and up (e) components of Aogashima do not show significant changes in 2004. Hachijojima shows a step in 2002 August associated with a shallow earthquake swarm that started on Aug. 13 and culminated 2–3 days later (JMA, 2003). In (b), we give the equation used to model the excessive movement *u*. The red curves in (b) and (c) show best-fit models in which we assumed that the transient component started on July 17, 2004. The standard deviations of the individual daily solutions in the six time series are, downward from the top, 3.1 mm, 4.3 mm, 6.0 mm, 6.1 mm, 7.1 mm, and 14.4 mm.

decays in a few years, resulting in ~3 cm excessive eastward movements in 3 years. The selection of τ is not sensitive to the cumulative movements; changing τ to 0.10 year alters the cumulative movement less than 2 mm. The movements lack north and up components (Fig. 2d, e) and are nearly perpendicular to the trench and the rift axes. The limited distribution of the GNSS stations (located one-dimensionally along the volcanic arc) makes the geophysical interpretation of the acceleration non-unique. We will discuss this issue in the next section.

3. Discussion: Geophysical models of the transient crustal movements

3.1. Contemporary seismic events and three hypotheses

Before discussing the mechanism of the transient movement of the Izu Islands, we examine if its start time coincides with a certain earthquake. Fig. 2a compares the post-fit residuals at three stations for various onset times of the transient movement. The observed time series are best explained by an onset time in the middle of 2004, but the time resolution is not better than a month.

In this time window, three relatively large earthquakes occurred near the Izu Islands (epicenters shown in Fig. 1c). The first is the M_w 6.7 interplate thrust event on May 29 close to the Boso triple junction, ~200 km east of the Izu Islands (Eq. (1)). The second is the M_w 5.6 event on July 17, also an interplate earthquake on the subducting PA slab surface, at the Sagami Trough (eq#2). The last one is the September 5–6 earthquake sequence composed of the foreshock (M_w 7.2), the main shock (M_w 7.4), and the largest aftershock (M_w 6.6), off the Kii Peninsula. They occurred within the subducting PH slab, ~250 km west of the Izu Islands (eq#3). Seismic intensities were 2–3 for eq#2 and eq#3, but was 1 for eq#1 in the Izu Islands.

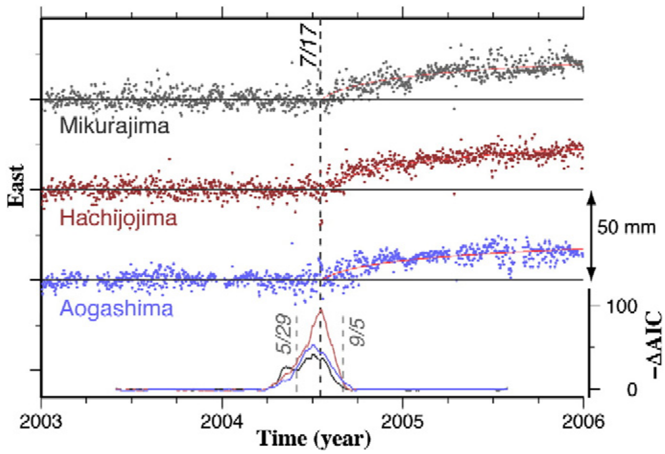

Fig. 3. 2003–2006 east component time series of GNSS stations at Mikurajima (grey), Hachijojima (red), and Aogashima (blue). The significance of the start of a temporary movement inferred as −ΔAIC, obtained using the moving time window of ±150 days, is shown at the bottom with the same colors as the time series. The occurrence times of the three mid-2004 earthquakes possibly related to the temporary movement of the Izu Islands are marked with gray dashed lines. −ΔAIC show peaks closest to the July 17 earthquake.

The eastward transient movement could be explained by three scenarios related to these earthquakes. The first one is that the eastward movement represents the postseismic movement of eq#3 (Hypothesis A). The movement could be also interpreted as the acceleration of the back-arc rifting, or a rifting event, dynamically triggered by eq#2 (Hypothesis B). The eastward movement could also be the afterslip of eq#1 (or an independent SSE) at the Izu–Bonin Trench (Hypothesis C). In Section 3.3, we show that Hypothesis A is unlikely. In Sections 3.4 and 3.5, we will discuss which of the other two hypotheses are more plausible from geophysical points of view.

3.2. Start of the transient crustal movements

Fig. 2a does not have sufficient resolution to identify the exact starting date of the transient movement. Therefore, we further pursue this issue at Mikurajima, Hachijojima, and Aogashima stations by using Akaike's Information Criterion (AIC) (Fig. 3). We first set up a moving time window of the width of ±150 days. We then fit the time series within the window in two different ways, i.e. the first case with a simple straight line and the second case with an SSE starting at the center of the window. The decrease of AIC (−ΔAIC) in the second case gives the measure of the significance of the SSE onset at the center of the window. By moving the window in time (time step was set to 2 days), we expect to get a sharp peak of −ΔAIC at the most likely start time of the transient movements. This is similar to the method Nishimura et al. (2013) and Nishimura (2014) used to detect small SSEs in Japan, and to the method Heki and Enomoto (2015) detected trend changes in ionospheric total electron content. The only difference from these past studies is that they looked for discontinuities (Nishimura et al., 2013) or bending (Heki and Enomoto, 2015) while we look for the start of the change expressed with Eq. (1) in this study.

In Fig. 3, we searched for the −ΔAIC peak in 2003–2006 using the east component of Mikurajima, Hachijojima, and Aogashima. The changes in −ΔAIC (bottom of Fig. 3) show better time resolution than Fig. 2a. The −ΔAIC of Hachijojima shows a clear peak that coincides with the July 17 earthquake (eq#2). The peaks of the other two stations

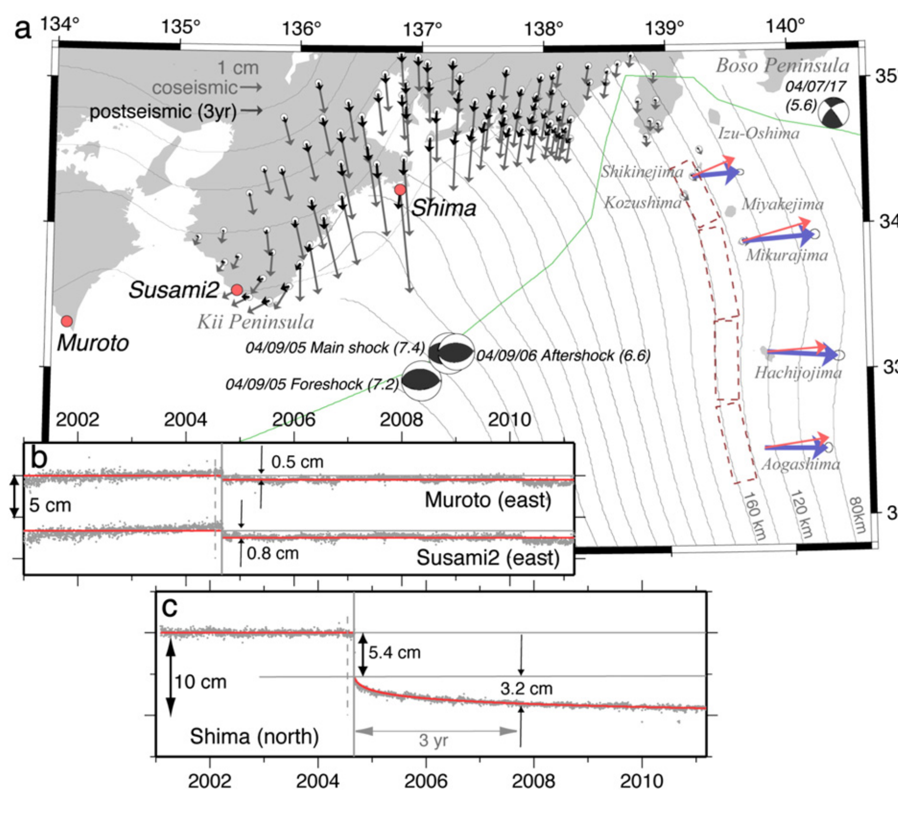

Fig. 4. (a) Blue arrows show 3-year cumulative excessive movements of the four stations in the Izu Islands due to the transient crustal movement starting in July 2004. Red circles in (a) show 3 stations: Muroto, Susami2, and Shima, whose time series are shown in (b) and (c). The solid and dashed vertical lines in the time series indicate September 5 and July 17, respectively. Coseismic crustal movements of the foreshock and the main shock of the 2004 September 5 earthquake sequence off Kii Peninsula are shown with thin gray arrows. Three-year postseismic displacements by the viscoelastic relaxation of the upper mantle with viscosity 10^{19} Pa s (Suito and Ozawa, 2009) are shown with black arrows. Red arrows are the calculated displacements of the four Izu stations by the slips of 4, 10, 12, and 8 cm of the four segments, from north to south, of the normal faults drawn with dashed lines. Contour lines show the depths of the PA slab surface with 20 km interval, and the rift axis is assumed to align between the 140 and 160 km depth contours.

are less clear. They show slightly earlier maxima, but it is difficult to discuss between-island differences of the onset times within a few days.

3.3. Hypothesis A: Postseismic deformation of the 2004 September earthquake sequence

Generally speaking, two major mechanisms of postseismic crustal movements are the afterslip and the viscous relaxation of the upper mantle. Here we discuss if the 2004 Kii Peninsula earthquake sequence can account for the observed eastward transient movement of the Izu Islands. At first, we note that the onset of the transient movement seems to deviate significantly from September 5–6 (Fig. 3). This makes Hypothesis A less likely than the other hypotheses. In addition to this time difference, Fig. 4 provides evidence strong enough to rule out Hypothesis A.

The possibility of afterslip (at a fault patch close to the main shock) can be simply ruled out by comparing the time series in Fig. 2b, c (they show only slow transient movements without significant discontinuous steps) with a point much closer to the epicenter. For example, the Shima GNSS station, Central Japan, showed the largest coseismic step (~5.4 cm, southward) by this earthquake sequence (Fig. 4c). However, its 3-year postseismic movement is only ~3.2 cm (this includes contributions from afterslip and viscous relaxation). This indicates that an afterslip exceeding the main shock in moment release did not occur. If the eastward acceleration of the Izu stations were due to the afterslip of the 2004 earthquake sequence, they should have shown coseismic jumps larger than the 3-year cumulative eastward movements. Fig. 2b, c shows that this is not the case.

Fig. 4a gives coseismic crustal movements of the foreshock and the main shock of the 2004 September 5 earthquake off Southeast Kii Peninsula at GEONET stations, calculated using the fault parameters in Hashimoto et al. (2005) and an elastic half space (Okada, 1992). They are below 1 mm at the Izu Islands, which is consistent with the lack of coseismic steps in the time series (Fig. 2b–d). Such coseismic displacement was small but clear (0.5/0.8 cm) at the Muroto/Susami2 stations (Fig. 4b), ~250/150 km to the west of the epicenters. Observations also show that there were little post-2004 transient movements at Muroto/Susami2 stations, in contrast to the clear transient movements in the Izu Islands (Fig. 2b, c).

We consider that the viscous relaxation cannot explain the eastward transient movement of the Izu Islands (Fig. 2b, c), either. At first, a numerical calculation does not support this. Suito and Ozawa (2009) showed the 3-year postseismic displacement field of this earthquake due to viscous relaxation of the upper mantle with the viscosity of 1×10^{-19} Pa s. They are plotted as black arrows in Fig. 4a. In the Izu Islands studied here, these vectors are ~1 mm or less (~0.97 mm northward in Mikurajima, and ~1.1 mm northwestward in Shikinejima). In contrast, the observed movements (Fig. 2b, c) are eastward and up to a few centimeters there.

By reducing the assumed upper mantle viscosity, we could increase the movements in the Izu Islands. However, this requires that GNSS stations on the opposite side of the epicenter to behave similarly. The Izu stations are located ~250 km to the “east” of the epicenter. The Muroto station, Shikoku, is located ~250 km to the “west” of the epicenters. Fig. 4b shows that Muroto does not show a measurable westward transient movement after 2004 September. If the eastward movement of the Izu Islands was caused by the viscous relaxation of the 2004 Kii Peninsula earthquake, a similar westward movement should emerge at Muroto. This is obviously not the case.

Fig. 4b also shows that the Susami2 station, located only ~150 km WNW of the epicenters, jumped westward by ~8 mm in the earthquakes but exhibit little postseismic transients. Unless we significantly

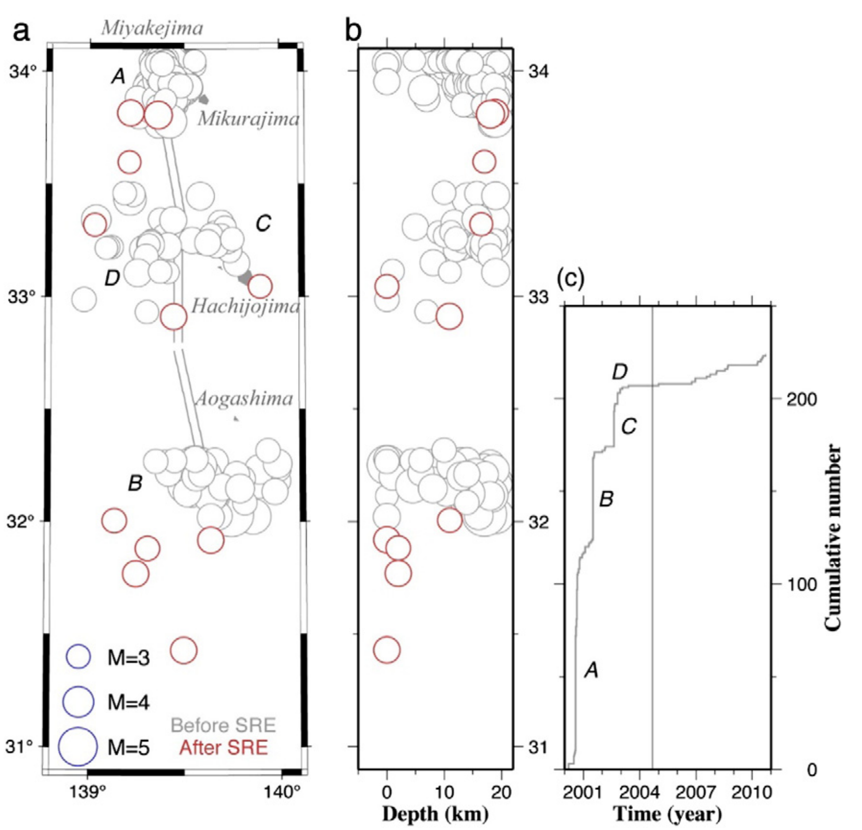

Fig. 5. Distribution of M ≥ 3 earthquakes 2000–2010 in the Izu Islands from Japan Meteorological Agency catalog (Kei Katsumata, pers. comm.) in a horizontal map (a) and cross-section (b). There are earthquake swarms north of Mikurajima (A, 2000), south of Aogashima (B, 2001), and beneath Hachijojima (C, 2002) and west of Hachijojima (D, 2002–2003). The cumulative number of earthquakes shown in (c) does not show notable change after the mid-2004 onset of the transient crustal movement in the Izu Islands (vertical solid line). The approximate position of the back-arc rift axis is shown with double lines.

assume non-uniform upper mantle viscosity, viscoelastic relaxation following the 2004 earthquake sequence would not be able to explain the eastward acceleration of the Izu Islands. We also note that co-existence of the stations with and without transient movements excludes the reference frame problem, i.e. leakage of the movement(s) of fixed reference point(s) used in the F3 solution, is not responsible for the observed transient movements.

3.4. Hypothesis B: A slow rifting event triggered by a nearby earthquake

This transient movement accelerates the secular eastward velocity caused by the back-arc rifting. Hence, it could be interpreted as a temporary activation of the rifting, or a rifting event. Lack of clear discontinuities in the time series (Fig. 2b, c) suggests that the whole sequence proceeded as a slow event. Hence, we tentatively call it a slow rifting event (SRE) analogous to SSE.

Fig. 3 suggested that the onset of this movement seems to coincide with eq#2, i.e. the July 17 M_w5.6 earthquake at the Sagami Trough. An earthquake could trigger rifting by two mechanisms, i.e. by static and by dynamic stress perturbations. Both of eq#1 (May 29) and eq#2 (Jul. 17) cause static stress changes that encourage the rifting event. However, the E-W tensile stress increase at the rift axis by the larger event (eq#1) is only ~1 kPa, and dynamic triggering by the shaking would be more likely. It is known that SSEs in convergent plate boundaries are often dynamically triggered by seismic waves from remote earthquakes (e.g. Itaba and Ando, 2011). The seismic waves from eq#2 (seismic intensity was 2 at Hachijojima and Aogashima, and 3 in Mikurajima (JMA, 2004)) might have dynamically triggered the SRE in the Izu back-arc.

A rifting event in a young continental rift involves both normal faulting and magmatism in the shallower and deeper parts, respectively (e.g. Calais et al., 2008). The Izu back-arc rifting is also a young rift, and both of them may have occurred in this episode. However, strain partitioning between them cannot be constrained with the limited geodetic data in this case (the GNSS stations are only on the east side of the source at similar distances from the rift axis).

For example, the eastward movements of 3–4 cm of the Izu Islands can be explained as the response of an elastic half space to the intrusion of a dike extending by 200 km or more along the axis of back-arc rifting. There, if the dike extends from surface to the depth of 10 km, the rifting of 4–20 cm in 3 years would explain the observed eastward displacements. It is noteworthy that several earthquake swarms preceded the SRE in this region. After the major dike intrusion between the Miyakejima and Kozushima (Ozawa et al., 2004) in 2000 summer, there were swarm activities to the south of Aogashima in middle 2001, west of Hachijojima from 2002 to 2003 (Fig. 5). However, the seismicity did not increase along the rift axis after the start of the middle 2004 transient movement (Fig. 5). Therefore, this possible SRE would not have been associated with simultaneous dike intrusions at depth.

Fig. 4 shows that slow slips along a long normal fault running above the rift axis can also explain the eastward movements. Four fault segments dipping eastward by 30 degrees from surface to 10 km depth, with the slip of 7, 15, 15, 12 cm, from north to south, can reproduce the observed displacements. We emphasize that the model of the deformation source is not unique, i.e. we do not have information to further constrain the source of deformation. For example, if the faults extend down to 20 km, half of the slip would make similar displacement fields.

The causal relationship between these earthquake swarms in 2000–2003 and the possible SRE is unknown. Fig. 2 shows that the earthquake swarms did not cause significant surface movements in these islands. The only exception is the 2002 August swarm activity in Hachijojima, which caused eastward jump of the GNSS station of a few centimeters. This event was, however, not followed by immediate post-rifting transient movements. On the other hand, lack of such jumps before the onset of the 2004 acceleration suggests that large-scale dike intrusions did not take place immediately before this hypothetical SRE.

Considering these points, the post-2004 eastward acceleration of the Izu Islands would not be the post-rifting stress diffusion as seen in NE Iceland after the Krafla rifting episode (e.g. Heki et al., 1993). However, these minor intrusion events in 2001–2003 may have localized the strain with magmatic heat and enhanced east–west tensile stress in the overlying lithosphere. This may have made it sensitive to dynamic stress perturbations, and slow normal faulting may have been triggered in the shallow part of the back-arc rift axis in response to the seismic wave of the 2004 July 17 earthquake (Eq. (2)).

3.5. Hypothesis C: A large SSE to the east

As the third hypothesis, we examine the possibility that the eastward transient movements were caused by an interplate large SSE (silent earthquake) at the Izu–Bonin Trench. The May 29 M_w 6.7 earthquake (Eq. (1)) near the Boso triple junction (Fig. 4) did not cause coseismic displacements exceeding 2 mm in the Izu Islands, which is consistent with the lack of discontinuities in the time series (Fig. 2). If its afterslip area has expanded southward covering N-S extent >200 km, it would let all the four islands move eastward as seen in Fig. 2b, c. Such an expansion of the afterslip area may also have occurred

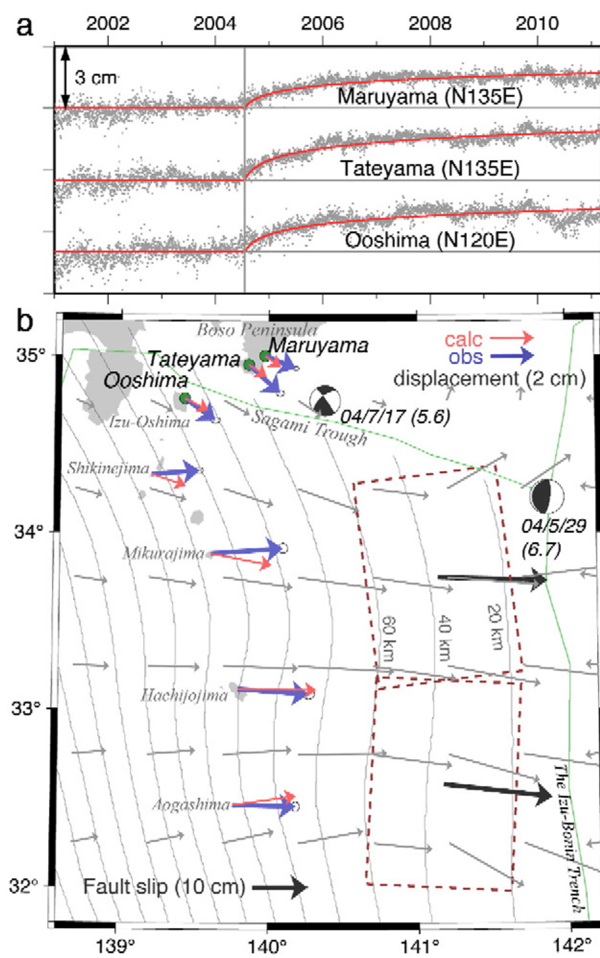

Fig. 6. (a) De-trended time series of southeast (N135E) component of Tateyama and Maruyama, and the south-southeast (N120E) component of Ooshima stations. Blue arrows in the map (b) show 3-year cumulative excessive movements of the GNSS stations due to the transient movements starting in mid-2004. Green circles in (b) show the three stations whose time series are given in (a). The solid vertical line in (a) indicates 2004 July 17. Contour lines show the depths of the PA slab surface with 20 km interval, and the SSE of 20 cm dislocation is assumed to have occurred at the PA slab surface with depths 20–60 km (two rectangles drawn with red dashed lines). Thin gray arrows are calculated displacements at grid points by this hypothetical SSE.

in the down-dip direction, which might have induced eq#2, the July 17 Sagami Trough earthquake. Generally speaking, SSEs could start without triggering earthquakes (Rubinstein et al., 2009), and the lack of such candidate seismic event would not be a problem in Hypothesis C.

Fig. 6b shows that fault patches on the PA slab surface, with the total length of 260 km (or more), could cause fairly uniform eastward motions of Mikurajima, Hajijojima, and Aogashima. We assumed 100 km width of the fault patch with depth range of 20–60 km. This depth corresponds to those of the SSEs repeating beneath the Bonin Islands further to the south (Arisa and Heki, 2015). We assumed 20 cm slip of the faults in the direction of plate convergence (N84 W). With the shear modulus of 40 GPa, this corresponds to the total M_w ~ 7.5. Needless to say, this model is non-unique. For example, even if we decrease the depth range of the fault, similar surface displacements in the Izu Islands would be realized by increasing the slip. Although the amount of necessary slips depends on the location of the slipped patch, the required moment release would remain within ± 0.1 in M_w. After all, the total M_w keeps fairly robust against such non-uniqueness.

According to the scaling law of slow slips (Ide et al., 2007), an SSE of M_w 7.5 would occur over a timescale of 1–2 years, which is consistent with our observations (Fig. 2). By this slip, Aogashima is expected to subside by ~8 mm. This is, however, not large enough to be detected because the post-fit residual of the time series is larger than this value (Fig. 2e).

Fig. 6a shows time series of three additional GNSS points (Ooshima in Izu-Oshima, and Tateyama and Maruyama in the southern part of the Boso Peninsula). Because these stations are near (the first) or beyond (the second and the third) the plate boundary (Sagami Trough), we removed the pre-2004 trends from the entire time series in Fig. 6a to isolate the transient components. They show clear southeastward transient movements starting in the middle of 2004. Their movements are similar to those expected by this possible SSE. The observed vectors exceed the calculated ones in the Boso Peninsula stations, and this suggests that the actual slip was non-uniform and was larger in the northern part of the fault. Considering that the SRE in Hypothesis B cannot move the two Boso Peninsula stations more than 1 mm, we consider Hypothesis C more likely than Hypothesis B.

The SSE shown in Fig. 6 is the largest ever observed in Japan. There are several series of repeating long-term SSEs in various places in Japan, e.g. southwest Ryukyu (average M_w 6.6) (Heki and Kataoka, 2008), Hyuganada (M_w 6.7–6.8) (Yarai and Ozawa, 2013), and the Boso Peninsula (M_w 6.6) (Ozawa et al., 2007). The SSE that started in 2000 off the Tokai district, Central Japan, had been considered the largest SSE in Japan, but its M_w has recently been revised downward from 7.0–7.1 to 6.6 (Ochi and Kato, 2013). The SSE repeating every 6–7 years beneath the Bungo Channel would then be the largest SSE observed in Japan. For example, Ozawa et al. (2013) estimated the fault dimension of 100×100 km and the slip 10–30 cm (M_w 7.0–7.1) for those in 1997, 2003, and 2010.

The SSE in Fig. 6 is ~4 times as large in seismic moment as the Bungo Channel SSEs. Outside Japan, one of the best-studied repeating SSEs would be those in the Cascadia subduction zone, Canada. They have M_w 6.3–6.8 (Szeliga et al., 2008). The SSE shown in Fig. 6 is comparable only to the M_w 7.5 silent earthquake that occurred in the Guerrero seismic gap, Mexico, in 2001 (Kostoglodov et al., 2003).

The slip accumulation rate of repeating SSE should not exceed the plate convergence rates. The PA–PH plate convergence rate in this region is ~49 mm/yr. If we assume 20 cm slip by an SSE, their average recurrence should not be less than 5 years. The 2004 event is the only transient eastward movement episode in the observed time span (1997–2015), and the percentage of slips accommodated by repeating SSE would not be large in the northernmost Izu–Bonin Arc.

4. Concluding remarks

Among the three hypotheses given in the previous chapter, we consider Hypothesis C the most likely and Hypothesis A the least likely. Nevertheless, the idea of SRE in Hypothesis B is still attractive considering that Hypothesis C requires the occurrence of a very large (M_w 7.5) SSE and that the onset time (Fig. 3) favors Hypothesis B. The problem

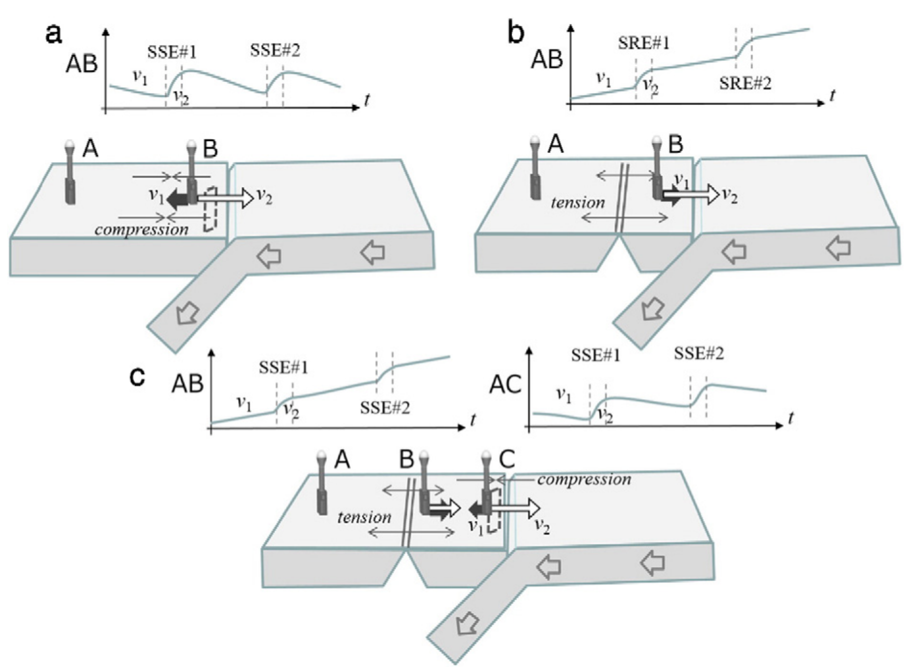

Fig. 7. Schematic illustration of the movement of a GNSS point B relative to point A (distance between A and B) on an island arc in response to episodic occurrences of SSE (a) and SRE (b). The velocities are drawn relative to the reference point A. The black and white arrows are velocities in interseismic (inter-rifting) times (v_1) and during the events (v_2). The top panels of (a, b) show the trenchward movement of the point B relative to the reference point A (length of AB). Reversal (a) or acceleration (b) occurs during the events. In the case (c), SSE is assumed to recur in a subduction zone where both active back-arc rifting and interplate coupling at the trench co-exist. Both B and C move trenchward during SSE, while the polarity of v_1 (interseismic velocity) depends on the distance from the trench.

will be finally solved when the ocean floor movement of the next event is monitored with a submarine benchmark located somewhere between the Izu Islands and the Izu–Bonin Trench. The mixture of Hypotheses B and C will also be possible, i.e. the SRE and SSE, to the west and east of the Izu Islands, respectively, may have occurred simultaneously encouraging each other.

Fig. 7a depicts hypothetical cycles of SSE in a subduction zone without back-arc spreading. Secular landward movements of the fore-arc would develop east–west compressional stress within the lithosphere. This accumulation eventually leads to the fault slip at the trench (SSE in this case). Fig. 7b shows hypothetical recurrence of SRE in a young back-arc rifting axis. Secular trenchward movements of the fore-arc would develop east–west tensile stress within the lithosphere. This accumulation eventually leads to the failure of the rocks at the axis and would let an SRE start and release accumulated tensile stress. Hypothesis C of the present case corresponds to Fig. 7c, i.e. SSE occurs at the trench in a subduction zone with active back-arc rifting. In this case, inter-event velocity at a station close to the rift (Point B in Fig. 7c, and the Izu Islands correspond to this) would be trenchward (eastward) and SSE causes further movements in the same direction. However, if there is an island closer to the trench (Point C in Fig. 7c), its inter- and co-event movements would be different from Point B.

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