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FULL PAPER

New hypothesis to explain Quaternary forearc deformation and the variety of plate boundary earthquakes along the Suruga–Nankai Trough by oblique subduction of undulations on the Philippine Sea Plate

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Abstract

Plate-boundary earthquakes of magnitude 8 or greater along the Suruga–Nankai Trough subduction zone have repeated at intervals of 90–150 years, but with widely varying magnitudes and rupture areas. We propose, based on geologic data on crustal movements of the forearc wedge, that these earthquake variations are controlled by two separate locked zones in the deeper part of the plate boundary. Long-wavelength topographic undulations, composed of alternating zones of uplift and subsidence along the forearc wedge, are associated with 2000 to 3000 m of vertical relief that has accumulated during Quaternary time. We suggest that this crustal deformation in the forearc wedge is caused not by stress loading and release during earthquake cycles, but rather by vertical displacements of the plate boundary caused by the westward movement of undulations in the obliquely subducting slab of the Philippine Sea Plate as it subducts beneath Southwest Japan. Dating of emergent marine shell fossil assemblages shows that the Kii Mountains, an uplift zone at the midpoint of the trough, has undergone uplift events at intervals of 400–600 year, and the latest event of those occurred when the 1707 Hoei earthquake ruptured the entire plate boundary along the trough. We infer that the plate boundary under the Kii Mountains is a locked zone and that slips of this zone, which accompanied ruptures of the entire plate boundary, caused uplift of the mountains by decreasing the plate boundary depth. A similar locked zone is inferred under the uplift zone of the Akaishi Mountains, along the eastern margin of the trough, and the 1854 Ansei earthquake pair was presumably caused by the slip of this zone. During the two 1854 events, the locked zone under the Kii Mountains presumably restricted the rupture propagation to the eastern half of the trough, then a rupture of the western half of the trough followed within 32 h. These locked zones are inferred to slip independently every few hundred years and determine the major patterns of characteristic ruptures along the Suruga–Nankai Trough.

Keywords: Nankai trough, Suruga trough, Philippine Sea Plate, Earthquake cycle, Quaternary crustal movement, Oblique subduction, Undulations of slab geometry

Introduction

The Philippine Sea Plate (PSP) has been subducting under Southwest Japan at the rate of 3–7 cm/year from the Suruga–Nankai Trough (Heki and Miyazaki 2001), and great plate-boundary earthquakes of magnitude (M) 8 and greater have been repeating at an interval of

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90–150 year along the trough (Ishibashi and Satake 1998; Ishibashi 2004). However, the rupture areas and magnitudes of these earthquakes differ widely. The Kii Mountains, at the midpoint of the trough, have often been a boundary between rupture areas in the eastern and western parts of the trough, although sometimes the entire trough ruptures in larger earthquakes. The differences in rupture areas have been explained in terms of a division of the plate boundary into four or five segments, in which ruptures extending through two or more segments cause a wide range of large earthquakes (Ando 1975; Ishibashi 2004), although the factors controlling the patterns of these earthquakes are not clear.

Variable earthquake ruptures have been reproduced by 3D numerical simulations of earthquake cycles incorporating frictional parameters and stress conditions for a subducting PSP slab that has an undulating form (Hori et al. 2004; Hyodo and Hori 2013). Although these studies have suggested that undulations in the slab are one important reason for the variety of great earthquakes, they have not successfully reproduced the historical series of earthquakes.

In this paper, we show that the crustal movements of the forearc wedge during the last 10^3 to 10^6 year have not been caused by earthquake cycles and that the uplift and subsidence of the large-scale N–S trending zones in the middle and eastern parts of the forearc wedge can be explained by passage beneath the wedge of large-scale undulations on top of the obliquely subducting PSP slab. We propose on the basis of correlations between historical earthquakes and crustal movements that the variation in magnitudes and rupture areas of great earthquakes is largely controlled by two major locked zones that are related to the undulating geometry of the slab.

Geologic structure of southwest Japan

The southwestern Japan arc is underlain mainly by pre-Neogene basement rocks that are divided into the Outer and Inner zones, separated by the Median Tectonic Line (Fig. 1). The Inner zone on the north side comprises Mesozoic and older accretionary prism rocks, plutonic rocks and high-temperature metamorphic rocks, and the Outer zone on the south side is composed mainly of Mesozoic to Paleogene accretionary prism rocks and high-pressure metamorphic rocks (Ito et al. 2009).

In the Inner zone, several elongated basins oriented NE–SW to ENE–WSW developed in Pliocene time, and the Inner zone has been deformed during Quaternary by many active faults that have generated tectonic ridges and modified the basins (Huzita 1980; Sugiyama 1992; Itoh et al. 2000). These active faults include N–S trending reverse faults and NE and NW trending strike–slip faults generated by E–W to ESE–WNW compressional stress, which are consistent with focal mechanisms of earthquakes in the upper crust of the Inner zone (Tsutsumi et al. 2012). Right-lateral motion on the Median Tectonic Line is active to the west of the Kii Mountains, but is absent to the east (Nakata and Imaizumi 2002). In the Outer zone, active faults are rare, whereas zones of uplift and subsidence define large-scale topographic undulations along the arc, with wavelengths of 100 to 200 km and amplitudes of 2000 to 3000 m, that have been growing during the Quaternary (Otsuka 1931; Watanabe 1932; Research Group for Quaternary Tectonic Map 1968). Deformation styles are very different in the Inner and Outer zones, and we mainly consider the deformation of the Outer zone in this paper.

The undulating topographic profile of the Outer zone consists of major uplift zones in the Akaishi, Kii and Shikoku Mountains and depressions in the Kii and Irako Straits (Fig. 1). Ise Bay, Nobi Plain and Osaka Bay are depressions in the Inner zone. The Akaishi Mountains, trending N–S and reaching elevations of about 3000 m, are at the east end of the Suruga–Nankai Trough facing the collision zone between the Izu-Ogasawara and Japan arcs. The NNE–SSW trending Kii Mountains reach elevations of 2000 m, and the uplift zone extends northward into the Inner zone. The Shikoku Mountains also reach elevations of 2000 m, but trends ENE–WSW, parallel to the arc. Two N–S trending uplift zones extending to the south from the Shikoku Mountains form the Capes Muroto and Ashizuri. Although Pliocene and Quaternary sediments are of limited distribution, elevations of erosional flat surfaces in these mountains suggest that they have undergone more than 1000 m of uplift since the Late Pliocene or Early Quaternary (Research Group for Quaternary Tectonic Map 1968; National Research Center for Disaster Prevention Science and Technology Agency 1973). Ohmori (1987, 1990) used the relationship between erosion rate and elevation to infer uplift rates as high as 7 mm/year and 2.5 mm/year in the Akaishi and Shikoku Mountains, respectively. The Kii Mountains, with elevations similar to the Shikoku Mountains, are inferred to have similar uplift rates (2.5 mm/year). The two topographic depressions forming straits in the Outer zone were first submerged below sea level in the Early-to-Middle Pleistocene, as recorded by intercalated marine sediments in the Late Pliocene to Pleistocene lacustrine sediments in and around the Osaka Bay (Itoh et al. 2000) and the Ise Bay (Mori 1980; Sugai et al. 2016).

The offshore forearc slope south of the Outer zone is divided into forearc basins, outer ridges, an accretionary prism and the Suruga–Nankai Trough (Fig. 1b; Yonekura 1983; Okino and Kato 1995). The N–S trending uplifts extend offshore into the forearc (Okamura and Joshima 1986; Okamura et al. 1987, 1998; Okamura

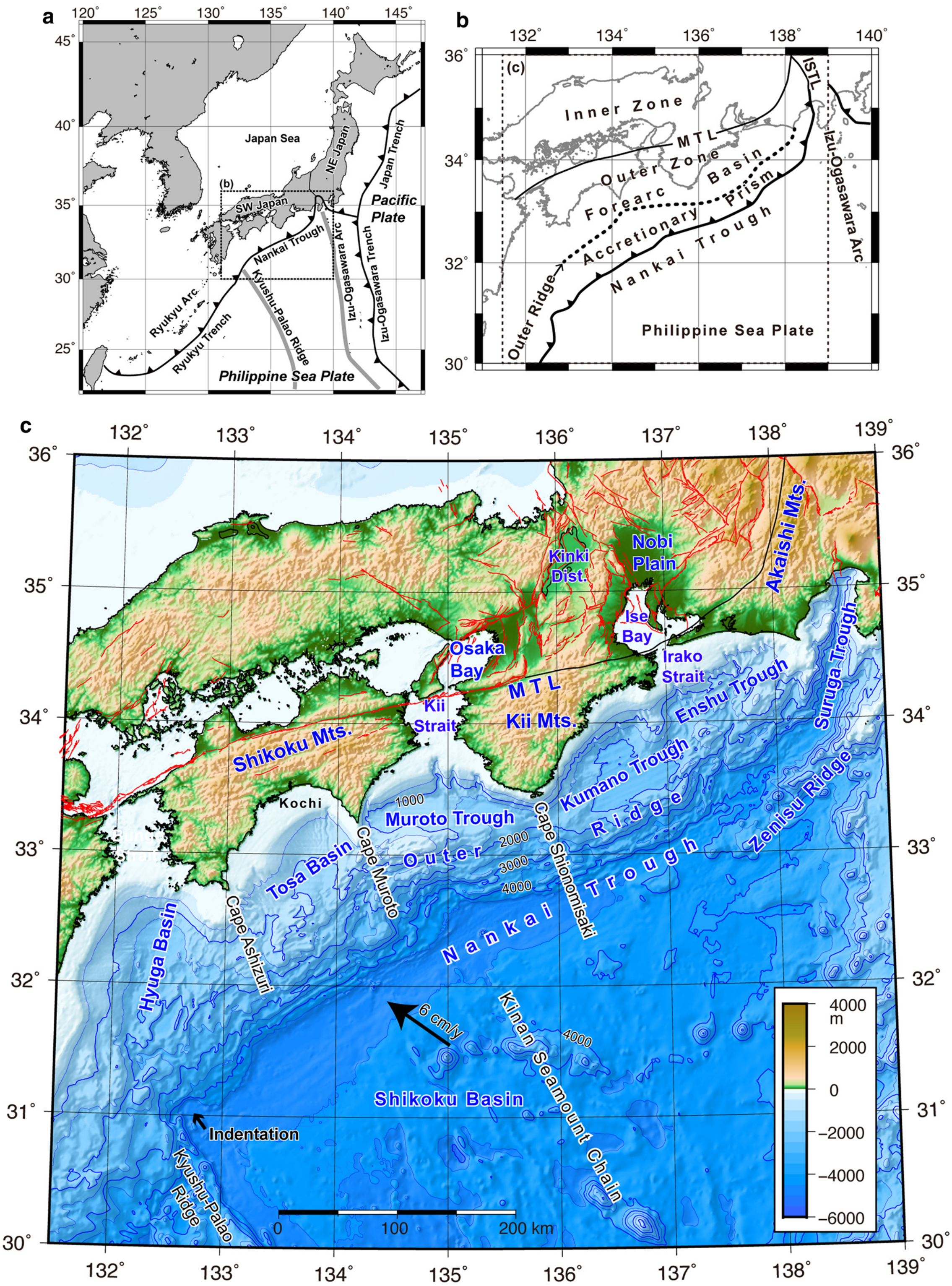

Fig. 1 Location and topography of the Suruga–Nankai Trough and Southwest Japan. **a** Location map and plate tectonic setting of the study area. **b** Tectonic zones of the southwestern Japan arc. MTL, Median Tectonic Line; ISTL, Itoigawa–Shizuoka Tectonic Line. **c** Shaded topography and bathymetry of Southwest Japan. Red lines are active faults modified from the Active Fault Database of the Geological Survey of Japan (https://gbank.gsj.jp/activefault/). The arrow shows the direction of plate convergence

1990; Sugiyama 1992) and define several basins, named from east to west the Enshu, Kumano and Muroto Troughs and the Tosa and Hyuga Basins (Fig. 1c). Okamura (1990) and Okamura and Blume (1993) analyzed seismic profiles south of Shikoku to reveal the detailed structure of the Pliocene to Quaternary sediments in the forearc basins and offshore uplift zones (Fig. 2). The landward shelves and slopes of the forearc basins are underlain by progradational sequences of Quaternary sedimentary units, the lowest of which have subsided to depths greater than 500 m below sea level. The uplift zones off Capes Muroto and Ashizuri separating these basins and the NE–SW trending outer ridges defining their seaward margins are composed of folded and faulted Pliocene sediments that are unconformably overlain by Quaternary sediments in the forearc basins, which show downward-increasing inclinations on the slopes of the ridges. This structural evidence indicates that the offshore basins and ridges have been growing mainly during the Quaternary (Okamura 1990; Okamura and Blume 1993).

The accretionary prism is 50–100 km wide and develops along the trough and its top corresponds to the outer ridge at water depths of 200 to 2000 m (Okino and Kato 1995). The Suruga–Nankai Trough is a continuous depression that increases in depth from 2000 m in the northeast to 4800 m in the southwest (Fig. 1c). The accretionary prism and outer ridge are deformed by subduction of a seamount southeast of Cape Muroto (Yamazaki and Okamura 1989; Okino and Kato 1995; Kodaira et al. 2000) and by subduction of a ridge east of the Kumano Trough (Kodaira et al. 2003; Park et al. 2004).

Philippine Sea Plate

The geometry of the plate boundary, the upper surface of the subducting PSP slab, under the southwest Japan arc has been modeled from seismicity, velocity structure and seismic reflection data (Baba et al. 2002; Hori et al. 2004; Hirose et al. 2008). Although these models differ somewhat, they agree in showing that the plate boundary consisting of alternating ridges and troughs, trending highly obliquely to the Suruga–Nankai Trough, that define large-scale undulations with wavelengths of about 200–250 km along the strike of the trough (Fig. 3). Major ridges lie under Shikoku, northwest of Ise Bay and north of the Izu Peninsula, and troughs lie under the western Kii Mountains and east of Ise Bay. These plate boundary features appear within the subduction zone under the southwestern Japan arc and increase in amplitude with depth (Fukahata 2019). No undulations of the slab are observed to the west of the Suruga–Nankai Trough (Fig. 3), where the NNE–SSW striking plate boundary dips steeply WNW beneath the Ryukyu arc. The slab reaches 350 km depth and is inferred to be anchored in the mantle (Lallemand et al. 2001; Hayes et al. 2012).

The slab under Southwest Japan corresponds to the northern extension of the Shikoku basin, a back-arc basin of the Izu-Ogasawara arc that opened during 28 to 15 Ma (Okino 2015). The basin has symmetric magnetic anomalies with the fossil spreading center trending in NNW, on which the Kinan Seamount Chain lies (Figs. 1c, 3). The northern extension of the seamount chain passes under eastern Shikoku, and one of these seamounts is subducting under the accretionary prism off Cape Muroto (Yamazaki and Okamura 1989; Kodaira et al. 2000).

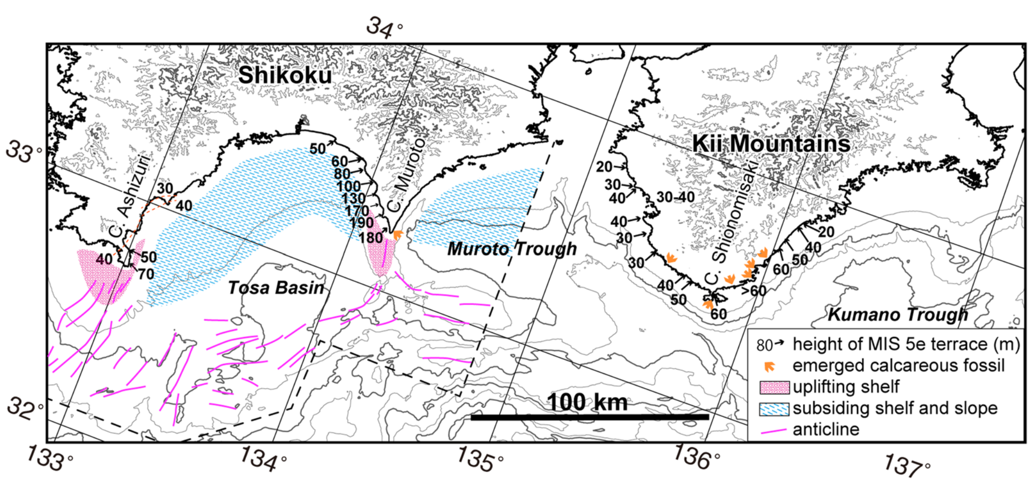

Fig. 2 Offshore geologic structure and marine terrace height in Shikoku and the Kii mountains. Offshore geologic structures south of Shikoku (within the dashed line) are simplified from Okamura (1990). Heights of the MIS 5e marine terrace are from Koike and Machida (2001). Locations of emergent fossil assemblages are from Maemoku (2001) and Shishikura et al. (2008)

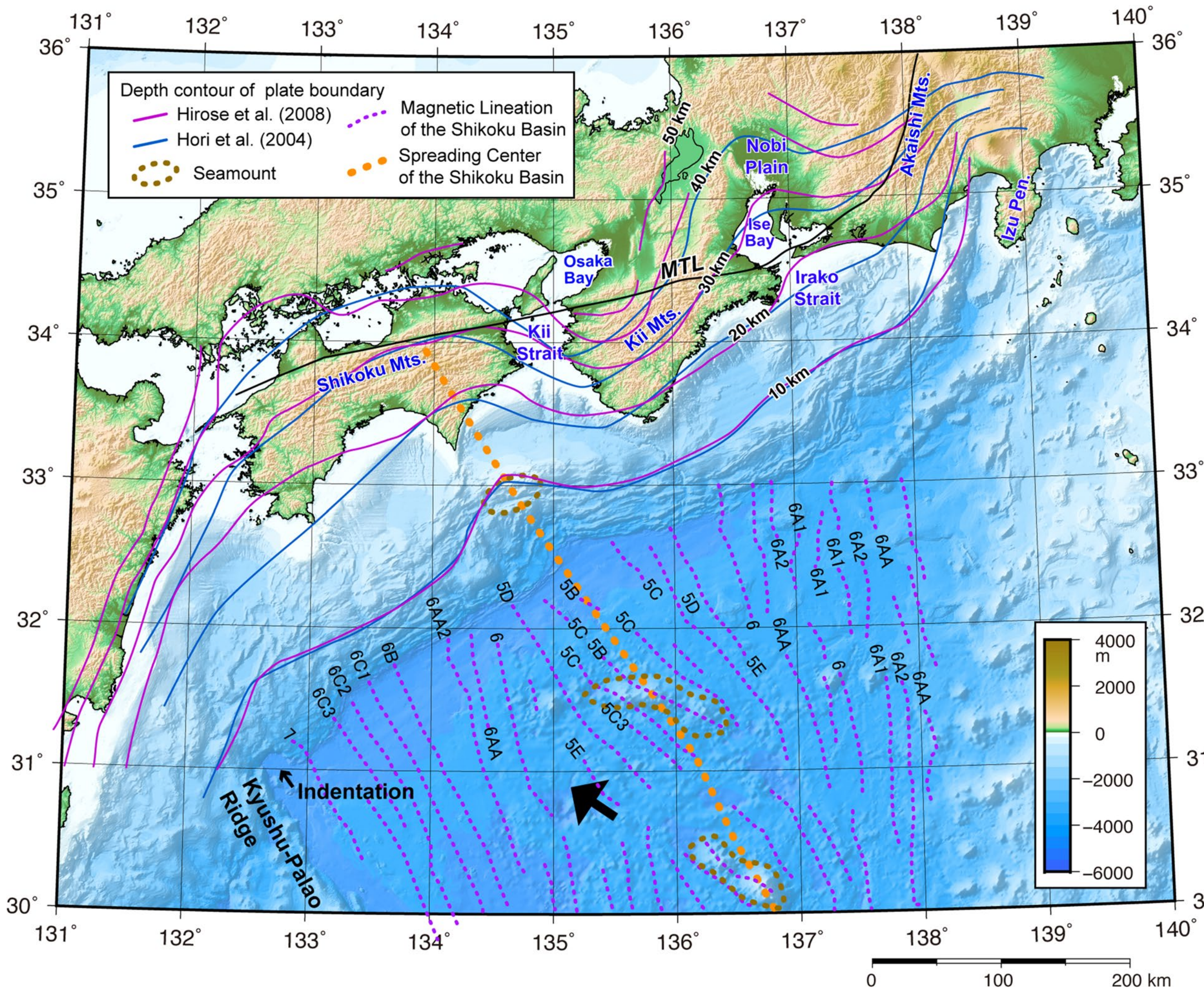

Fig. 3 Depth contours of the plate boundary (Hori et al. 2004; Hirose et al. 2008) and magnetic lineations in the Shikoku Basin (Okino 2015). The fossil spreading center of the Shikoku basin is inferred to extend beneath eastern Shikoku (orange dotted line). Seamounts (brown dotted line) are members of the Kinan Seamount Chain along the spreading center

The PSP is inferred to have changed its direction of motion from N to NW during the Pliocene (e.g., Seno and Maruyama 1984; Sugiyama 1992; Itoh et al. 2000) or Pleistocene (Sato et al. 2015; Nakamura et al. 1984). These different age estimations are based on different types of tectonic movement in different areas. We presume that the plate motion direction changed gradually during 5 to 1 Ma and that various tectonic movements in the upper plate occurred asynchronously in response to the specific state of stress at particular places and times. Thus, we ascribe the growth of the NE–SW to N–S elongated basins and ridges in the Inner and Outer zones and forearc basins to this change of the PSP motion.

Plate boundary earthquakes

Historical documents record nine series of great earthquakes ($M \geq 8$) since AD 684 along the Suruga–Nankai Trough in (Ishibashi and Satake 1998; Ishibashi 2004). Their recurrence intervals of these series are 203–265 year before the fourteenth century and 90–147 year after the fourteenth century (Fig. 4). It is not clear whether this difference reflects a true change in intervals or an imperfect historical record. In addition, four of the earthquakes before the sixteenth century (all except the 1096 and 1099 events) have reliable records of the ruptures only in the eastern or western part of the trough, although indirect historical, archeological and geological evidence suggests that the ruptures extended to the

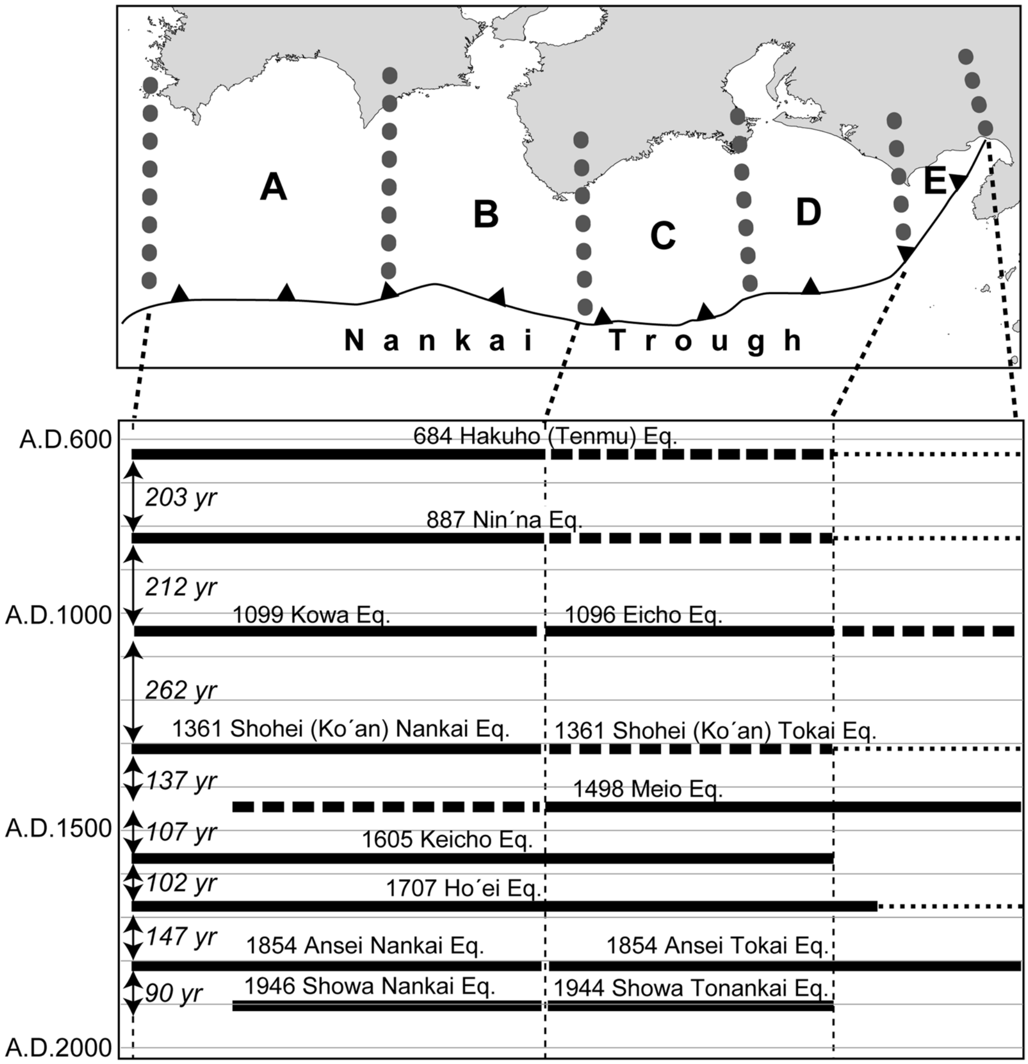

Fig. 4 Ages and rupture areas of historical earthquakes of the Suruga–Nankai Trough. The Suruga–Nankai Trough is divided into A to E segments. Solid lines are rupture areas from Ishibashi and Satake (1998), broken lines are probable ruptures from Ishibashi (2004), and thin dotted lines in segment E are possible ruptures from Ishibashi (2004)

other end of the trough. Three series, in 1096 and 1099, 1854, and 1944 and 1946, occurred as pairs of ruptures in which the first was east of the Kii Mountains and the second was west of the range. The 1707 Hoei earthquake was caused by a rupture of the entire Nankai Trough. It has been proposed, but not confirmed, that the earthquakes in 887, 1361 and 1498 were also caused by a rupture of the entire trough. The 1605 earthquake is inferred to have been a tsunami earthquake because there are few historical records of damage due to ground shaking. Magnitude estimates of these earthquakes range from M7.9 for the 1944 Showa Tonankai earthquake to M8.6 for the 1707 Hoei earthquake (Usami 2001).

The wide variations in magnitudes, intervals and rupture areas of these earthquakes have been attributed to ruptures on different combinations of five plate-boundary segments (Fig. 4). However, Seno (2012) compared seismic intensities, tsunami heights and crustal movements of the 1707, 1854, 1944 and 1946 events and showed that the asperities of the 1707, 1944 and 1946 earthquakes were in the middle part of the trough around the Kii Mountains and those of the two 1854 earthquakes were in the eastern and western parts of the trough, respectively. Seno proposed that these earthquakes can be grouped into Hoei and Ansei types, respectively, from the difference in their asperities and proposed that they repeat independently at intervals greater than 350–400 years.

Crustal movements

Crustal movements related to earthquake cycles

Crustal deformation of the Southwest Japan arc has been observed by leveling and triangulation surveys since the late nineteenth century (Sagiya and Thatcher 1999) and by satellite geodetic measurements during the last about 20 years (Kimura et al. 2019). These data indicate NW–SE contraction and southward-tilting subsidence of the forearc due to strong coupling on the plate boundary during interseismic periods.

Coseismic crustal movements during the 1944 Tonankai and 1946 Nankai earthquakes consisted of horizontal motion toward the southeast and landward-tilting uplift on the forearc wedge, and these deformations are interpreted to be due to the release of strain accumulated during the interseismic period (Ando 1975; Sagiya and Thatcher 1999; Ito and Hashimoto 2004). Uplifts were 1.3 m at Capes Muroto and 0.7 m Shionomisaki (Usami 2001).

Late pleistocene crustal movements

In the same area where these coseismic and interseismic deformations have been observed, marine terraces of Middle-to-Late Pleistocene age that indicate coastal uplift are widespread along the Pacific coast (Fig. 2). Their elevations decrease to the north from the southern promontories of the Kii and Shikoku Mountains. Terraces correlated with Marine Isotope Stage (MIS) 5e along the coast of the Kii Mountains have a maximum elevation of 68 m about 15 km northeast of Cape Shionomisaki and decrease to 30 m at about 55 km northeast and at about 30 km northwest of the cape (Yonekura 1968; Koike and Machida 2001). At Cape Muroto, the maximum elevation of the MIS 5e terraces is about 190 m, decreasing to 50 m about 50 km northwest of the cape (Yoshikawa et al. 1964; Koike and Machida 2001). At Cape Ashizuri, the highest MIS 5e terrace is at 75 m high, decreasing to 30 m at about 40 km northeast of the cape (Ota and Odagiri 1994; Koike and Machida 2001). Assuming a terrace age of 125 ka, the estimated uplift rates of the terraces in the southeastern coast of the Kii Mountains and Cape Muroto and Cape Ashizuri are about 0.5, 1.5 and 0.6 m/kyr, respectively.

Yoshikawa et al. (1964) estimated that the coseismic uplift of Cape Muroto during the 1946 earthquake was greater than the interseismic subsidence, and they proposed that the resulting net uplift accounts for the emergence of the Pleistocene terraces. However, Watanabe (1932) and Tsuchi (1975) proposed that N–S trending uplift zones represented by the Kii Mountains and Capes Muroto and Ashizuri have been growing throughout the Quaternary in the Outer Zone, and they attributed the tilting to this uplift. Elevation data from the coastal terraces alone cannot confirm whether their uplift has been caused by the northward tilting or the growth of N–S trending uplift zones; however, the latter cause is strongly supported by the offshore structure of the N–S trending zones of uplift and subsidence around Capes Muroto and Ashizuri (Okamura 1990).

Holocene crustal movements

Detailed crustal movements during the last several thousand years have been revealed by analyses of assemblages of calcareous fossils exposed above sea level on the coasts around Cape Muroto (Maemoku 2001) and Cape Shionomisaki (Shishikura et al. 2008). The assemblage, consisting of the sessile polychaete annelid *Pomatoleios kraussii*, lives in the midst of the intertidal zone and is an indicator of ancient sea level (Kayanne et al. 1987). At Cape Muroto, assemblages at 8.3–9.1 m and 4.7–6.0 m above sea level have ages of 4.5–2.8 ka and 2.7–1.2 ka, respectively, suggesting that Cape Muroto underwent uplift of about 2–3 m at about 2.8 ka and about 4 m at about 1.0 ka, while sea levels before and after the two uplift events were relatively stable (Maemoku 2001). These results suggest that the Holocene uplift rate is about 1.9 m/kyr, if we ignore eustatic sea-level changes during the last several thousand years. This uplift rate is nearly the same as that of the MIS 5e terrace. Maemoku (2001) also found that the assemblages are internally divided by discontinuous boundaries at average age intervals of 100–150 year, which was interpreted as result of coseismic uplift and interseismic subsidence during earthquake cycles of 100–150 years with little or no net crustal movement.

Shishikura et al. (2008) reported similar uplifted fossil assemblages dating from the last 5500 years at four levels in the cliffs along the southern coast of the Kii Mountains and a fifth level was identified in an additional survey (Fig. 5). Each assemblage, representing 400–600 year of development, consists of alternating fossil layers and discontinuous boundaries with an age interval of 100–150 year (Fig. 5d), similar to the assemblages at Cape Muroto. Although there are gaps in the ages of the fossil blocks, Shishikura et al. (2008) inferred that the coast has been uplifted at intervals of 400–600 year.

The fossil assemblages reach their greatest elevation along the coast northeast of Cape Shionomisaki, where the MIS 5e marine terraces also are highest (Fig. 5b, c; Shishikura et al. 2008). In contrast, uplift between 1928 and 1947, including coseismic uplifts during the 1944 and 1946 earthquakes, was greatest at Cape Shionomisaki and decreased to the northeast (Fig. 5a; Yonekura

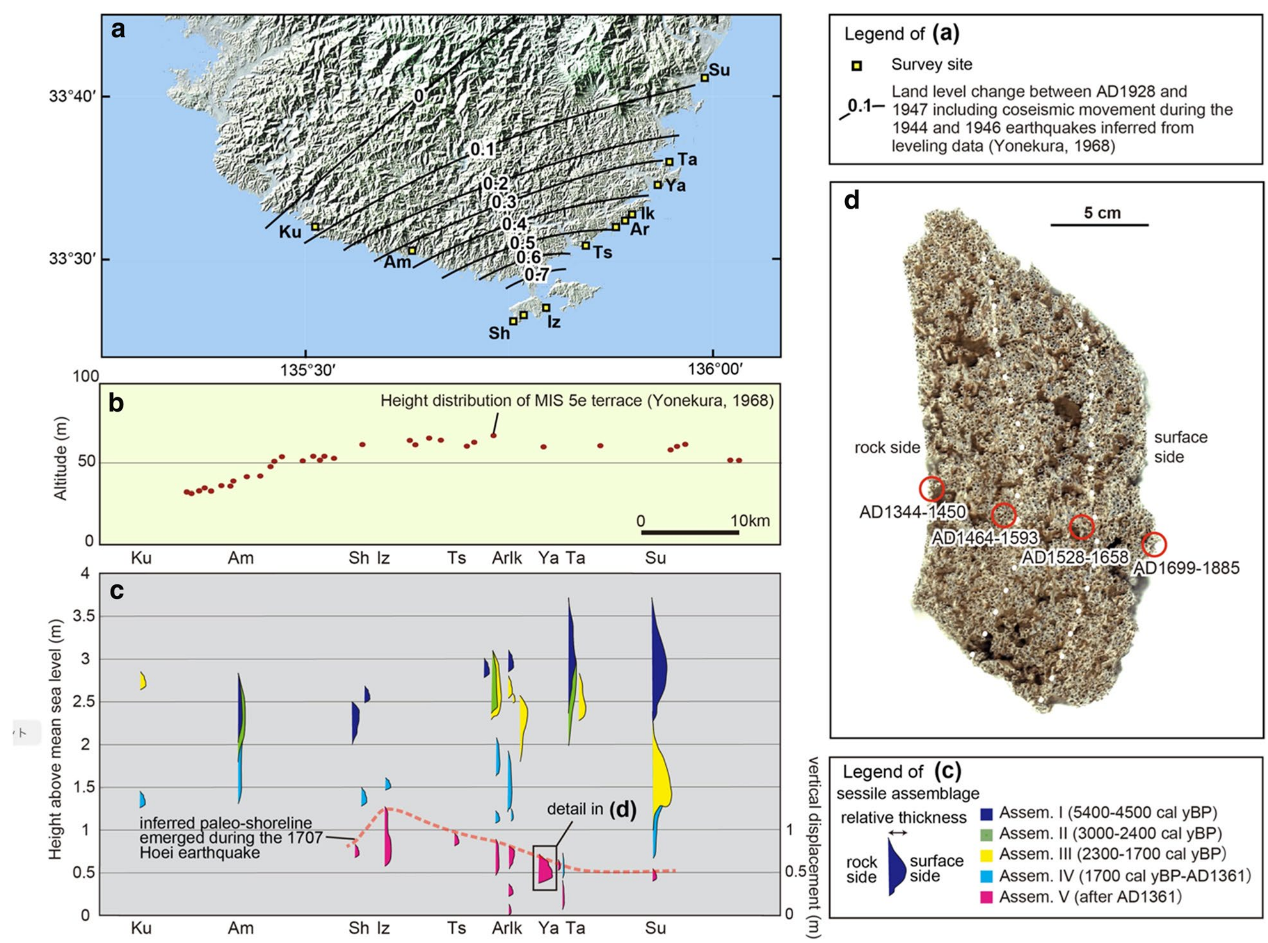

Fig. 5 Vertical movement along the southern coast of the Kii Mountains. **a** Location of survey sites shown by small squares with symbols and coseismic vertical movements during the 1944 and 1946 Showa earthquakes by black solid lines in meter. **b** Height distribution of the MIS 5e terrace (Yonekura 1968). Symbols at the bottom indicate locations shown in **a**. **c** Height distribution of emergent fossil assemblages. Symbols at the bottom indicate locations shown in **a** (revised from Shishikura et al. 2008). **d** Photo of a vertical slice from fossil assemblage shown in **c**. Red circles are positions of ^{14}C age samples. White dotted lines indicate discontinuous boundaries

1968). Fossils dating from about 4.5 ka are about 3 m above sea level, thus the estimated uplift rate since 4.5 ka, ignoring eustatic sea-level changes, is 0.67 m/kyr. Uplift rates and patterns during the Holocene and Late Pleistocene are nearly the same along the coast south of the Kii Mountains, even though the 1944 and 1946 earthquakes produced different uplift profiles (Shishikura et al. 2008).

Shishikura et al. (2008) showed that the youngest ages in the lowest fossil assemblages range from the seventeenth to early eighteenth centuries and attributed the latest uplift to the 1707 Hoei earthquake, in which the plate boundary of the entire trough ruptured. They also suggested that this and earlier multi-segment earthquakes were accompanied by unusual crustal movements that were greater than those from recurring earthquakes.

Model

Mechanism of crustal movements

Two types of crustal movements have been observed along the forearc wedge of the southwestern Japan arc: elastic deformation associated with earthquake cycles on the plate boundary and permanent deformation, the latter of which is responsible for the growth of the uplift and subsidence zones along the forearc wedge. We compared the geometry of the plate boundary with the uplift zones in the overlying forearc wedge. The uplift zones of the Akaishi and Kii Peninsulas do not correspond to the ridges and troughs of the plate boundary, but lie above portions of the plate boundary with a NE–SW strike and northwestward dip (Fig. 3). The subsiding zones of the Kii Strait and Nobi Plain approximately correspond to the NW–SE striking, northeast-dipping plate boundary. From these relationships between the plate boundary geometry and the vertical crustal deformation of the forearc wedge, we propose the following models.

We assume that the undulations of the plate boundary have been fixed to the Shikoku Basin, thus the ridges and troughs on the slab surface are moving WSW relative to the forearc wedge during the northwestward subduction of the slab. For example, the Kyushu-Palau Ridge defining the western margin of the Shikoku Basin has swept WSW the accretionary prism along the Nankai Trough due to NW motion of the PSP and left an indentation 20 km wide on the prism (Figs. 1, 3; Yamazaki and Okamura 1989).

Figure 6a shows the relationship between the forearc wedge and plate boundary geometry on a schematic cross section along the arc. At places where the plate boundary strikes NE–SW and dips NW, the WSW motion of the undulations of the plate boundary is uplifting the overriding plate. Where the plate boundary strikes NW–SE and dips NE, the WSW motion of the undulations is causing the overriding plate to subside. This simple model explains the uplift of the Kii and Akaishi Mountains and the subsidence of Kii Strait, Ise Bay and Nobi Plain (Fig. 6).

Irako Strait, to the south of the Ise Bay, is a pass between two small ENE–WSW trending peninsulas (Fig. 1). The depth contours of the plate boundary there are nearly parallel to the Nankai Trough (Fig. 6), suggesting that little or no vertical movement is currently being caused by the subduction of the PSP. The peninsulas are covered with Late Pleistocene marine terraces (Koike and Machida 2001), which indicates geologically recent uplift of the peninsulas, but Pleistocene sediments of the Atsumi Peninsula on the east side of the strait indicate that vertical movement of the peninsula has changed from subsidence to uplift about 331 ka (Hiroki 1994). To the south of the peninsula, the exposure of eroded Pleistocene sediments implies that the shelf is undergoing uplift (Arai 2008), and the Enshu Trough farther offshore is widely deformed and uplifted by the subduction of ridges (Kodaira et al. 2003). We infer that the vertical movements of region around the Irako Strait are affected by ridge subductions.

Miyoshi and Ishibashi (2008) proposed a model similar to ours to explain the abundance of active faults in the Kinki district of the Inner zone (Fig. 1). They inferred that oblique subduction of the ridge on the plate boundary north of the Ise Bay (Fig. 3) caused strong E–W compression and generated many active faults to the west of the ridge in the Kinki district. We infer that the difference in crustal movements between the Inner and Outer zones reflects differences in the physical properties of the crust.

Our model is less successful at explaining the uplift of the Shikoku Mountains. Their ENE–WSW trend, parallel to the arc, suggests that their uplift mechanism is different from that of the Kii and Akaishi Mountains, which trend obliquely to the arc (Fig. 6). In fact, the depth contours of the slab under the western part of the range strike subparallel to the Nankai Trough (Hori et al. 2004; Hirose et al. 2008), thus a decrease in the depth of the plate-boundary depth due to oblique subduction of the PSP may not be plausible. Further studies are needed to investigate the uplift mechanism of the Shikoku Mountain.

Cape Muroto is located on a N–S trending anticline that has been interpreted as the hanging wall of a west-dipping reverse fault (Okamura 1990), and the high uplift rate of Cape Muroto has been attributed to reverse faulting (Maemoku 2001). Cape Muroto lies on the landward extension of the Kinan Seamount Chain, and a subducting seamount is located southeast of the cape. We infer that motion on this N–S striking reverse fault originates in the subduction of the seamount chain. The uplift of Cape Ashizuri is difficult to relate to slab geometry or seamount subduction. One possible model is that the decrease of dextral strike slip rates along the Median Tectonic Line in western Shikoku (Tsutsumi and Okada 1996) causes the forearc sliver south of the Median Tectonic Line to collide with and deform western Shikoku. We infer that these N–S trending uplifts have been caused by internal deformation of the forearc wedge due to oblique subduction of the PSP under Shikoku.

Locked zone on the plate boundary under the Kii Mountains

If the uplift model of the Kii and Akaishi Mountains described above is correct, the uplift at 400–600 year intervals indicated by the emergent marine fossil assemblages along the coast of the Kii Mountains suggests that the plate boundary under the Kii Mountains is locked, and slips of the locked zone every 400–600 year have uplifted of the Kii Mountains. The latest slip of this locked zone was during the 1707 earthquake, which ruptured the entire Nankai Trough, suggesting that the slip on this locked zone causes ruptures to propagate along the plate boundary to the east and west simultaneously.

In contrast, the uplifts during the 1854 pair of earthquakes and the 1944 and 1946 earthquake pair have been canceled by subsidence during the following interseismic periods, indicating that coseismic movements from these earthquakes have not contributed to the permanent uplift of the Kii Mountains. The first event of these earthquake pairs ruptured the eastern part of the trough, and the second events ruptured the western part shortly afterward (32 h and 2 year, respectively), which suggests that the

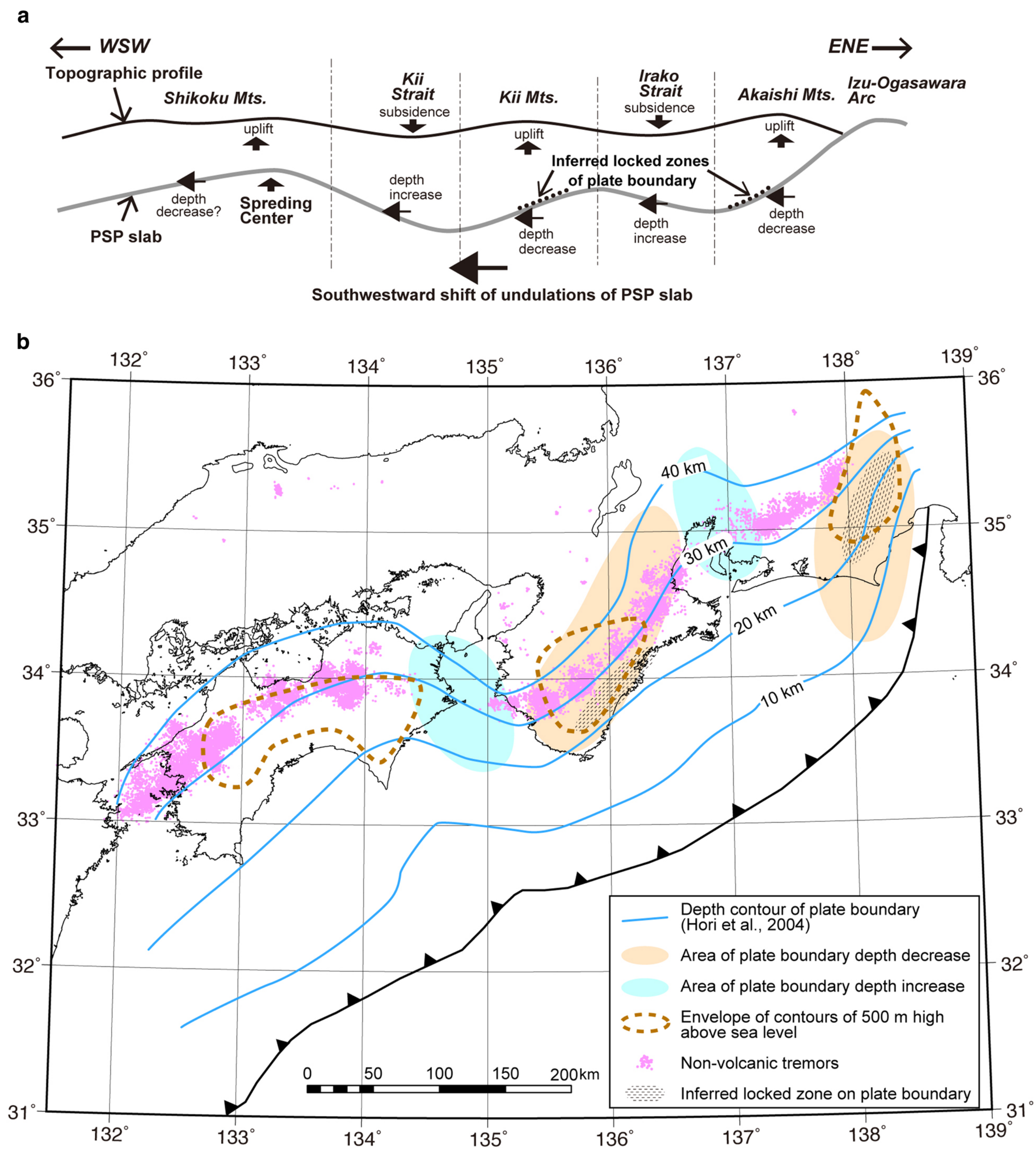

Fig. 6 Relationship between the vertical movement of the forearc wedge and the plate boundary. **a** Schematic cross section showing the geometry of the plate boundary and the uplift and subsidence zones along the Outer zone of southwest Japan. Top solid line indicates a topographic profile of the forearc wedge and the bottom solid line show geometry of the plate boundary. Ridges and troughs of the plate boundary are supposed to move to the southwest as shown by horizontal arrows due to oblique subduction of the PSP slab, then the depth of the plate boundary changes. The areas of increase and decrease of the plate boundary depth approximately correspond to the subsidence and uplift zones of the forearc wedge, respectively. **b** Map showing the relationship between the depth contours of the plate boundary and crustal movement of the forearc, and the location of inferred stack zone on the plate boundary. Areas of plate boundary depth decrease are inferred to correspond to the areas where the plate depth contours strike NE–SW, and the those of plate boundary depth increase are inferred to correspond the areas of depth contours strike E–W to NW–SE. The mountains in the Outer zone (dashed outlines) approximately coincide with the area of plate boundary depth decrease. Plate boundary is inferred to be locked where the depth of the plate boundary decreases. The uplift zone of the Shikoku Mountains is not clearly explained by this model. The non-volcanic tremor locations are from the JMA catalog from 2014 to 2018

locked zone was a barrier against the rupture propagation across the Kii Mountains during these events.

Some evidence constrains the location and extent of the locked zone. Short-term slow slip events and non-volcanic tremor have been observed deeper than about 30 km on the plate boundary under the Kii Mountains (Obara 2011), suggesting that the plate boundary is not locked in that area. Several studies have modeled the source faults of the 1944 and 1946 earthquakes in the southern Kii Mountains and the forearc basins to their south (Sagiya and Thatcher 1999; Tanioka and Satake 2001; Ichinose et al. 2003), but a high-resolution source model by Baba and Cummins (2005) showed that the most of the Kii Mountains was not included in the rupture areas of the 1944 and 1946 earthquakes. These studies suggest that the area that might be locked under the Kii Mountains lies between the area of non-volcanic tremor and the coast (Fig. 6). The depth of the plate boundary there is 20–30 km, similar to the depth of long-term slow slip events under the Kii Strait and Lake Hamana, but long-term slow slip events have not been observed under the Kii Mountains (Kobayashi 2017).

Sagiya and Thatcher (1999) modeled the slip distribution of the 1944 and 1946 earthquakes on 33 fault segments along the plate boundary and showed that slip vectors of many of the fault blocks are subparallel to the relative plate motion while those along the coast southeast of the Kii Mountains are unusually small and disrupted. They inferred that dip variations of the slab under the Kii Mountains were an obstacle to fault slip during these earthquakes. Cummins et al. (2002) also suggested that a steeply dipping portion of the slab influenced the 1944 earthquake rupture. These studies are favorable to our model of a locked zone on the plate boundary beneath the southeastern Kii Mountains.

Locked zone on the plate boundary under the Akaishi mountains

The plate boundary geometry under the Akaishi Mountains is similar to that under the Kii Mountains, and we suggest that another locked zone exists there. Leveling surveys during approximately the last about 100 year have documented uplift rates greater than 3 mm/year in the western part of the mountains, but a large area between the eastern part of the mountains and Suruga Bay has been subsiding (Geographical Survey Institute 2002). Sagiya (1999) and Ochi and Kato (2013) have inferred from satellite geodetic measurements that a wide area of the plate boundary between the eastern Akaishi Mountains and the Suruga Trough is locked. On the contrary, the presence of uplifted Middle-to-Late Pleistocene sediments exposed on the coastal hills along the coast west of the Suruga Trough indicates that the coastal area has been rising during the last 10^5 year (Tsuchi 1984; Kitamura et al. 2005). Uplift was widely reported along this coast during the 1854 Ansei Tokai earthquake; however, reliable records of uplift of this coast during the 1707 earthquake have not been found (Ishibashi 1984), and the 1944 earthquake rupture did not extend to the Suruga Trough and the Akaishi Mountains (Sagiya and Thatcher 1999; Tanioka and Satake 2001; Ichinose et al. 2003). These studies suggest that the coseismic uplift from the 1854 Ansei Tokai earthquake was unusual and that strain has been accumulating along the eastern part of the Suruga–Nankai Trough. Reliable geologic data on the timing of uplift are not available from the forearc wedge along the Suruga Trough, whereas Fujiwara et al. (2016) reported five events of rapid subsidence at 100- to 400-year intervals during the last 1500 year in the lowland located on the PSP north of Suruga Bay and inferred that these were caused by slips on the plate boundary that extended to the north from the Suruga Trough. We propose that a locked zone independent of the one under the Kii Mountains exists under the area between the Akaishi Mountains and the Suruga Trough (Fig. 6) and suggest that ruptures of this locked zone generate Ansei-type earthquakes.

Plate boundary under the Shikoku mountains

The plate boundary under the Shikoku Mountains shows no clear undulations that may have caused deformation of the overriding plate during its oblique subduction. There is no geologic evidence suggesting the existence of a locked zone that has persisted for a few hundred years or more. Plate boundary ruptures in the western Nankai Trough, including Shikoku, appear to have generally been triggered by plate-boundary ruptures in the eastern and middle parts of the trough. We infer that the plate boundary under the Shikoku Mountains is not an independent locked zone.

Discussion

Slip deficits along the plate boundary of the Suruga–Nankai Trough subduction zone have been investigated in studies based on satellite geodetic measurements (Ito and Hashimoto 2004; Yoshioka and Matsuoka 2013, Loveless and Meade 2016, Noda et al. 2018; Kimura et al. 2019). However, our model is based on longer-term crustal movements that were not considered by these studies.

We propose that two independent locked zones produce great plate-boundary events like the 1707 Hoei and 1854 Ansei Tokai earthquakes, respectively, and this hypothesis is consistent with the Hoei and Ansei earthquake types proposed by Seno (2012). One difference is that Seno (2012) classified the 1944 and 1946 Showa earthquakes as Hoei-type earthquakes, but those events did not rupture our proposed locked zones under the Kii or Akaishi Mountains. This fact suggests that ruptures on the shallow plate boundary generate M8 earthquakes without breaking the deep locked zones. We propose that the Hoei-type and Ansei-type earthquakes are generated by ruptures of the deep locked zones under the Kii and Akaishi Mountains, respectively, and that the Showa type earthquakes result from shallow plate-boundary ruptures. Our evidence does not suggest that the plate boundary under the Shikoku Mountains contains a locked zone.

We correlate ruptures of the locked zone under the Kii Mountains with Hoei-type earthquakes that rupture the whole trough. The ages of emergent fossil assemblages suggest that the most recent coastal uplift event along the Kii Mountains preceding the 1707 earthquake occurred in the 13th or 14th century, an event that can be correlated with the 1361 earthquake or an unknown earthquake between the 1361 and 1099 events (Shishikura et al. 2008). If the 1361 earthquake ruptured the locked zone under the Kii Mountains, the recurrence interval was about 350 year.

Our model offers a simple explanation of the variety of earthquake magnitudes and rupture areas along the Suruga–Nankai Trough, and it may offer clues as to the type of the next great earthquake along the Suruga–Nankai Trough. As further studies examine the reliability of our model, and we would like to emphasize the significance of studies of past earthquakes based on geological surveys and historical documents.

Conclusion

Topographic and geologic data from the Outer zone of the southwestern Japan arc indicate that undulations defined by zones of uplift and subsidence along the forearc wedge have been growing throughout the Quaternary. However, strain accumulation and release during earthquake cycles along the Suruga–Nankai Trough cancel each other out and do not contribute to the growth of these structures. We propose that the topographic zones of uplift and subsidence to the east of Shikoku are consequences of the passage of undulations in the upper surface of the PSP slab during its oblique subduction.

This tectonic model can account for the large variety in magnitudes and rupture areas of great earthquakes along the Suruga–Nankai Trough. The Kii Mountains, one of the uplift zones in the middle of the trough, have undergone uplift events at intervals of 400–600 year, and the most recent of these occurred during the 1707 Hoei earthquake. We suggest that the plate boundary under the Kii Mountains is a locked zone with a rupture recurrence interval of 400–600 year, and slip on this locked zone accompanies ruptures of the entire plate boundary along the Suruga–Nankai Trough. Another locked zone on the plate boundary is inferred under the Akaishi Mountains, which controls rupture of the eastern part of the trough. The most recent break in this zone is correlated with the 1854 Ansei Tokai earthquake, when the locked zone under the Kii Mountains prevented rupture propagation to the west. These two deep locked zones, inferred to be at depths of 20–30 km, are the primary control on the types of great earthquakes along the Suruga–Nankai trough. Shallower parts of the plate boundary rupture independently of breaks of the deep locked zones and cause events like the 1944 and 1946 earthquakes. Because our model is mainly based on long-term crustal movements and paleoearthquakes, further reliable data on ancient earthquakes are necessary to test the model.

Abbreviations
ISTL: Itoigawa–Shizuoka Tectonic Line; M: Magnitude; MIS: Marine isotope stage; MTL: Median tectonic line; PSP: Philippine Sea Plate.

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Authors' contributions
YO conceptualized deformation model and wrote the manuscript. MS provided data emergent marine shell fossil assemblages and discussed the relation of the crustal movement to historical earthquakes. Both the authors read and approved the final manuscript.

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