Seismic reflection and bathymetric evidences for the Nankai earthquake rupture across a stable segment-boundary

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Seismic re ection pro les reveal steeply landward-dipping splay faults in segment B (the 1946 Nankai earthquake rupture, *M* 8.3) as well as segment C (the 1944 Tonankai earthquake rupture, *M* 8.1) of the Nankai subduction zone. The splay faults, branching upward from the plate-boundary interface, almost reach the sea oor, producing sea oor fault scarps. The swath-bathymetry map exhibits a ∼200-km-long, remarkable sea oor lineament with which the sea oor fault scarps align in the segments B and C. The sea oor lineament, which we believe is produced by repeating slips on the splay faults, is almost laterally continuous across a stable boundary off Kii Peninsula inbetween the two segments. These sea oor and subsurface features could be due to multiple, simultaneous coseismic slips across the B–C boundary, when subduction thrust earthquakes accompany the coseismic slips on the splay fault. The splay faults are associated with (1) uid expulsion, (2) dynamic deformation, and (3) tsunami generation.

Key words: Nankai, subduction zone, splay fault, segment boundary, simultaneous slip.

1. Introduction

It is well known that a subduction zone is divided into several discrete segments marked by a megathrust earthquake rupture. While the segment boundary limits the rupture area of an individual earthquake, sometimes a great earthquake across a segment boundary occurs, causing strong shaking and devastating tsunamis, e.g., Nankai (Ando, 1975), Cascadia (Satake *et al.*, 1996), Chile (Campos *et al.*, 2002), Kuril (Sawai *et al.*, 2004), Sumatra (Lay *et al.*, 2005), and Japan Trench (Ide *et al.*, 2011). However, except for recent earthquakes such as the 2004 Sumatra (*M* 9.2), whether or not a great earthquake occurred across a segment boundary may be controversial, because it often depends solely on historical documents.

The Nankai Trough subduction zone off southwest Japan is one of the convergent margins best suited for studying large megathrust earthquakes, as well as the formation of accretionary prisms. At the Nankai Trough margin, the Philippine Sea plate (PSP) is being subducted beneath the Eurasian Plate to the northwest at a convergence rate of ∼4 cm/yr (Seno *et al.*, 1993). The Shikoku Basin, the northern part of the PSP, is estimated to have opened between 25 and 15 Ma by backarc spreading of the Izu-Bonin arc (Okino *et al.*, 1994).

Historically, great megathrust earthquakes with a recurrence interval of 100–200 yr (e.g., Ando, 1975) have generated strong motions and large tsunamis along the Nankai Trough margin. In particular, the Nankai subduction zone off Kii Peninsula (Fig. 1) is characterized by steeply landward-dipping megasplay faults (Park *et al.*, 2002; Moore *et al.*, 2007) in the rupture area of the 1944 Tonankai (*M* 8.1) earthquake. This megasplay fault branches upward from the plate interface (i.e., the megathrust fault), breaking through the overlying accretionary wedge. The 1944 Tonankai megasplay and megathrust faults are major targets for the Integrated Ocean Drilling Program (IODP) project Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE).

Based on historical documents and observation on subduction thrust earthquake occurrence, the Nankai subduction zone is segmented into ve different domains, i.e., A, B, C, D, and E (Ando, 1975), each of which roughly corresponds to a geologically well-de ned forearc basin (Sugiyama, 1994). The earthquake rupture pattern over those ve segments suggests that a boundary between segments A–B and C–D has been stable over the historic earthquake cycles. For example, the last 1944 Tonankai earthquake ruptured the segments C and D. About two years later, the 1946 Nankai (*M* 8.3) earthquake ruptured the segments A and B. Two events of the 1854 Ansei (*M* 8.4) earthquake were also separated by the B–C boundary. Tsunami waveform inversion results (Baba and Cummins, 2005) support the presence of the B–C boundary off Kii Peninsula. In contrast, the 1707 Hoei (*M* 8.7) earthquake is presumed to have extended across the B–C boundary and ruptured the segments A, B, C, and D at a single event, based on historical documents and numerical simulation (Kodaira *et al.*, 2006). However, it has been controversial whether, or not, there has been an earthquake rupture

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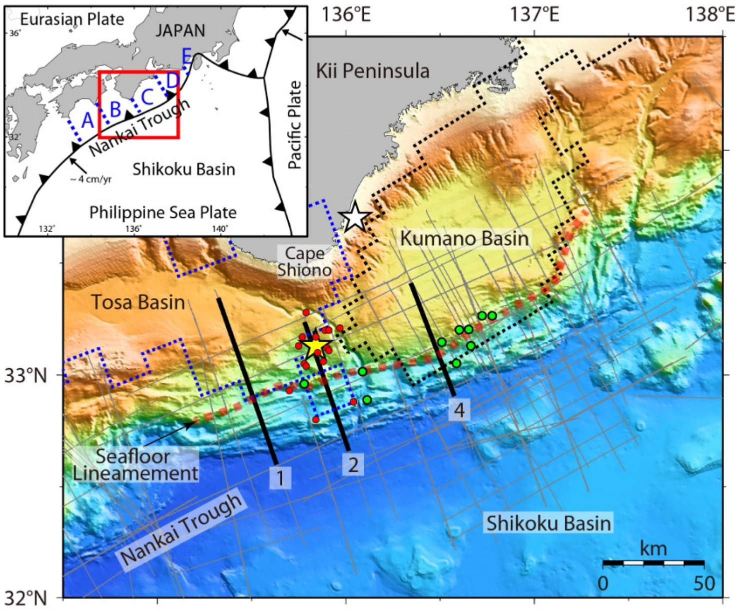

Fig. 1. Seafloor bathymetry and locations of multi-channel seismic (MCS) reflection lines (gray thin) in Nankai Trough margin off southwest Japan. Inset: Regional map showing the location of the study area (red box). The Nankai subduction zone may be divided into five discrete segments (A through E) (Ando, 1975). Heavy black parts on lines 1, 2, and 4 mark the MCS profiles shown in Figs. 2, 3, and 4. The areas with slip >1 m for the 1944 Tonankai and 1946 Nankai earthquakes (Baba and Cummins, 2005) are shown in black and blue dotted lines, respectively. White and yellow stars show epicenters of the 1944 and 1946 events, respectively. Red circles are very low-frequency earthquakes (Obara and Ito, 2005). Green circles are cold seeps (Ashi *et al.*, 2009). A seafloor lineament (heavy dotted line shaded in red) at the seaward edge of the Kumano basin appears to extend westward across the B–C boundary off Cape Shiono, Kii Peninsula.

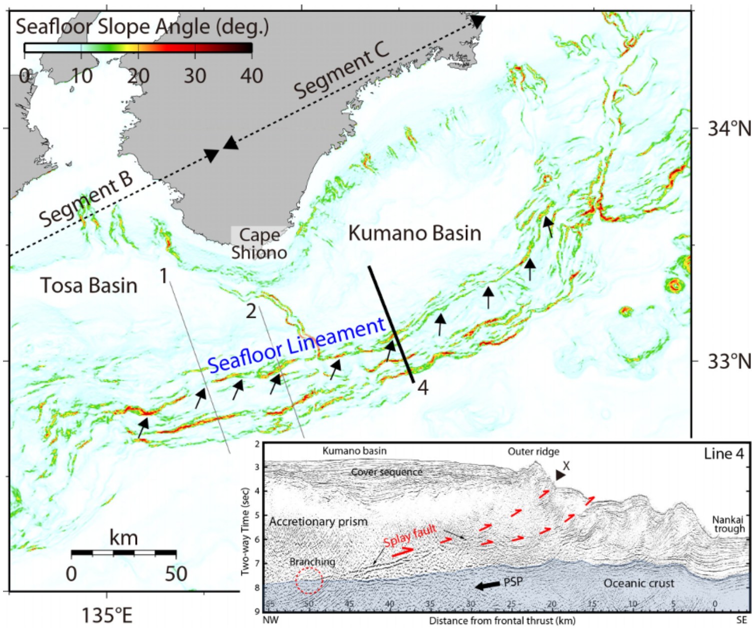

Fig. 2. Seafloor slope angle map off the Kii Peninsula. Inset: Time-migrated MCS profile of line 4 (modified after Park *et al.*, 2003) showing the splay fault in segment C, vertical exaggeration about 4:1 at the seafloor. Red arrows show the motions of the splay fault slip. Fault scarps, which are marked by black arrows on the slope angle map and "X" on the MCS profile, produce a ∼200-km-long, laterally continuous seafloor lineament.

across the stable B–C boundary, due to the lack of modern geophysical and geological evidence.

In this paper, we show multi-channel seismic (MCS) reflection profiles crossing the Nankai Trough, and Seabeam swath-bathymetry data off the Kii Peninsula, to resolve the controversy of whether, or not, coseismic rupture includes a previously-defined segment-boundary. Finally, we present the potential implications of the splay faults in the Nankai subduction zone.

2. Swath-Bathymetry Data and Their Interpretation

Combining swath-bathymetry and seismic reflection data has demonstrated a causal relationship between splay-fault behavior and seafloor lineament topography in segment C, i.e., the 1944 Tonankai earthquake rupture area (Park *et al.*, 2002). Many 2-D and 3-D seismic reflection data (Park *et al.*, 2003, 2010; Moore *et al.*, 2007) have revealed a steeply landward-dipping splay-fault system in segment C, e.g., line 4 in Fig. 2. The splay fault branches upward from the plate-boundary interface, breaking through the overlying accretionary wedge. It was considered that slip on the splay fault heaved the seafloor upward, producing a remarkable seafloor fault scarp and a subsequent seafloor lineament along the strike.

On the seafloor topography map (Fig. 1), the seafloor lineament looks roughly continuous over the segments B and C. In order to verify the continuity of the seafloor lineament along the strike, we have calculated the seafloor slope angle from the swath-bathymetry data. The slope-angle map (Fig. 2) highlights that the seafloor lineament of segment C is almost continuous to segment B, i.e., the 1946 Nankai earthquake rupture area, completely passing through the stable segment-boundary off Cape Shiono, Kii Peninsula. Most of the seafloor fault scarps, which are also denoted by "X" on the MCS profile 4, show a 15° to 25° dip. The seafloor lineament across the two segments is ~200-km long. It enables us to deduce the existence of a similar splay-fault system in segment B. Accordingly, we have re-examined the MCS data off the Kii Peninsula.

3. Seismic Reflection Data and Interpretation

The MCS data that we have used for this study was collected in the Nankai Trough margin off the Kii Peninsula by R/V *Kairei* of the Japan Marine Science and Technology Center (JAMSTEC) in 2001. For deep-penetration seismic imaging, we used a large volume (~200 liter) air gun array as the controlled sound source. The MCS data recording was made with a 4 km, 160-channel streamer with a 25-m group spacing. Figure 1 shows the positions of the MCS lines. Data processing included trace editing, pre-filtering, spherical divergence correction, signature deconvolution, CMP (Common Mid-Point) sort, NMO correction, multiple suppression by parabolic radon transform, CMP stack, and time-migration.

On profile 1 (Fig. 3) crossing the Nankai Trough, a strong reflection from the oceanic crust of the PSP is continuously traceable, at least 75 km landward from the frontal thrust (FT), as the PSP subducts beneath the forearc accretionary wedge. A clear décollement reflection is observed at least 25 km landward from the FT. This profile reveals a landward-dipping thrust fault which branches upward from the plate-boundary interface at ~70 km landward from the FT and produces the fault scarp at the seafloor. This thrust fault steepens as it approaches the seafloor, breaking through the upper crustal plate. Because the thrust fault almost reaches the seafloor and is apparently within the 1946 Nankai coseismic rupture area estimated from tsunami waveform inversion (Baba and Cummins, 2005), we suggest that it corresponds to a splay fault branching upward from the plate-boundary fault. The fault scarp, which is denoted by "X" on MCS profile 1, is located exactly on the westward extension of the seafloor lineament that is identified in segment C, as shown in Fig. 2.

A thrust fault with similar structural features is identified on MCS profile 2 in the 1946 Nankai coseismic rupture area. On profile 2 (Fig. 4), a strong reflection from the oceanic crust of the PSP is roughly traceable at least 60 km landward from the FT, while it is not easy to identify the décollement reflection. This profile reveals a landward-dipping thrust fault branching upward from the plate-boundary interface at ~50 km landward from the FT, which produces the fault scarp at the seafloor. Because the thrust fault almost reaches the seafloor and is apparently within the 1946 Nankai coseismic rupture area, we suggest that it corresponds to a splay fault branching upward from the plate-boundary fault. The fault scarp, which is denoted by "X" on MCS profile 2, is also located on the westward extension of the seafloor lineament that is identified in segment C. In particular, this profile exhibits apparent landward-dipping bedding planes within the cover sequence just above the splay fault. Such a tilted onlap structure suggests multiple episodes of seafloor uplifting due to the splay fault slip.

4. Implications of the Splay Faults

Combining the MCS and swath-bathymetry data provides crucial evidence for the Nankai earthquake rupture across the stable B–C boundary. The MCS profiles reveal steeply landward-dipping splay faults in segment B (the 1946 Nankai earthquake rupture area) as well as segment C (the 1944 Tonankai earthquake rupture area). These splay faults branch upward from the plate-boundary interface at ~50 to 70 km landward from the FT, and eventually reach the seafloor, producing the seafloor fault scarps. Vitrinite reflectance geothermometry on IODP NanTroSEIZE cores suggests coseismic slip to the updip end of the 1944 Tonankai splay fault (Sakaguchi *et al.*, 2011). The swath-bathymetry map exhibits a ~200-km-long, remarkable seafloor lineament with which the seafloor fault scarps align in the segments B and C. The seafloor lineament, which we believe is produced by repeating slips on the splay faults, is almost laterally continuous across the B–C boundary off the Kii Peninsula. Assuming that the position of the splay faults is constant over the multiple earthquake cycles, we speculate that the continuous seafloor lineament has grown primarily by "*simultaneous*" coseismic slips (e.g., the 1707 Hoei earthquake) across the B–C boundary (Fig. 5). Individual slips (e.g., the 1944 Tonankai or 1946 Nankai events) could help the growth of the seafloor lineament, even though we cannot quantify each event's contribution.

As a matter of fact, we do not know if the coseismic slip on the splay fault was regular over the historical earthquakes. Because it is not possible to account for all of the recent coseismic slips, it is difficult to tell if the along-strike continuity of the splay fault directly indicates the coseismic rupture across the B–C boundary. Even the seafloor lineament could be caused by aseismic slip. The splay fault system may play a significant role in rupture propagation across the B–C boundary only when a subduction thrust earthquake accompanies the coseismic slip on the splay fault.

Recent submersible observations (Ashi *et al.*, 2009) in segment B, as well as in segment C, reported the presence of chemosynthetic benthic colonies around the seafloor fault

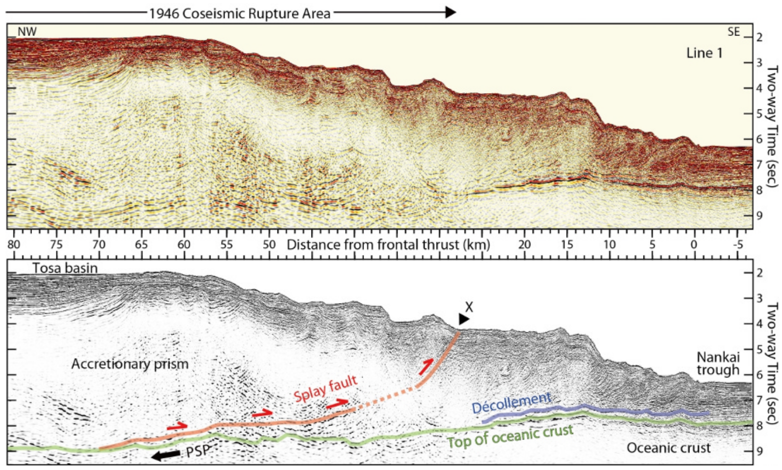

Fig. 3. Time-migrated MCS profile (upper section) of line 1 and its interpretation (lower section) showing the splay fault in segment B, vertical exaggeration about 4:1 at the seafloor. Red arrows show the motions of the splay fault slip. The fault scarp is marked by "X" on the interpretation section.

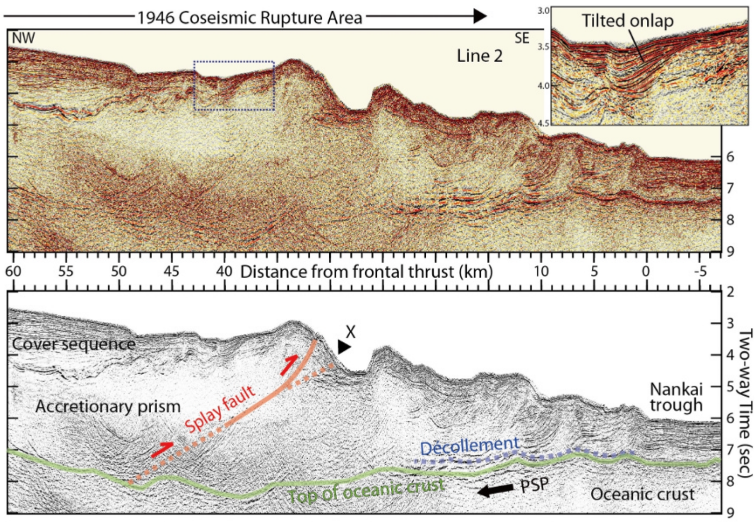

Fig. 4. Time-migrated MCS profile (upper section) of line 2 and its interpretation (lower section) showing the splay fault in segment B, vertical exaggeration about 4:1 at the seafloor. Inset: Tilted onlap structure at the seaward tip of the cover sequence. Red arrows show the motions of the splay fault slip. The fault scarp is marked by "X" on the interpretation section.

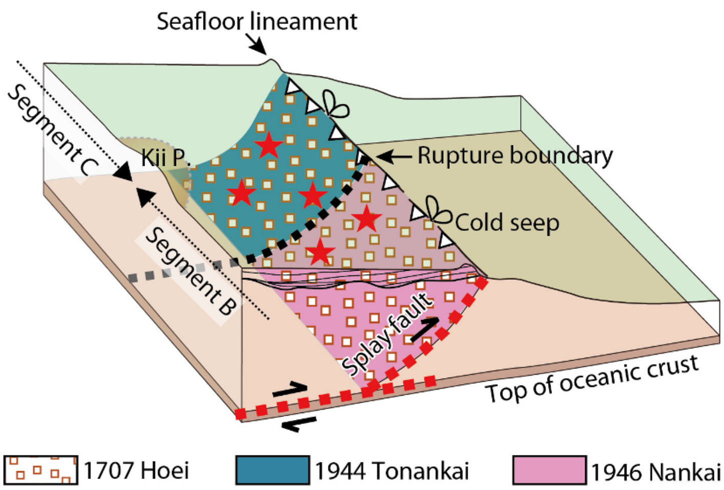

Fig. 5. Schematic diagram showing that the seafloor lineament across the B–C boundary off the Kii Peninsula was produced by simultaneous (e.g., the 1707 Hoei earthquake) splay fault slips. Individual (e.g., the 1944 Tonankai or 1946 Nankai events) splay fault slips could help the growth of the seafloor lineament. Very low-frequency earthquakes and tremors around the splay fault are marked by red stars.

scarp of the splay faults, indicating the presence of cold seeps (Figs. 1 and 5) and possible uid expulsion along the fault.

Low-frequency tremors associated with reverse faults in a shallow accretionary prism were observed in segment C (Obana and Kodaira, 2009). Many of the low-frequency tremors were located near the shallowest part of a splay fault. The episodic activity of the low-frequency tremors suggests that the splay faults are conditionally stable and thus can become unstable under suf ciently strong dynamic loading. It is also well known that very low-frequency (VLF) earthquakes occur on the well-developed reverse fault system in the accretionary prism along the Nankai Trough (e.g., Obara and Ito, 2005). The activity of VLF earthquakes is considered to be the result of slips on the reverse fault system and, thus, the signature of a dynamic deformation process in the accretionary prism. The VLF earthquakes occurred around the splay fault in segment B in 2005 (Obara and Ito, 2005), as shown in Figs. 1 and 5. Most of the VLF earthquakes are located landward from the sea oor lineament. We infer that the VLF earthquakes occur along the splay faults as identi ed on MCS pro les 1 and 2, because the splay fault is the only major reverse fault in the accretionary prism. The splay faults could be under dynamic deformation during an interseismic period.

A tsunami waveform inversion study (Baba and Cummins, 2005) indicated that the 1946 Nankai coseismic rupture off Cape Shiono, Kii Peninsula, propagated anomalously seaward, compared to adjacent areas (Fig. 1). The splay fault system shown in Figs. 3 and 4, which is recognized as a rst-order feature in the Nankai Trough margin off the Kii Peninsula, could be adopted to explain the anomalous rupture pattern.

5. Conclusions

Combining the seismic re ection and swath-bathymetry data provides evidence for the large earthquake rupture across a stable segment-boundary off the Kii Peninsula in the Nankai subduction zone. Seismic re ection pro les reveal steeply landward-dipping splay faults in the segments B and C. The splay faults, branching upward from the plate-boundary interface, almost reach the sea oor, producing the sea oor fault scarps. The swath-bathymetry map exhibits a ∼200-km-long, remarkable sea oor lineament with which the sea oor fault scarps align in the segments B and C. The sea oor lineament, which may be produced by repeating slips on the splay faults, is almost laterally continuous across the B–C boundary off the Kii Peninsula. These sea oor and subsurface features could be due to multiple, simultaneous coseismic slips across the B–C boundary when subduction thrust earthquakes accompany coseismic slips on the splay fault. The splay faults are related to uid expulsion, dynamic deformation, and tsunami generation.

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