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Intraoceanic thrusts in the Nankai Trough off the Kii Peninsula: Implications for intraplate earthquakes

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[1] We identified intraoceanic thrusts developed as imbricate structures within the subducting Philippine Sea plate off the Kii Peninsula in central Japan manifesting as strong-amplitude reflections observed in an industry-standard three-dimensional (3D) seismic reflection data set. These imbricate intraoceanic thrusts cut through the oceanic crust as a discontinuous thrust plane striking approximately parallel to the trench. In our survey area, large intraplate earthquakes with moment magnitudes (Mw) over 7 occurred on 5 September 2004, causing strong ground motions on the islands of Japan and tsunami waves. The locations of the intraoceanic thrusts recognized in the seismic data are distributed around the estimated hypocenters of the mainshocks and aftershocks of the 2004 earthquakes. Furthermore, their geometry extracted from the 3D seismic data could explain the kind of complex rupture pattern observed during the 2004 events. Therefore we propose that the intraoceanic thrusts are seismogenically active. **Citation:** Tsuji, T., J.-O. Park, G. Moore, S. Kodaira, Y. Fukao, S. Kuramoto, and N. Bangs (2009), Intraoceanic thrusts in the Nankai Trough off the Kii Peninsula: Implications for intraplate earthquakes, *Geophys. Res. Lett.*, *36*, L06303, doi:10.1029/2008GL036974.

1. Introduction

[2] The Nankai Trough is the convergent margin where the Philippine Sea plate is subducting beneath southwest Japan (Figure 1). This subduction zone has repeatedly generated great earthquakes with $M_w > 8$ [*Ando*, 1975]. Because large thrust earthquakes in this setting have been interpreted to occur along the plate interface or mega-splay fault within the sedimentary sequence, seismic reflection studies have been intensively carried out in the Nankai accretionary prism to image these faults [*Park et al.*, 2002; *Moore et al.*, 2007]. However, structures within the oceanic crust have not been very well imaged on seismic reflection profiles, because it is difficult to image geological structures below the thick accretionary wedge due to seismic signal attenuation [*Yilmaz*, 2001]. Furthermore the resolution of two-dimensional (2D) seismic profiles is not enough to interpret the complicated geometry of oceanic crust mainly because 2D seismic data usually cannot consider 3D geometrical effects in seismic processing [*French*, 1974]. Therefore the role of oceanic crust in plate convergent margins has not been well understood. Here we identify intraoceanic thrusts from 3D seismic reflection data obtained in the Nankai Trough off the Kii peninsula (Figures 1 and 2). The 3D seismic data were acquired using a commercial seismic vessel towing four hydrophone streamers and two airgun source arrays (see *Moore et al.* [2009] for a description of acquisition and processing parameters). In this study, we use a 3D pre-stack depth migration data set processed by using an interval velocity determined by tomographic inversion.

[3] In our survey area, large earthquakes with $M_w > 7$ occurred within the oceanic crust off Kii Peninsula on 5 September 2004 [*Hara*, 2005; *Hashimoto et al.*, 2005; *Ito et al.*, 2005; *Park and Mori*, 2005; *Seno*, 2005] and generated tsunamis [*Satake et al.*, 2005]. The 2004 earthquake off the Kii Peninsula had two mainshocks of first mainshock (M_w 7.0) and second mainshock (M_w 7.3) [*Ito et al.*, 2005]. These mainshocks further excited very low frequency (VLF) earthquakes [*Obara and Ito*, 2005]. Here we focus on the intraoceanic thrusts in the south-eastern part of the 3D seismic survey area (Figure 1) and discuss the relationship between intraoceanic thrusts and the 2004 events.

2. Intraoceanic Thrusts

[4] Spatially continuous reflections from several intraoceanic thrusts reflect their complex 3D geometries (Figure 3); the faults are distributed as imbricate thrusts within the subducting plate and cut through the oceanic crust. The large displacements of the intraoceanic thrusts elevate the crust surface, and the offset due to cumulative displacements reaches ~1 km at the sediment-igneous crust interface (Figure 2). Furthermore, the pop-up structure carried on a back-thrust and fore-thrust pair is clearly observed (Figure 2c). Therefore, the geometry of the oceanic crust surface has been mostly controlled by intraoceanic thrust displacements (Figure 3). The intraoceanic thrusts strike nearly parallel to the trend of the trough axis and dip north at ~30°. Only landward-dipping thrusts had strong enough reflection amplitudes to interpret as continuous surfaces, although some reflections indicative of seaward-dipping faults were also evident seaward of the trough axis.

[5] The fault planes extend upward from side edges of the underlying intraoceanic thrusts with steep dips near the sediment-igneous crust interface and work as lateral faults

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(Figure 4a). The lateral faults are developed at the boundary of each intraoceanic thrust, and they strike almost parallel or slightly oblique to the subduction direction of the Philippine Sea plate (Figure 3e). On the previous 2D seismic profiles, intraplate thrusts have been imaged under the Zenisu Ridge in the eastern Nankai Trough [*Aoki et al.*, 1982; *Lallemant et al.*, 1989; *Mazzotti et al.*, 2002]. However the intraplate thrust reflections extracted from 2D seismic data are discontinuous (Figure S1 of the auxiliary material), and their 3D geometries have not been clearly defined.[1]

[6] The intraoceanic thrusts are clearly visible on the seismic profiles, although signal attenuation and a broader Fresnel zone result in a dominantly low-frequency seismic signal within the deep oceanic crust [*Yilmaz*, 2001]. If we assume that the hanging-wall and footwall of the intraoceanic thrusts have similar velocities, the reflections from the intraoceanic thrusts may be attributed to the localized low-velocity zones in areas dominated by fracturing [*Ranero et al.*, 2003]. Intraoceanic thrusts that can be resolved as reflections must have a vertical scale greater than a quarter of the wavelength (Rayleigh's criterion [*Sheriff*, 2002]). When the upper frequency of an intraoceanic thrust reflection is $\sim$15 Hz and the seismic velocity is $\sim$6.6 km/s, the one-quarter wavelength thickness is >110 m. Because a thrust on which there has been numerous displacements can be expected to have a broad fracture zone [*Scholz*, 1987], it might be imaged as a strong-amplitude reflection. There is another possibility that large displacements on the thrusts have produced the velocity contrasts necessary to generate such reflections, because the deeper (and, therefore, higher velocity) lithology in the hanging wall was uplifted due to thrust displacements. Although we cannot specify the origin of strong amplitude of intraoceanic thrusts, in both cases, the strong reflection amplitude represents large displacements along the intraoceanic thrusts. Therefore an intraoceanic thrust which has large offset at the sediment-crust interface could be imaged as strong reflection (Figure 2a).

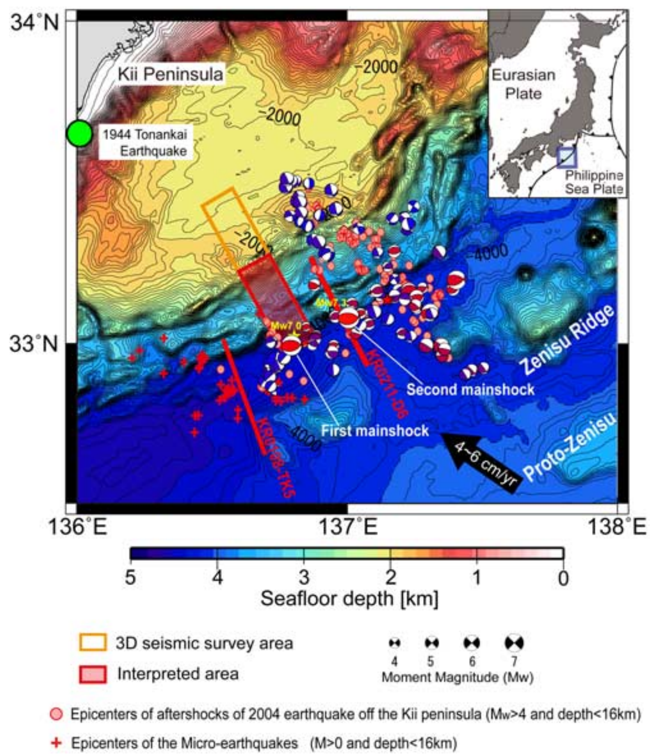

Figure 1. Bathymetric map of the Nankai Trough off the Kii peninsula with focal mechanism distribution of mainshocks and aftershocks of the 2004 off the Kii Peninsula earthquake [*Ito et al.*, 2005]. Colour of moment tensors indicates the Kagan's angle. Red circles show the locations of aftershock epicenters determined from a dense array of ocean-bottom seismometer data [*Sakai et al.*, 2005], and red crosses show the locations of micro-earthquake epicenters during the inter-seismic period [*Obana et al.*, 2004]. The orange and red rectangles show the entire 3D seismic survey are and the interpreted area in this study (30 $\times$ 13 km), respectively. The red lines indicate 2D seismic surveys (Figures S1 and S2).

3. Relationship Between Intraoceanic Thrusts and the 2004 Earthquakes

[7] The 3D seismic survey area covered the area of the hypocenters of the first mainshock and aftershocks of the 2004 earthquake off the Kii Peninsula (Figure 1) [*Ito et al.*, 2005; *Park and Mori*, 2005]. Although normal fault events are expected within the shallow oceanic crust in the trench – outer-rise region [*Ranero et al.*, 2003; *Seno and Yamanaka*, 1996], reverse faults in relatively shallow oceanic crust were responsible for the 2004 earthquake off the Kii Peninsula (Figure 2). The compressive stress for reverse fault may accumulate in shallow oceanic crust since the slip is locked on the subduction interface [*Christensen and Ruff*, 1988; *Park and Mori*, 2005], maybe due to collision of the trough-parallel Zenisu Ridge with central Japan [*Seno*, 2005].

[8] The intraoceanic thrusts revealed by our seismic data are distributed around the hypocenter of the first mainshock of the 2004 earthquake off the Kii peninsula (Figures 1 and 2) [*Ito et al.*, 2005]. The aftershock hypocenters accurately determined (±1km horizontal, ±3km in depth) by a dense array of ocean-bottom seismographs [*Sakai et al.*, 2005] are also scattered around the locations of intraoceanic thrusts. Centroid moment tensors [*Ito et al.*, 2005] show that the focal mechanism of the first mainshock of the 2004 event was almost pure reverse faulting with a dip angle of 30°–50° (Figure 2b). The first mainshock occurred on a plane dipping north (landward) [*Satake et al.*, 2005; *Yagi*, 2004], which is consistent with the thrust geometries revealed by our interpretation of the seismic data. Furthermore, the mechanisms of almost all aftershock events within oceanic crust are similar to those of the first mainshock. Therefore although it is difficult to clarify whether the thrusts imaged on seismic profile experienced first mainshock or not, we believe that the thrusts with similar characteristics should have slipped during the first mainshock.

[9] The rupture mechanism of the second mainshock was complicated [*Hashimoto et al.*, 2005; *Park and Mori*, 2005; *Satake et al.*, 2005]. Analysis of long-period body-wave

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL036974.

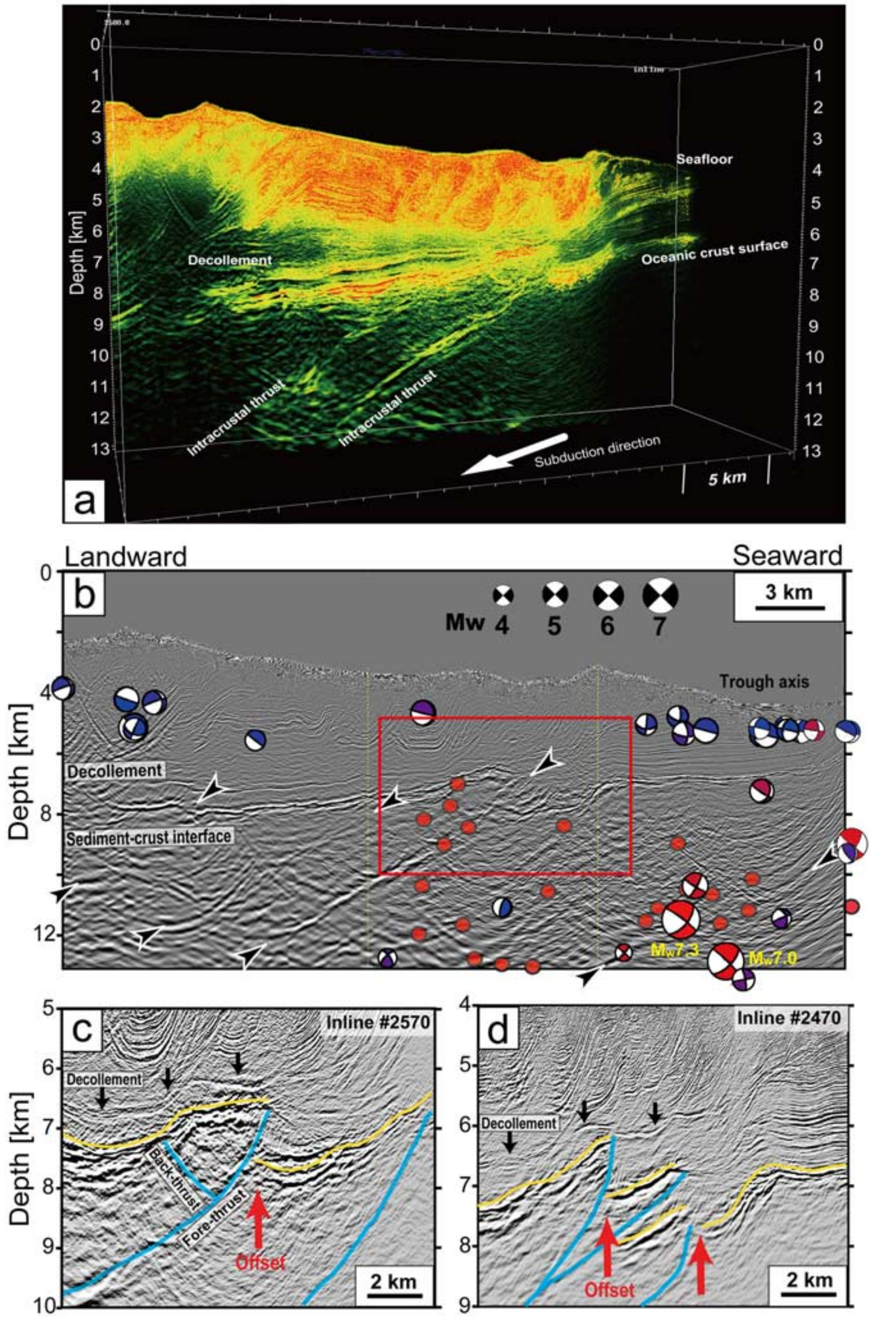

Figure 2. (a) Opacity-limited seismic data for line #2590-2670. Only strong-amplitude reflections are imaged on this figure. The seismic volume is viewed from the western side of the survey area. The offset due to cumulative displacements along the intraoceanic thrust can be seen at the oceanic crust surface. (b) Seismic profile showing the projected focal mechanism distribution (focal spheres from a lateral view) [*Ito et al.*, 2005] and aftershock hypocenters ($M_w > 4$) distributed around our survey area (red circles) [*Sakai et al.*, 2005] (see Figure 3e for line locations). Black arrowheads represent intraoceanic thrusts. The earthquake mechanism within oceanic crust is consistent with the thrust geometry shown here. (c) Enlarged profile from line #2570 showing pop-up structure due to thrust displacement (red rectangle in Figure 2b). Blue and yellow lines represent intraoceanic thrusts and the sediment-igneous crust interface, respectively. (d) Enlarged profile from line #2470 showing offsets due to thrust displacement.

data [*Hara*, 2005] revealed that the second mainshock was a compound event consisting of two different source mechanisms (Figure 4b): a strike-slip component dominated during the first 20 s and was followed by a thrust mechanism generated between 30 and 40 s after the rupture initiation. Inversion of the tsunami data [*Satake et al.*, 2005] further demonstrated that multiple faulting was involved in the second mainshock. The hypocenter of the second mainshock was shallower and closer to the oceanic crust upper surface than that of the first mainshock [*Ito et al.*, 2005].

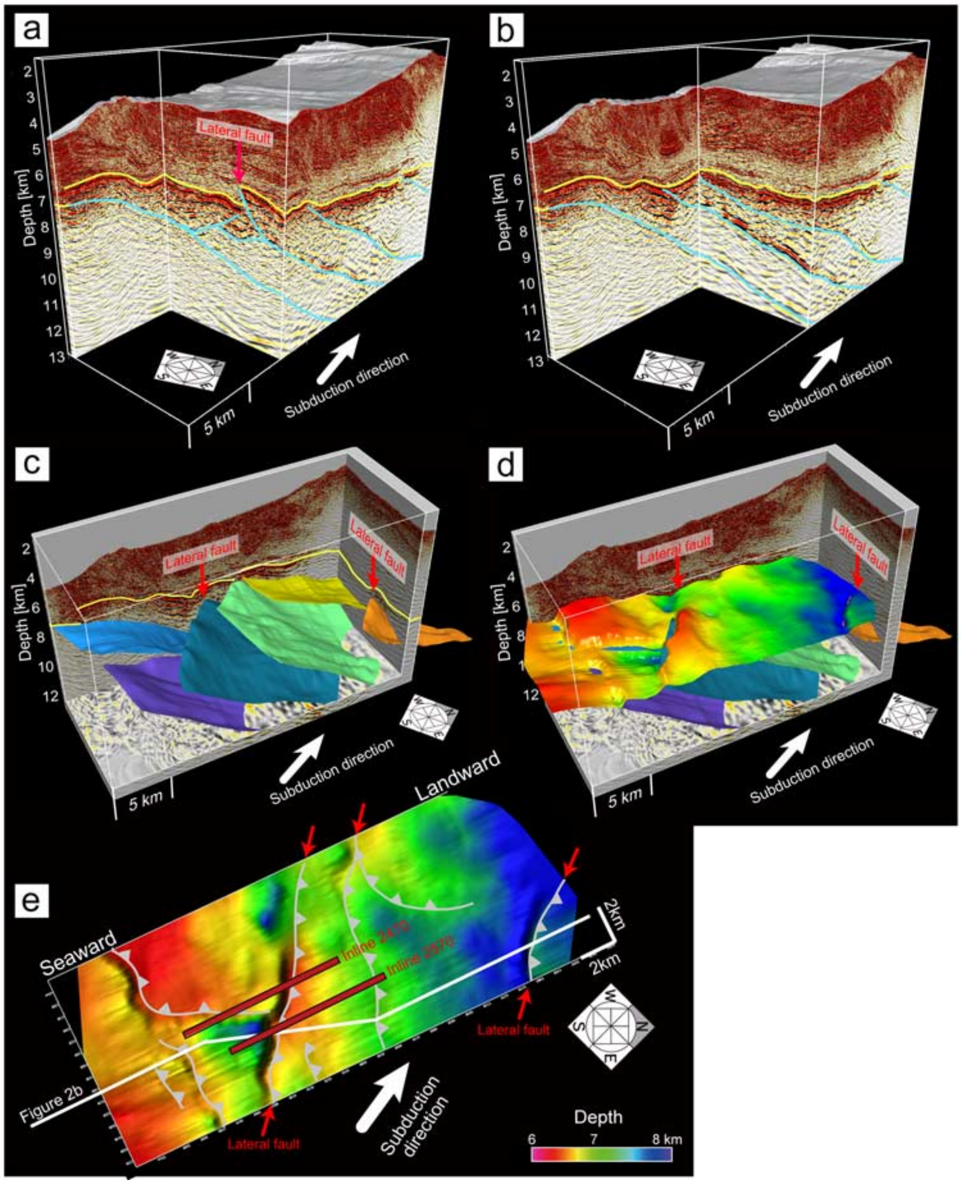

Figure 3. (a and b) 3D prestack depth migrated volumes. Blue lines show the intraoceanic thrusts that have strong and continuous reflections. Yellow lines represent the sediment-igneous crust interface. A lateral faults near the sediment-igneous crust interface are also shown (red arrows). (c) Geometry of intraoceanic thrusts. Almost all intraoceanic thrusts strike E-W and dip to the north. (d) Geometry of oceanic crust upper surface and intraoceanic thrusts. Colours of the crust surface represent depth. (e) Map view of the oceanic crust upper surface. Gray lines represent the traces of several intraoceanic thrusts at the crust surface. The white line shows the location of the seismic profile displayed in Figure 2a. The red lines show the locations of seismic profiles displayed in Figures 2c and 2d.

[10] Because the lateral faults extended upward from an underlying thrust near the sediment-igneous crust interface strike almost parallel or slightly oblique to the subduction direction of the Philippine Sea plate, the geometry of intraoceanic thrusts, including lateral faults, generates both strike slip and reverse slip when the slip direction during an earthquake rupture corresponds to the subduction direction (Figure 4a). Therefore, slip along the intraoceanic thrust explains the complicated composite earthquake mechanisms of the second mainshock. Because the strike of second mainshock during first 20 s is nearly parallel to the subduction direction, the second mainshock initiated at the lateral fault and originated strike slip in the NNW-SSE direction [*Hara*, 2005]. Then, the displacement propagated to the neighbouring deeper intraoceanic thrusts and initiated reverse faulting slip (Figure 4b). Because multiple fault planes as observed from our seismic data may have experienced displacements during the second mainshock, the rupture area of the second mainshock and the aftershock hypocenters cover a wide area [*Satake et al.*, 2005; *Park and Mori*, 2005; *Sakai et al.*, 2005]. Although the 3D seismic survey area does not cover the hypocenter of the second mainshock (Figure 1), the thrusts and lateral faults as observed from our seismic data (Figures 3 and 4a) may exist around the hypocenter of the second mainshock. The 2D seismic data across the hypocenter of the second mainshock

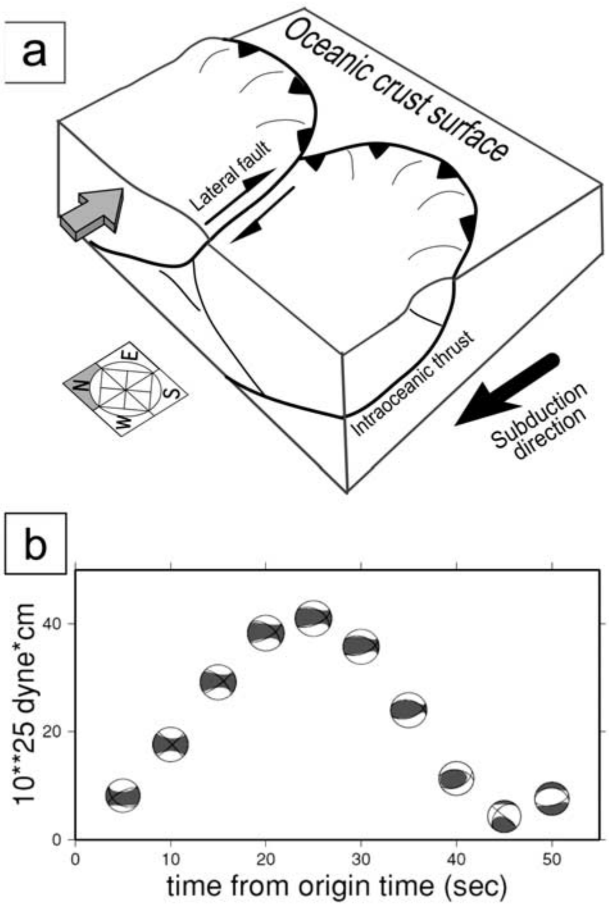

Figure 4. (a) Schematic images of the intraoceanic thrusts and lateral faults observed near the oceanic crust surface. The reverse fault displacement in the subduction direction (black arrow) induces strike-slip movement at the lateral fault developed between intraoceanic thrusts. (b) Temporal change of the moment stress release and focal mechanism for the second main shock of the 2004 off the Kii Peninsula earthquake [*Hara*, 2005]. The vertical axis is the scalar moments of subevents. The complex thrust network revealed by our seismic data explains the compound earthquake mechanisms shown here.

(Figure S1) suggest that intraoceanic thrusts with similar geometry are distributed around the second mainshock area, although we only recognize 2D features of the thrusts as ambiguous reflections.

4. Implications for Periodical Intraplate Earthquake

[11] The cumulative displacements inferred from deformation at the sediment-igneous crust interface suggest that there is potential for large periodic earthquakes, similar to the 2004 earthquake, to occur along the densely-distributed intraoceanic thrusts in the future. Similar intraoceanic thrusts are observed seaward of our survey area (Figure S2) [*Aoki et al.*, 1982], and we suggest that the displacement recently occurred along the thrusts because the sediment above the thrusts including the seafloor is also deformed.

[12] Assuming that the elevation of the crust surface initiated from 70 km seaward of its present position as in the case of the proto-Zenisu ridge east of our survey area (Figure 1), and also assuming plate movement at 5 cm/yr, this allows ~1.4 million years for the thrusts to generate ridges. If each of these earthquakes cause ~1.5 m of up-dip displacement (2–3 m slip along the thrust in the shallower oceanic crust [*Yagi*, 2004]), their repeat cycle will be ~2100 years to construct 1 km offset at the crust surface. Furthermore, the existence of multiple intraoceanic thrusts suggests that there will be more frequent earthquakes within the subducting Philippine Sea plate.

5. Summary

[13] 1. We identified intraoceanic thrusts developed as imbricate structures within the subducting Philippine Sea plate off the Kii Peninsula from 3D seismic reflection data.

[14] 2. The intraoceanic thrusts extracted from our 3D seismic data are distributed around the hypocenters of the first mainshock and aftershocks of the 2004 earthquake. Because the intraoceanic thrust geometries are consistent with the focal mechanism of the first mainshock, we believe that the thrusts with similar characteristics have slipped during the first mainshock.

[15] 3. The geometry of intraoceanic thrusts extracted from the 3D seismic data could explain the complex rupture patterns observed during the second mainshock.

[16] 4. The cumulative displacements inferred from deformation at the crust surface suggest that there is potential for periodic earthquakes, similar to the 2004 earthquake, to occur in the future.

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