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3D geometry of a plate boundary fault related to the 2016 Off-Mie earthquake in the Nankai subduction zone, Japan

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ABSTRACT

We used recent seismic data and advanced techniques to investigate 3D fault geometry over the transition from the partially coupled to the fully coupled plate interface inboard of the Nankai Trough off the Kii Peninsula, Japan. We found that a gently dipping plate boundary décollement with a thick underthrust layer extends beneath the entire Kumano forearc basin. The 1 April 2016 Off-Mie earthquake (Mw6.0) and its aftershocks occurred, where the plate boundary décollement steps down close to the oceanic crust surface. This location also lies beneath the trenchward edge of an older accretionary prism (∼14 Ma) developed along the coast of the Kii peninsula. The strike of the 2016 rupture plane was similar to that of a formerly active splay fault system in the accretionary prism. Thus, the fault planes of the 2016 earthquake and its aftershocks were influenced by the geometry of the plate interface as well as splay faulting. The 2016 earthquake occurred within the rupture area of large interplate earthquakes such as the 1944 Tonankai earthquake (Mw8.1), although the 2016 rupture area was much smaller than that of the 1944 event. Whereas the hypocenter of the 2016 earthquake was around the underplating sequence beneath the younger accretionary prism (∼6 Ma), the 1944 great earthquake hypocenter was close to oceanic crust surface beneath the older accretionary prism. The variation of fault geometry and lithology may influence the degree of coupling along the plate interface, and such coupling variation could hinder slip propagation toward the deeper plate interface in the 2016 event.

1. Introduction

Rupture behavior along plate boundary faults has been intensively investigated because it directly relates to the magnitudes of earthquakes and tsunamis. Many previous studies have analyzed the behavior of deep seismogenic faults from seismic velocity data (e.g., Kamei et al., 2012; Nakanishi et al., 2008; Operto et al., 2006), seismicity observations (e.g., Ito et al., 2012a; Mochizuki et al., 2010), geodetic data (e.g., Ito et al., 2011; Yokota et al., 2016), modeling studies (e.g., Hori et al., 2004; Kimura et al., 2012), borehole observatories (e.g., Davis et al., 2006; Fulton et al., 2013; Wallace et al., 2016), outcrop studies (e.g., Kondo et al., 2005; Rowe et al., 2009; Hashimoto et al., 2013), and laboratory experiments for frictional properties of fault rocks (e.g., Ikari et al., 2015; Ujiie et al., 2013; Saffer and Marone, 2003). These studies contribute to our understanding of the dynamic behavior of plate boundary faults, including slow slip. However, the factors that control coupling degree along plate interface and the location of coseismic zone are still uncertain.

The geometry of the plate boundary fault could also influence rupture behavior, including coupling degree along the plate interface. For example, large topographic features on the subducting plate, such as seamounts, may inhibit rupture propagation and thus serve as fault segment boundaries (e.g., Mochizuki et al., 2008; Kodaira et al., 2006; Henstock et al., 2016). Understanding of detailed fault geometry, such as underplating structures, is poorly constrained by the low resolution of seismic velocity models based on traveltime tomography. The limited resolution of fault geometry models, in turn, has hindered understanding of the influence of geologic structures on coseismic behavior. Moreover, laboratory experiments on the slip behavior of small rock samples (centimeter-scale) cannot consider the influence of larger fault geometry or its roughness. Using modern seismic data and advanced techniques, we can identify the deep plate interface at ∼10 km depth as a re-

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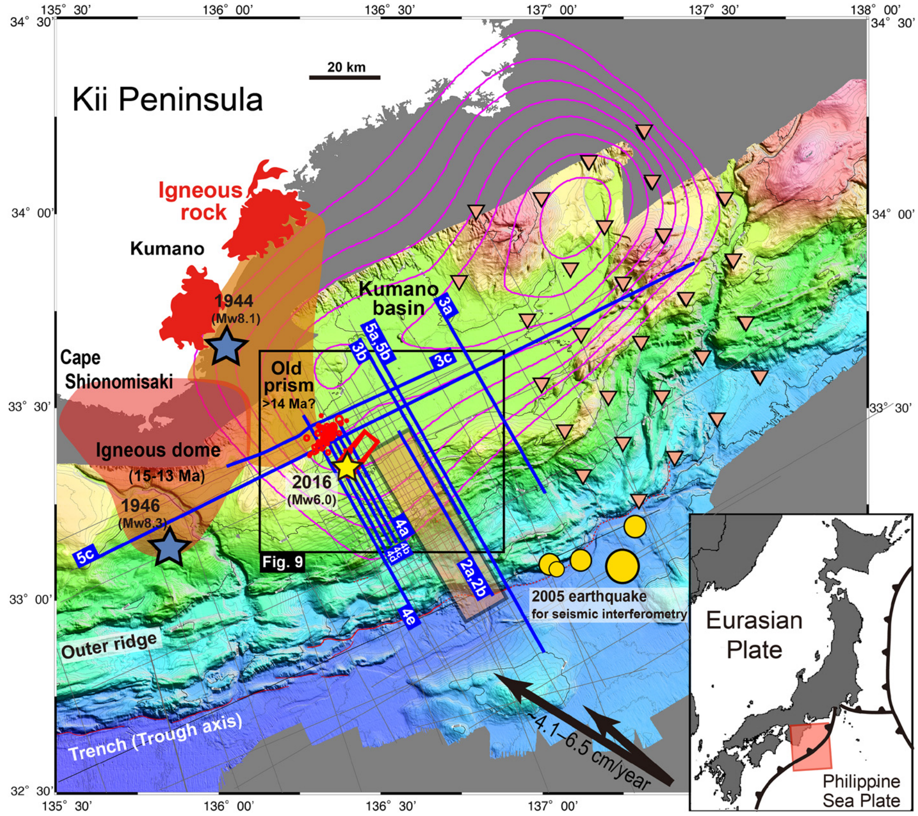

Fig. 1. Location map showing tectonic, bathymetric, and geologic features of the study area. Hypocenters of the 2016 Off-Mie earthquake (yellow star) and the 1944 Tonankai earthquake (blue star) are shown along with the coseismic slip distribution of the 1944 earthquake (red contours, 0.5 m intervals; Kikuchi et al., 2003). Blue lines are the locations of seismic survey lines; numbers on the lines indicate the figure numbers of the corresponding seismic profiles. Triangles indicate ocean bottom seismometer used for seismic interferometry analysis (Fig. 6), and yellow circles indicate the hypocenters of the 2005 earthquake. Black rectangle indicates the area shown in Fig. 9. Fine lines are other seismic survey lines referred in this study. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

flector. The reflection seismic profiles that image the deep plate interface with a higher resolution of ∼100 m may be helpful in analyzing the relationship between fault geometry and earthquake rupture processes (Kimura et al., 2010; Plaza-Faverola et al., 2016; Park et al., 2002).

In the Nankai Trough, where the Philippine Sea plate is subducting beneath the Japanese Islands (Figs. 1 and 2), the 1 April 2016 Off-Mie earthquake (Mw6.0) occurred near the plate boundary (Wallace et al., 2016). This earthquake is believed to have ruptured the same plate boundary fault responsible for great earthquakes (Mw $>$ 8) along the plate interface such as the 1944 Tonankai earthquake (Mw8.1), although the 2016 rupture area was much smaller than that of the 1944 earthquake. Because of this coincidence, it is important to characterize the 2016 Off-Mie earthquake to clarify the factors controlling the coupling degree on plate interface.

The Nankai subduction zone has quasi-periodically generated great interplate earthquakes (Ando, 1975), thus many seismic surveys and drilling campaigns have been carried out to characterize the fault system in the accretionary prism (e.g., Moore et al., 2009; Park et al., 2002). Recent studies using seismic data have shown that the deeper part of a Megasplay Fault in the Nankai accretionary prism can function as a plate boundary décollement, forming a landward continuation of the décollement near the trench (Fig. 2; Tsuji et al., 2014). However, this continuation of the plate boundary décollement is not well mapped at its landward end around the coseismic zone (∼10 km depth). Furthermore, a horizontal reflector identified close to the plate boundary décollement at ∼10 km depth (gray arrow in Fig. 2; white arrow in Fig. 3) has been interpreted as the top of the island arc crust (e.g., Nakanishi et al., 2008; Park et al., 2002; Tsuru et al., 2005; Tsuji et al., 2011). However, recent waveform tomography studies (Kamei et al., 2012, 2013; Fig. 2b) have delineated an area of lower velocity beneath this reflector rather than the higher velocity that would be typical of island arc crust underlying accretionary wedge sediment. As this feature is located in a seismogenic rupture area (contour in Fig. 1; Kikuchi et al., 2003) and at a depth similar to the updip limit of the coupled plate interface, its structure and properties may influence the rupture process. The Off-Mie earthquake (Mw6.0) occurred near the plate boundary décollement and the horizontal reflector beneath the Kumano forearc basin in the Nankai subduction zone (yellow star in Fig. 1; Wallace et al., 2016). It is possible that geometry of the plate interface as well as geologic structures around the fault influenced the coseismic rupture of the 2016 event.

In this study, we analyzed reflection characteristics in the vicinity of the coseismic plate interface (∼10 km depth). We characterize and interpret the plate boundary décollement and surrounding geologic structures (e.g., the horizontal reflector close to the plate boundary décollement) in the transition from the partially coupled to the fully coupled regions in the Nankai Trough. We further address the difference between the partially coupled and fully coupled plate interface by comparing the inferred fault geometry and hypocenters of the 2016 Off-Mie earthquake.

2. Methods and results

To characterize the fault geometry around the plate interface, we analyzed several seismic datasets acquired in the Nankai subduction zone off Kumano, southwest Japan (Fig. 1). In addition to conventional reflection seismic analyses, we used the results de-