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Pore pressure distribution of a mega-splay fault system in the Nankai Trough subduction zone: Insight into up-dip extent of the seismogenic zone

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ABSTRACT

We use the pore pressure distribution predicted from a waveform tomography (WT) velocity model to interpret the evolution of the mega-splay fault system in the Nankai Trough off Kumano, Japan. To map pore pressure around the mega-splay fault and plate boundary décollement, we integrate the high-resolution WT velocities with laboratory data and borehole well log data using rock physics theory. The predicted pore pressure distribution shows that high pore pressures (close to lithostatic pressure) along the footwall of the mega-splay fault extend seaward to the trough region, and the normalized pore pressure ratio is nearly constant over that extent. This continuity of the overpressured zone indicates that a coseismic rupture can potentially propagate nearly to the trough axis. We interpret a high-pressure belt within an accretionary wedge on the landward side of the present mega-splay fault as evidence of the ancient mega-splay fault. Because the ancient mega-splay fault soles into the active mega-splay fault, the active mega-splay fault may function as a basal detachment fault and is directly connected to the seaward plate boundary décollement.

1. Introduction

Earthquakes at convergent plate margins frequently occur at plate interfaces or on splay faults that branch from the interfaces and propagate upward into an overlying wedge (e.g., Park et al., 2002). The structure of these seismogenic faults have been characterized in many subduction zones primarily using seismic images of the tectonic structures (e.g., Kopp et al., 2009; Kopp, 2013; Moore et al., 2009; Ranero and von Huene, 2000; Van Avendonk et al., 2013). Pore pressure distributions around the faults are also a key to understanding coseismic rupture propagation (e.g., Kimura et al., 2012; Moore and Saffer, 2001; Scholz, 1998). Various studies have estimated pore pressure conditions, but these have mostly been limited to the areas around plate boundary décollements near the trough axes (e.g., Bangs et al., 1999; Cochrane et al., 1994; Hayward et al., 2003; Shipley et al., 1994; Westbrook, 1991; Tobin and Saffer, 2009; Tsuji et al., 2008). A lack of accurate estimations of pore pressure from the deeper parts of mega-splay faults has precluded the prediction of pore pressure variations extending from deep mega-splay faults to shallow plate boundary décollements. The variations in pore pressure are crucial in the evaluation of coseismic rupture propagation (e.g., Conin et al., 2012) and the up-dip limit of the coseismic region (Moore and Saffer, 2001; Kimura et al., 2012).

The Nankai subduction zone where the Philippine Sea plate is subducting beneath the Japanese Island at approximately 4–6.5 cm/s (Fig. 1; Seno et al., 1993; Miyazaki and Heki, 2001) is a well studied plate convergent margin (e.g., Bangs et al., 2009; Moore et al., 2009; Park et al., 2010; Tobin et al., 2009). In this convergent margin, great earthquakes in excess of M_w 8 have occurred repeatedly (Ando, 1975) and caused large damage to mega-cities on the Japanese Island. Because of the high seismic risk, geophysical and drilling data have been intensively acquired in the Nankai accretionary prism. Several studies have mapped pore pressure distributions within the accretionary prism seaward of the mega-splay fault (i.e., the outer wedge in Fig. 2b) either using borehole data (e.g., Saffer, 2003; Screaton et al., 2002), or using seismic reflection data (e.g., Tobin and Saffer, 2009; Tsuji et al., 2008). These studies show evidence of high pore pressures beneath the plate boundary décollement near the trough axis.

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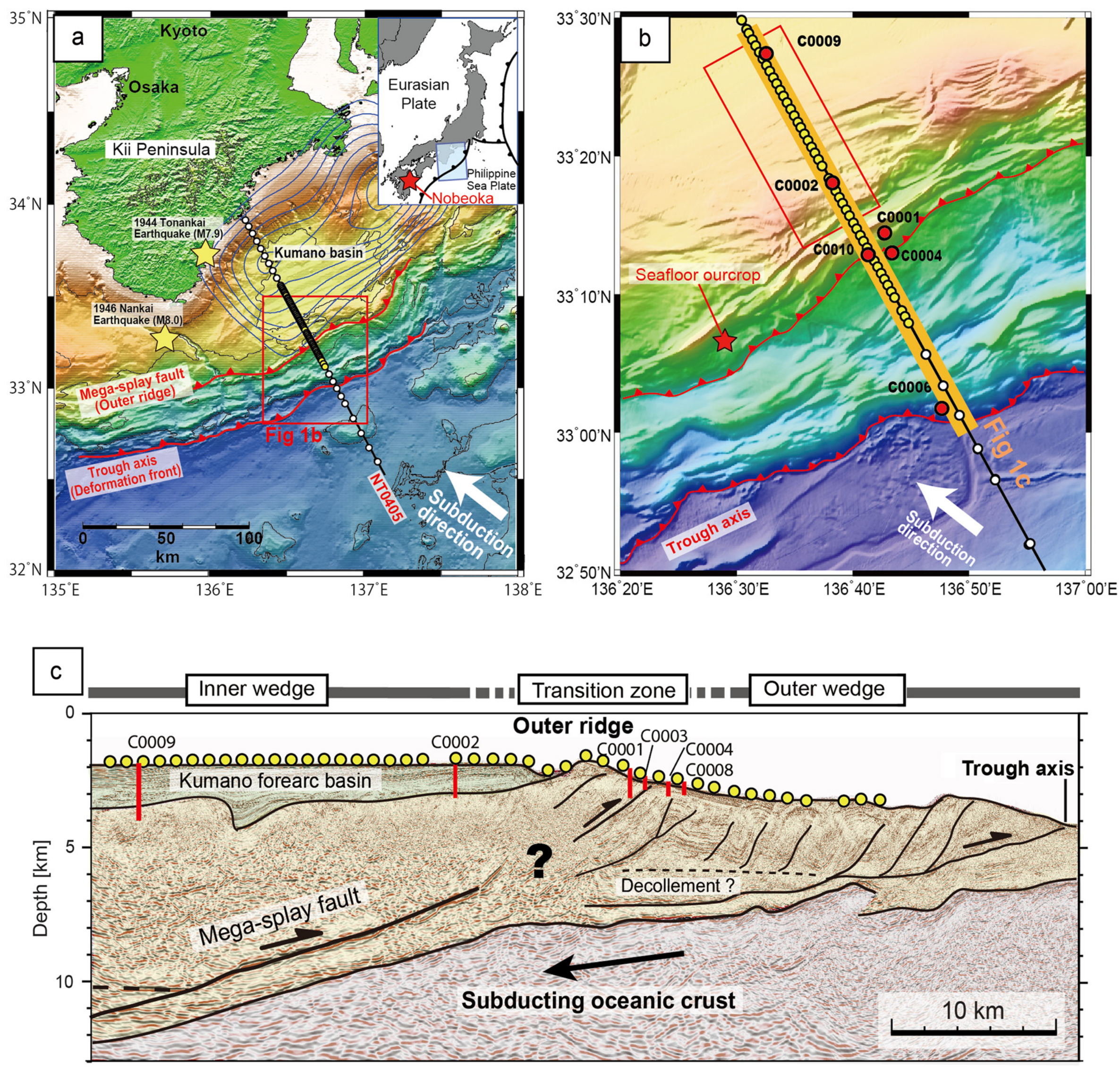

Fig. 1. (a) Seafloor topography in the Nankai Trough off Kumano with survey line location (NT0405). Blue contours show the coseismic slip distribution of the 1944 Tonankai earthquake (0.5 m increment; Kikuchi et al., 2003). Yellow stars show the hypocenters of the 1944 Tonankai earthquake and the 1946 Nankai earthquake. Red star indicates the locations of the Nobeoka thrust. (b) Enlarged seafloor topography around the survey area off Kumano. White and yellow circles on the solid black line indicate OBS positions; yellow circles indicate the OBSs used for Waveform Tomography analysis and correspond to the survey area displayed in Fig. 2(b). The red rectangle corresponds to the area shown in Fig. 8. The red star and circles indicate the locations of seafloor outcrop for rock sampling and boreholes. (c) Seismic reflection profile extracted from 3D seismic volume. The location of this seismic profile is approximately that of the OBS survey line (orange line in panel (b)).

In spite of the extent of the seismic data from the Nankai subduction region, unfortunately the signal-to-noise ratio of the reflection seismic data within the accretionary prism is low on the landward side of the mega-splay fault (Fig. 1; Moore et al., 2009), probably owing to rock consolidation and complicated geological structures. As a result of these data problems, the evolution of the mega-splay fault system cannot be interpreted from reflectivity data alone. Furthermore, the deeper part of the mega-splay fault (approximately 10 km in depth) is too deep to estimate reliable seismic velocities from short-offset (i.e., offsets of less than 6 km) reflection data (Yilmaz and Doherty, 2001), thus to date it has not been possible to predict pore pressures around the mega-splay fault where coseismic slip has believed to occurred (Kikuchi and Yamanaka, 2001; Kikuchi et al., 2003). Seismic velocities for the deep lithology can be revealed by applying traveltime tomography to long-offset ocean bottom seismometer (OBS) data (Nakanishi et al., 2008; Takahashi et al., 2002), but the resolution is typically limited to larger than approximately 1 km, which is not enough to characterize the pore pressure variations along the mega-splay fault.

The existing reflection images also poorly characterized the transition zone between the mega-splay fault developed in the landward inner wedge and the décollement in the seaward outer wedge (Figs. 1b and 2b), due to seafloor multiples that obscure the structural signature of this area (Moore et al., 2009; Yilmaz and Doherty, 2001). The structures and pressure conditions of the transition zone are critical for evaluating the possibility of the coseismic rupture propagation close to the trough axis (e.g., Wang and Hu, 2006). This rupture propagation may trigger large tsunamis, both because the seafloor slope is steeper on the seaward side of the transition zone (Satake, 1994; Tanioka and Satake, 1996) and because the uplift of the deep seafloor near the trough axis amplifies the height of the tsunami (Ryan et al., 2012). The mega-splay fault reaching the seafloor in the transition zone is believed to have ruptured during the 1944 Tonankai earthquake (e.g., Kikuchi and Yamanaka, 2001). However, the 1605 Keicho earthquake (M_W 7.9), was interpreted to have generated coseismic