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PICTORIAL ARTICLE

Bathymetric imaging of protothrust zone along the Nankai Trough

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Bathymetric features on the seafloor often show evidence for crustal deformation by tectonic events. Although the crustal structure obtained from seismic reflection surveys provides important information such as active faults, it is difficult to estimate the lateral continuity from sparse survey lines. In the Nankai Trough in central Japan, great earthquakes with accompanying tsunamis occur with recurrence intervals of 100–200 years. Recent analogue modelling of thrust fault initiation at the toe of a subduction zone, based on the Nankai region, suggests that a new thrust would initiate in the trench axis a few kilometers seaward of the currently active frontal thrust which is the uppermost plate boundary fault at the seaward end of accretionary prism (Dotare, Yamada, Adam, Hori, & Sakaguchi, 2016). In the central Nankai region (off Shikoku), this is the location of a protothrust zone (PTZ) which exists in the seaward region of the frontal thrust, consisting of many incipient thrusts within the trench sediment wedge, as imaged in legacy seismic reflection profiles (e.g. Moore, Mikada, Moore, Becker, & Taira, 2005). The PTZ is an area at the stage of frontal thrust initiation (Figure 2b), where several incipient faults with indistinctive displacement are formed. The PTZ is also recognized in other seismogenic subduction margins associated with incipient deformation by subduction (e.g. Barnes et al., 2010). Not only the splay fault from the seismogenic zone, but also the frontal thrust has the possibility to initiate the tsunamigenic rupture estimated by drilling results (Sakaguchi et al., 2011) Thus, it is important to investigate the PTZ along the trench for understanding the process of the development of a new frontal thrust.

In order to extract the micro-scale deformation of the PTZ at the seafloor, we applied a new developed elaborate visualization "Red Relief Image Map (RRIM)" (Chiba, Kaneda, & Suzuki, 2008) which is a new three-dimensional presentation technique to high-quality bathymetric data by the multi-narrow beam echo sounder which have been simultaneously acquired for high-resolution bathymetric data associated with seismic survey area (Figure 1). The RRIM method was developed to image by the multi-layered topographic information such as landform element layers, topographic slope, positive openness and negative openness using high-density, high-resolution Digital Elevation Model (DEM) data on onshore region (Chiba et al. 2008; Chiba, Suzuki, & Hiramatsu, 2007). The new parameter I using the RRIM method is calculated from the two following openness parameters:

$$I = (Op - On)/2$$

where Op and On represent positive and negative openness, respectively.

The method is known to be an effective tool for the extraction of slight active fault traces hidden under vegetation on land (e.g. Lin, Kaneda, Mukoyama, Asada, & Chiba, 2013). To understand the geomorphologic features in PTZ, we apply this RRIM method to integrate the overall DEM data with a minimum resolution of 50 m using high-quality bathymetric data obtained by legacy seismic surveys (e.g. Park et al., 2002). The RRIM method can be deduced from the deformation of a different scale in the same figure. Figure 1 shows the RRIM image from Izu Arc to Nankai Trough. Clear complicated deformation structures around the volcanic front, such as a volcano-bounded basin between rear arc volcanos (e.g. Yamashita, Takahashi, Tamura, Miura, & Kodaira, 2017), are recognized in Izu Arc.

We carried out a dense high-resolution seismic reflection survey with 10–20 km spacing over 1500 km of line length during 2013 and

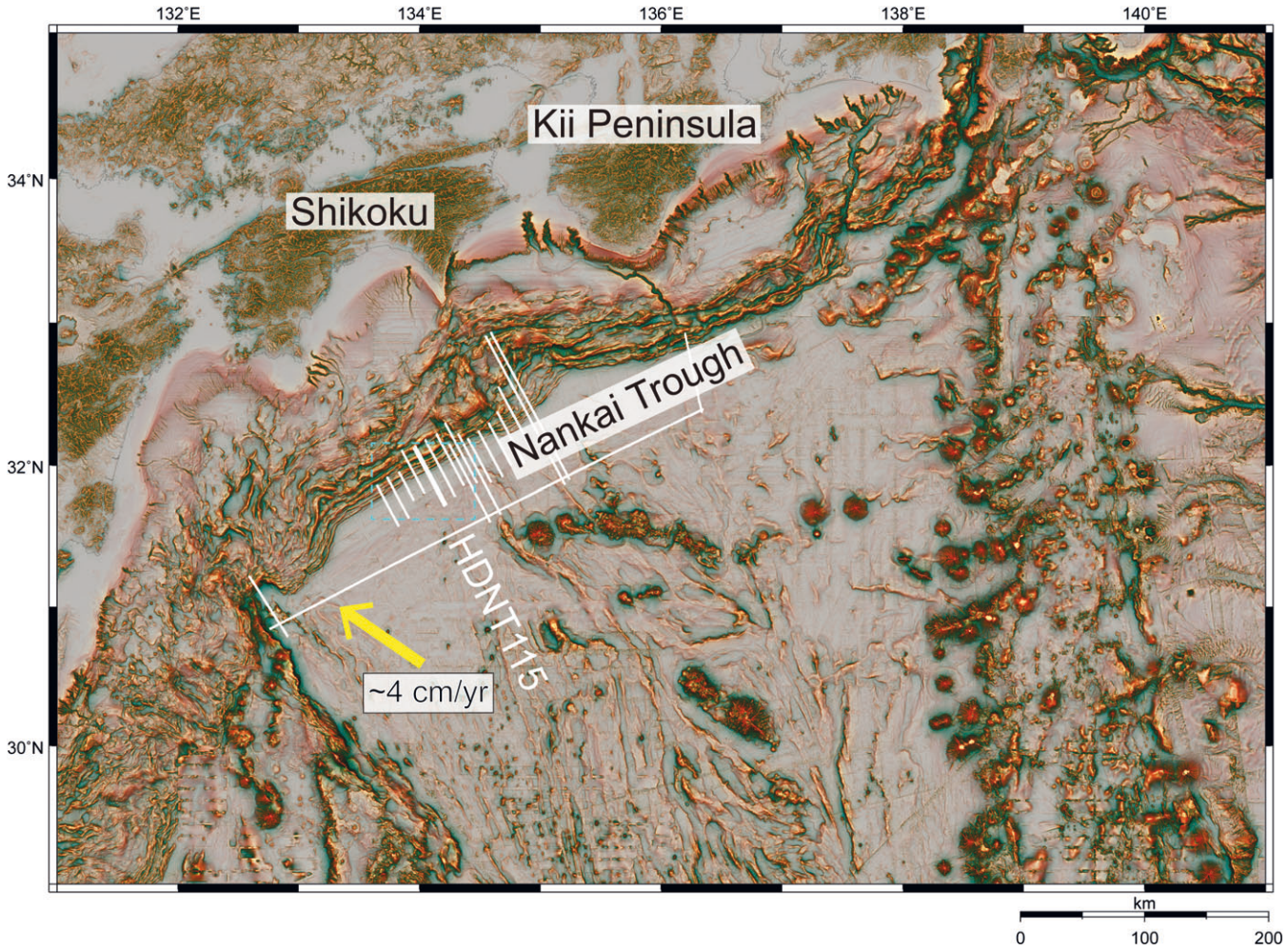

FIGURE 1 Map showing red relief image map around the Nankai Trough area, Japan. White lines represent our seismic reflection survey lines across the trench axis. The yellow arrow indicates the direction of plate convergence reported by Seno, Stein, and Gripp (1993). The light blue box shows the location of Figure 3a,b

2014 in order to understand the deformation around the frontal thrust at the trench axis (Figure 1). Clear seismic reflection images from frontal thrusts to PTZ along the trench axis are obtained between off Cape Muroto and off Cape Ashizuri (Figure 2).

It is difficult to image the deformation of both the frontal thrust and the protothrust zone by conventional bathymetric mapping due to the different scale of their deformation. To image the detailed characteristics of the seafloor, we use the RRIM method with color depending on the depth scale. Figure 3 shows the expanded edition of conventional bathymetric map and multi-colored relief image map around the Nankai Trough. Not only the visible deformation of the accretionary prism, but also some arrangements of incipient thrust beneath the seafloor within PTZ corresponding to seismic reflection profiles along the trench axis are sharply recognized by the RRIM method. Our findings can provide information about possible location of future frontal thrust within the PTZ.

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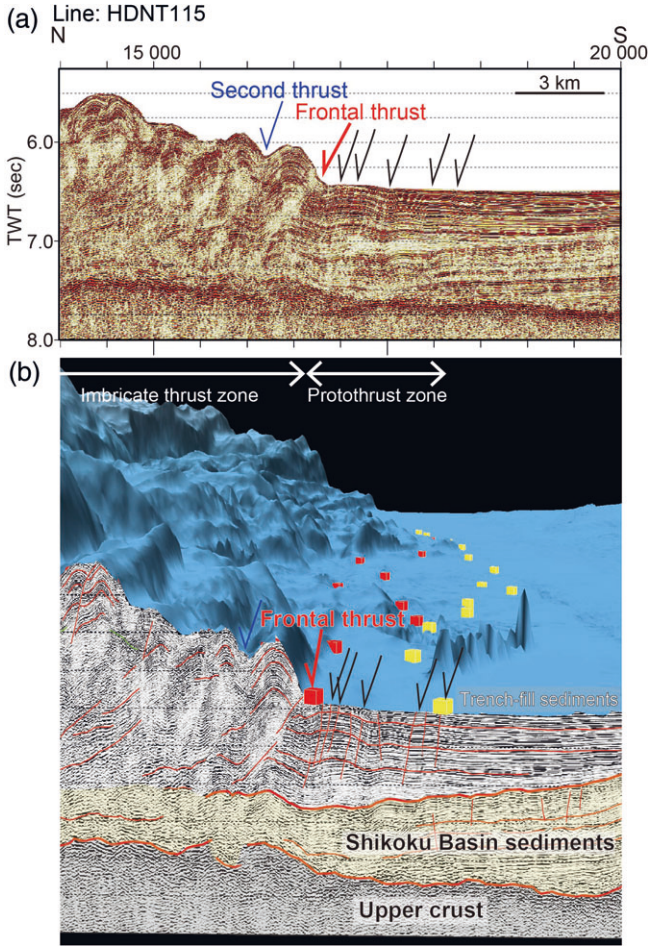

FIGURE 2 Poststack time migrated profile of line HDNT115 (a) and its interpretation with bathymetry (b) showing the detailed structure of the trench axis. The horizontal axis is the common depth point (CMP) number. The CMP interval is 3.125 m in this survey line. The vertical axis shows the two-way travel time (TWT) in seconds. Red arrow indicates the location of frontal thrust at seafloor. Red boxes on the seafloor indicate the location of frontal thrust at seafloor constrained by this study. Black arrows show the incipient thrust in the protothrust zone. Yellow boxes on the seafloor show the location of the seaward end of protothrust at seafloor constrained by this study. The vertical exaggeration of profile is approximately 5 assuming 1500 m/s for the velocity

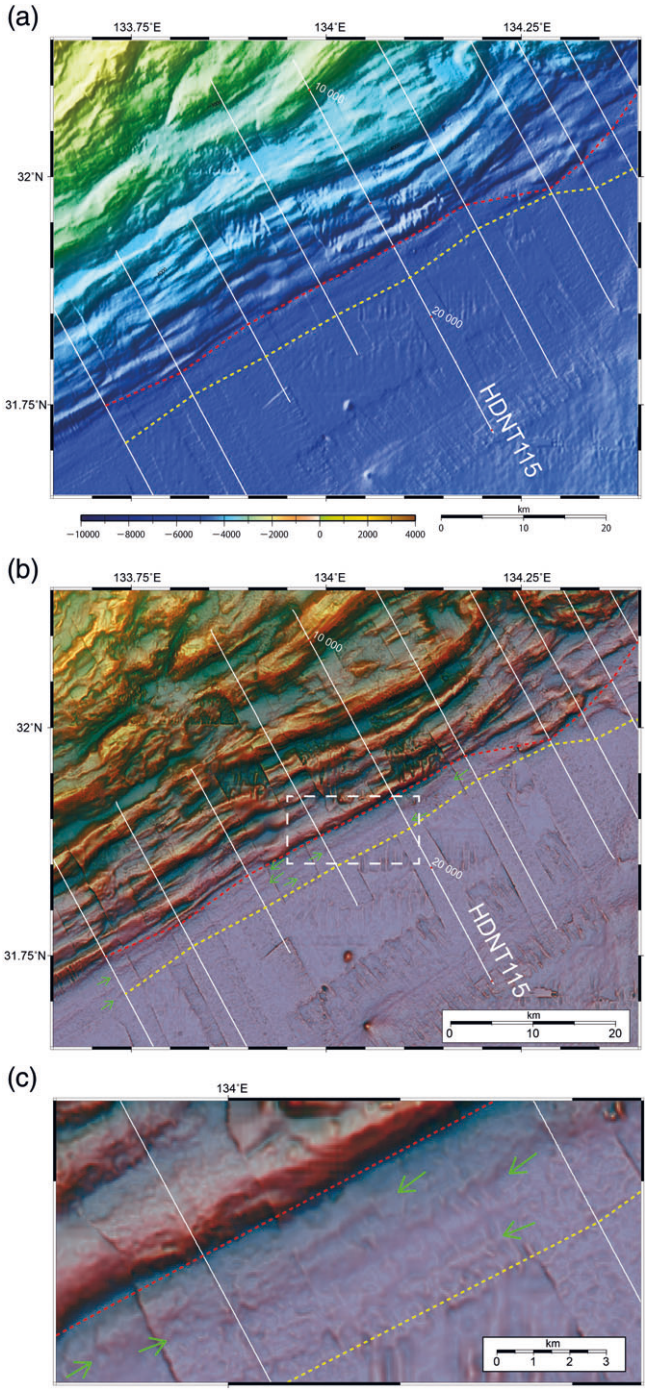

FIGURE 3 Detailed map around the protothrust zone in the Nankai Trough. Red dashed line shows the location of frontal thrust traced from seismic reflection profiles. Yellow dashed line indicates the seaward end of protothrust zone trace from seismic reflection profiles. Green arrows show the location of the lineation in the protothrust zone imaged by multi-color relief map. (a) Conventional bathymetric map. (b) Multi-color relief image map. White dashed box shows the area of (c). (c) Enlarged multi-color relief image map

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