Structural Anomaly at the Boundary Between Strong and Weak Plate Coupling in the Central-Western Nankai Trough

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Abstract To investigate structural characteristics associated with variations in slip behavior on the plate boundary in the Nankai subduction zone, we conducted seismic reflection surveys in the central-western Nankai Trough. Data were processed by pre-stack depth migration. The resulting depth map of the top of the subducting Philippine Sea plate shows detailed topographic features of the plate boundary, including subducting seamounts and large-scale undulations of the plate surface. We report the presence of a structurally anomalous region, potentially with low velocity, in the overriding plate at the boundary between the zone of large coseismic slip during the 1946 Nankai earthquake and the area producing slow earthquakes. This anomaly appears to be related to depth-dependent variations in plate boundary slip style and plate coupling in the central-western Nankai Trough.

Plain Language Summary The central-western Nankai Trough off southwestern Japan is one of the best locations to study variations in slip style on the plate boundary fault in subduction zones because the fault slip distribution during the latest great earthquake, the distribution of slow earthquakes, and interplate coupling are known from previous studies. We conducted seismic surveys along densely distributed survey lines to image detailed subsurface structures in the central-western Nankai Trough. A three-dimensional map of the plate boundary fault geometry was created from seismic profiles used in this study. We found a structural anomaly, interpreted as a low-velocity zone in the overriding plate, at the boundary between the slip zone of great earthquakes and the zone of slow earthquakes. This anomaly might be related to the variation of the plate boundary fault slip styles.

1. Introduction

Megathrust earthquakes in subduction zones generate strong ground motion and destructive tsunamis that cause devastating damage in populated areas. The updip limit of the megathrust rupture zone constrains the potential size of these earthquakes. Massive tsunamis are often caused by seafloor displacement in the shallow portion of subduction zones during megathrust earthquakes, such as the 2011 Tohoku earthquake (e.g., Satake et al., 2013; Yamazaki et al., 2018). Studies of the shallow subduction zone thus are indispensable to understanding the megathrust rupture process and also subduction zone tectonics.

The shallower part of subduction zones can be divided into two or three regions by their characteristic slip behavior, such as unstable, stable, and conditionally stable slip (e.g., Bilek & Lay, 2002). Recently, Obara and Kato (2016) presented a model of the Nankai Trough subduction zone off southwestern Japan based on the characteristic time scale of seismological and geodetic events. Their model has three regions in the shallow subduction zone; at increasing depths landward from the trench axis, these are the stable sliding zone, transition zone, and seismogenic zone. In the stable sliding zone, the plate boundary fault creeps without seismic ruptures. In the seismogenic zone, megathrust earthquakes rupture the plate boundary fault, and coupling is strong on the plate boundary. The transition zone is where intermittent slip events such as slow earthquakes occur. Coupling is relatively weak in the transition zone. The boundary between the seismogenic and transition zones corresponds to the updip edge of the rupture area of great earthquakes; therefore, it is important to understand the structural factors defining this boundary.

The Nankai Trough subduction zone, where the Philippine Sea plate subducts beneath the Amur plate, has experienced multiple great earthquakes (Nankai earthquakes) and tsunamis in the last millennium at recurrence intervals of ~100–200 yrs (Ando, 1975). The latest Nankai earthquake occurred in 1946 in the western Nankai Trough. Tsunami inversions revealing the slip distribution during this earthquake (Baba & Cummins, 2005;
Tanioka & Satake, 2001) suggest that large slip did not occur along the shallow part of the subduction zone in the central-western Nankai Trough, from off Kii Channel to off eastern Shikoku Island (Figure 1a). Recently, dense onshore and offshore observation networks have detected very low frequency earthquakes (VLFEs) (Nakano et al., 2018; Takemura, Matsuzawa, et al., 2019; Takemura, Noda et al., 2019). The blue rectangle is the location of a slow slip event from Yokota & Ishikawa (2020). Bold yellow dotted ellipses are the locations of subducted seamounts inferred by Bangs et al. (2006), Kodaira et al. (2000), and Park et al. (1999), from north to south. The red dashed line outlines the area of the large coseismic slip during the 1946 Nankai earthquake from Tsunami inversion (Baba & Cummins, 2005). The magenta shading indicates the region of strong interplate coupling from geodetic data (Nishimura et al., 2018). The white arrow shows the motion of the Philippine Sea plate relative to the Amur plate (Argus et al., 2011). The black dashed line is the location of the deformation front. (b) Straight black lines are the locations of PreSDM profiles from newly acquired (solid) and previously acquired (dashed) seismic data. Black dotted lines are locations of the depth-converted seismic profiles acquired with short streamer cables (Yamashita et al., 2018). Lines highlighted in green correspond to PreSDM profiles in Figures 2 and S1–S6. The green dashed line is the location of a seismic refraction line SK01 (Nakanishi et al., 2018). The cyan dashed line denotes the Tosabee Trough and its western extension.

To investigate the structural factors associated with slip behavior on the megathrust fault, we conducted seismic reflection surveys in the central-western Nankai Trough along densely distributed survey lines. We used prestack depth migration (PreSDM) to process the newly acquired and previously acquired seismic data and produce depth seismic profiles, which we interpreted to map the structural characteristics in the shallow subduction zone. This paper focuses on the structure around the plate boundary fault and presents a detailed depth map of the upper surface of the subducting Philippine Sea plate, which depicts the large-scale heterogeneous structure in addition to the detailed geometry of subducting seamounts inferred previously (Bangs et al., 2006; Kodaira et al., 2000; Park et al., 1999). We discuss these structural features and correlate them to the subduction zone model in the Nankai Trough.
2. Data and Processing Method

We relied on three types of seismic reflection data to map the detailed structures from the trough axis to the updip edge of the megathrust rupture zone in the central-western Nankai Trough (Figure 1b). These data covered the area from off Cape Shionomisaki to off Tosa Bay with line intervals of approximately 4–8 km.

The primary datasets were obtained by three dedicated seismic surveys, carried out in November–December 2018 by R/V Kaimei (cruise KM18-10), in December 2019 to January 2020 by R/V Kairei (cruise KR19-E03), and in August 2020 by R/V Kaimei (cruise KM20-05). As summarized in Table S1, we used large sound sources (>120 L) and towed streamer cables ∼4–5.5 km long at a depth of 25 m to enhance reflections from deep features such as the top of the subducting oceanic plate. The reflection data were processed by Kirchhoff prestack depth migration (PreSDM) by DownUnder GeoSolutions (DUG) in Kuala Lumpur, Malaysia to produce the depth seismic profiles. Noise reduction and signal enhancement techniques included deghosting, designature, debubbling, attenuation of surface-related multiples, and parabolic Radon transform filtering. The velocity model for PreSDM was initially built by conversion of the RMS velocity model determined from the prestack time migration analysis and then updated by the tomographic approach. The accuracy of velocity modeling in PreSDM analysis basically depends on the streamer cable length. In our study area, velocities within the older accretionary prism beneath the middle to upper trench slope and the oceanic crust in the landward part of the profiles are not accurately constrained because of their greater depths. We estimated velocities in regions deeper than ~2 km beneath the seafloor by combining forward modeling with reflection tomography. Velocity models in which velocities higher than 3 km/s were replaced with a uniform value were generated after several updates of the initial velocity model. PreSDM profiles were created using these velocity models. We tested uniform velocities of 3, 4, 5, and 6 km/s, and after evaluating them by visually inspecting the reflection from the top of the subducting oceanic plate, a uniform velocity of 4 km/s was selected. The resulting velocity model was then updated with reflection tomography to flatten reflection events in common image point gathers. Next, the velocity beneath the top of the oceanic plate was replaced with a uniform velocity of 5 km/s and updated by tomography.

To improve the spatial sampling of the reflection profile, we reprocessed reflection data acquired in 1997 and 1999 in the study area (Figure 1b and Table S1). Although the data were acquired with shorter cables and smaller sound sources than the newly obtained data, we applied the same noise reduction and signal enhancement techniques before PreSDM processing. The PreSDM images from the old data were helpful for interpreting the subducting plate interface.

Other recent reflection profiles obtained with a short streamer cable (∼1.2 km) and a small air gun array (∼6 L) in the trough axis area (Yamashita et al., 2018) were depth-converted and interpreted to fill gaps at the shallowest subduction zone off Shikoku Island (Figure 1b and Table S1). The depth conversion was based on the velocity models derived from our nearby seismic survey lines.

3. Results and Discussion

3.1. Three-Dimensional Image of the Subducting Philippine Sea Plate Surface

The depth profiles in the central-western Nankai Trough subduction zone clearly show the seismic structure of the overriding plate and the shallowest part of the subducting plate from the trough axis to the updip edge of the megathrust rupture zone (Figure 2). Reflections of the top of the subducting Philippine Sea plate (referred to hereafter as the basement) can be traced in most of the profiles. The fold-and-thrust deformation structure with a decollement is apparent in the shallowest part of the subduction zone, as imaged by previous studies in this region (e.g., Bangs et al., 2004; Moore et al., 1990).

The basement depths in the profiles were gridded with the nearest neighbor algorithm to produce a map showing the basement depth from the trough to ~60–100 km landward of the central-western Nankai Trough (Figure 3a). This map shows detailed topographic highs and lows on the upper surface of the subducting plate in addition to the large-scale plate geometry. The result is generally consistent with earlier models of the subducting plate (Baba et al., 2002; Nakanishi et al., 2018), which include a shallower portion of the subducting plate southeast of Cape Muroto. Our densely spaced seismic reflection data set reveals the detailed basement topography without relying on interpolation between sparse datasets. The position of the subducting plate is deeper off the western Kii Peninsula, which is consistent with a recent regional-scale tomographic study (Arnulf et al., 2022). In the
landward portion of the study area, the absolute depth of the subducting plate is 0.5–1.5 km shallower than in the previous models. This difference arises from the deeper part of the overriding plate, where our velocity estimate of ∼3.3–3.9 km/s (Figures S1–S4) is ∼10%–25% lower than estimates by previous refraction seismic studies in this region (e.g., Nakanishi et al., 2018; Qin et al., 2021).

Figure 2. Selected PreSDM profiles with interpretation. (a) Line KIN052 off Kii Channel. (b) Line SIN130 off eastern Shikoku. (c) Line SIN094 off central Shikoku. Profile locations are shown in Figure 1b. Green, brown, and cyan shading denote the Philippine Sea plate, accretionary prism, and the slope and basin sediment layer, respectively. Red and magenta lines indicate thrust faults and the decollement, respectively. Bold dashed red and bold magenta lines above each profile denote approximate locations of the rupture zone of the 1946 Nankai earthquake by Baba and Cummins (2005) and the strong coupling area by Nishimura et al. (2018), respectively. Seismic profiles without interpretation and PreSDM velocity models for each line are shown in Figures S1–S3. Vertical exaggeration is 2x.
Our depth map allows the basement to be visualized in unprecedented detail. Significant features include the surface topography of subducting seamounts previously detected off Cape Muroto (Kodaira et al., 2000; Park et al., 1999). The seismic refraction study of Kodaira et al. (2000) showed a large subducted seamount ∼50 km wide in the dip direction and ∼13 km thick. Although our surveys could not detect the base of the seamount, its upper surface could be imaged as part of the basement in our reflection data (feature A in Figure 3a and S4). The seamount appears to have two or three peaks reaching >1 km above a regional topographic high. It is similar in these respects to the Kinan Seamount Chain south of the Nankai Trough (Figure 1). We also confirmed the presence of another subducted seamount reported by a previous reflection study south off Cape Muroto by Park et al. (1999), as well as another seamount of similar size to its west (features B and C in Figure 3a). Local basement highs off Kii Channel may also be subducting seamounts that have not been previously reported (feature D in Figure 3a).

The Shikoku Basin south of the Nankai Trough was formed by backarc opening of the Philippine Sea during ∼30–15 Ma (Okino et al., 1999). Depressions with a NNW-SSE strike near the trough axis and on the incoming Philippine Sea plate appear in our basement map (features E and F in Figure 3a). These depressions represent grabens, formed during the formation of the Philippine Sea plate (e.g., Kimura et al., 2021), that are filled with thick sediments (e.g., Ike et al., 2008; Tilley et al., 2021).

3.2. Residual Basement Depth and Structural Anomaly

To accentuate the detailed basement topographic information, we produced a residual depth map (Figure 3b) by subtracting a smoothed basement depth (Figure S7) from the gridded depth map in Figure 3a. The smoothed basement map was computed by applying a boxcar filter with a length of 0.5° to the gridded depth map. The residual map clearly shows peaks on the subducting seamounts as local high anomalies and the NNW-SSE trending grabens as low anomalies. In addition, a narrow, arcuate depression that appears to extend intermittently over ∼100 km from off Kii Channel to off central Tosa Bay coincides with the location of the Tosabae Trough on the bathymetric map (Figures 1 and 4).

Figure 3. (a) Depth map of the Philippine Sea plate basement relative to sea level. The background shows the gray shaded bathymetry. A and B denote seamounts corresponding to those proposed by Kodaira et al. (2000) and Park et al. (1999), respectively. C and D indicate possible subducted seamounts found in this study. E and F indicate NNW-SSE trending grabens in the incoming Philippine Sea plate. The black dashed line is the location of the deformation front. (b) Residual depth map of the Philippine Sea plate basement, produced by subtracting the smoothed depth map (Figure S7) from the original depth map (Figure 3a). Blue and red areas indicate local depressions and local highs, respectively. Contours represent 500 m. The magenta dashed line indicates the location of the Tosabae Trough (Figure 1). Brown arrows indicate the arcuate anomaly mapped in this study. The black dashed line is the location of the deformation front.
Because our streamer cable was not long enough to accurately constrain seismic velocities at the depth of the mapped depression, this arcuate feature may represent velocity anomalies within the overlying plate along the Tosabae Trough rather than a basement depression. Seismic refraction data are more sensitive to velocity variations at depth than seismic reflection data because they have longer offsets. Recent seismic refraction studies from ocean bottom seismographs in our study area have documented velocity variations in the overriding plate ∼40–60 km landward from the trough axis (Fujie et al., 2020; Nakanishi et al., 2018; Qin et al., 2021). The velocity model from one of these studies (Line SK01 in Nakanishi et al., 2018, Figure 1b) shows a low-velocity zone down to ∼5 km depth within the hanging wall beneath the Tosabae Trough, that was not resolved by our PreSDM analysis of reflection data (Figures S1–S5). However, these seismic refraction data were not densely distributed in our survey area, and the low-velocity zone could be confirmed only along the refraction survey lines, thus the

Figure 4. Schematic view showing the relationship between the structural anomaly and the seismogenic zone model in the central-western Nankai Trough. Note that the depth of the low-velocity zone is unknown. The approximate location of the upper figure is shown in the lower figure. The lower figure is the same as Figure 3b with very low frequency earthquakes (VLFEs) (green crosses) and a slow slip event (green rectangle).
refraction data cannot unambiguously support an along-strike extension of the low-velocity zone along the Tosabae Trough. A previous 3D tomographic study in this area showed a low-velocity area in the overriding plate off Kii Channel (Yamamoto et al., 2017), but their low-velocity does not coincide with the structural anomaly in this study. Therefore, we cannot exclude the possibility that a basement depression extends along the Tosabae Trough. If there is little or no velocity variation around the putative depression, as used in PreSDM analysis, then a basement depression on the seismic profiles and the map would be the preferred interpretation. Absolute depths of the subducting plate could have errors, as mentioned in the previous section; however, both interpretations (basement depression or low-velocity zone in the hanging wall) are still possible because our maps were based on velocity models with little horizontal variation above the putative depression. Regardless of our interpretation, our seismic data analysis and basement mapping strongly suggest the presence of an anomaly along the Tosabae Trough.

Tsuij et al. (2013) identified widely distributed thrust and strike-slip faults within the subducting Philippine Sea plate off the eastern Kii Peninsula, which the authors connected to vertical offsets of the plate basement. Many of these interpreted faults showed strong reflections. In our survey area, to the west of that area, no such faults or strong reflections were imaged within the subducting plate beneath the putative depression (e.g., Figure 2b). The putative depression might be a basement low surrounding a subducting seamount chain such as the Kinan Seamount Chain. The leading flank of such a subducting topographic high would likely form backthrusts (Dominguez et al., 1998; Sun et al., 2020), which in turn would generate deformation in the hanging wall represented by the Tosabae Trough. The deformation might also cause low velocities along the backthrust faults. All things considered, we prefer the interpretation that a low-velocity zone exists in the hanging wall along the Tosabae Trough.

3.3. Structural Anomaly and Subduction Zone Model

The location of the imaged anomaly corresponds to the updip edge of the 1946 Nankai earthquake rupture zone (Baba & Cummins, 2005) and also lies at the downdip edge of the zone of slow earthquake activity (Nakano et al., 2018; Takemura, Matsuzawa, et al., 2019; Takemura, Noda, et al., 2019; Yokota & Ishikawa, 2020), where the boundary between seismogenic and transition zones is defined in the subduction zone model of Obara and Kato (2016). The structural anomaly also closely corresponds to the boundary between regions of strong and weak interplate coupling (Nishimura et al., 2018).

A bathymetric depression that apparently is an eastern extension of the Tosabae Trough is present at the seaward edge of the forearc Kumano Basin southeast of the Kii Peninsula. Martin et al. (2010) analyzed 3D seismic data and interpreted the presence of the Kumano Basin edge fault zone (KBEFZ) (Moore et al., 2009) below this depression. Although our data do not permit us to recognize faults beneath the Tosabae Trough, we speculate that a fault zone similar to the KBEFZ may underlie the Tosabae Trough. Fracturing in this fault zone, located at the boundary between zones of strong and weak interplate coupling, could account for the low-velocity zone suggested in the overriding plate.

The KBEFZ has a strike-slip component related to the oblique subduction of the Philippine Sea plate (Martin et al., 2010). The structural anomaly of this study also could be a strike-slip fault zone, like the Median Tectonic Line on the southwestern Japanese islands. A positive gravity anomaly is mapped landward of our structural anomaly (Basset et al., 2016). If it represents a strike-slip fault, our structural anomaly may be a boundary between a landward high-density portion of the hanging wall and a seaward lower-density portion of the hanging wall. The high-density portion could contribute to strong plate coupling landward of the anomaly, where megathrust earthquakes have nucleated (Figure 4).

Slow earthquakes have been studied as part of the broad spectrum of slip behavior along megathrust faults. These events have been often related to subducting roughness, such as seamounts and ridges, in several subduction zones (e.g., Barker et al., 2018; Nishikawa et al., 2019; Toh et al., 2020; Wang & Bilek, 2011). A recent modeling study reported the presence of a stress shadow in the wake of a subducting seamount, in which slow earthquakes occur (Sun et al., 2020). The VLFEs and slow slip events in the central-western Nankai Trough are scattered along the trough axis (Figure 1) and are not clearly connected to the individual seamounts in our map of basement topography (Figure 3a). The oblique subduction of the large basement bulge, shown on the smoothed depth map (Figure S7), may have pervasively damaged the hanging wall sediments in the seaward side of our study area, creating stress conditions favorable for slow earthquakes where plate coupling is weaker beneath the low-density
overburden. Further investigations including accumulation of slow earthquake records, detailed interpretation and mapping of hanging wall deformation will be necessary to reveal the relationship between structure and occurrence of slow earthquakes.

4. Summary

Newly acquired densely spaced seismic reflection profiles in the central-western Nankai Trough enabled us to investigate detailed topographic features on the upper surface of the subducting Philippine Sea plate. The locations and shapes of subducted seamounts are clear on the resulting basement map. An apparent arcuate depression of the basement was mapped from the seismic data extending ~100 km along the Tosa Bay from off Kii Channel to off central Tosa Bay. This anomaly could be interpreted as either a low-velocity zone in the sedimentary wedge in the overriding plate or a depression in the subducting plate surface. We prefer the former interpretation based on seismic refraction data and comparison with the eastern Nankai Trough. This anomaly is located at the boundary between areas of the strong and weak interplate coupling. The low velocity may be the result of faulting in the hanging wall plate at the updip edge of the seismogenic zone. This structural anomaly should be correlated with depth-dependent variations of slip behavior on the plate boundary.

Data Availability Statement

Seismic data used in this study are available at the JAMSTEC seismic survey database (http://www.jamstec.go.jp/obsmscs_db/e/index.html).

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