Research Article

Variations in sediment thickness and type along the northern Philippine Sea Plate at the Nankai Trough

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Abstract We documented regional and local variations in basement relief, sediment thickness, and sediment type in the Shikoku Basin, northern Philippine Sea Plate, which is subducting at the Nankai Trough. Seismic reflection data, tied with ocean drilling program drill cores, reveal that variations in the incoming sediment sequences are correlated with basement topography. We mapped the three-dimensional seismic facies distribution and measured representative seismic sequences and units. Trench-parallel seismic profiles show three regional provinces in the Shikoku Basin that are distinguished by the magnitude of basement relief and sediment thickness: Western (<200–400 m basement relief, >600 m sediment thickness), Central (>1500 m relief, ~2000 m sediments), and Eastern (<600 m relief, ~1200 m sediments) provinces. The total thickness of sediment in basement lows is as much as six times greater than that over basement highs. Turbidite sedimentation in the Shikoku Basin reflects basement control on deposition, leading to the local presence or absence of turbidite units deposited during the middle Oligocene to the middle Miocene. During the first phase of sedimentation, most basement lows were filled with turbidites, resulting in smooth seafloor morphology that does not reflect basement relief. A second phase of turbidite deposition in the Eastern Province was accompanied by significant amounts of hemipelagic sediments interbedded with turbidite layers compared to the other provinces because of its close proximity to the Izu–Bonin Island Arc. Both regional and local variations in basement topography and sediment thickness/type have caused lateral heterogeneities on the underthrusting plate that will, in turn, influence lateral fluid flow along the Nankai accretionary prism.

Key words: basement topography, Nankai Trough, sequence stratigraphy.

INTRODUCTION

Basement topographic irregularities, such as aseismic ridges, seamounts and fracture zones have significant effects on trench landward slopes when they are subducted (e.g. Cadet *et al.* 1987; Kobayashi *et al.* 1987; McCann & Habermann 1989; Dominguez *et al.* 2000; Kodaira *et al.* 2000; von Huene *et al.* 2000; Taylor *et al.* 2005), and specific examples off shore of Costa Rica have been implicated as source regions for several large earthquakes during the past decade (Protti *et al.* 1995; Bilek *et al.* 2003). In thickly sedimented convergent margins, variations in sediment thickness and type entering the subduction zone also lead to regional along-strike differences in accretionary prism structure (e.g. Moore *et al.* 1980; Bekins & Dreiss 1992; Saffer & Bekins 2002; Spinelli & Underwood 2004). In addition, basement topography and the overlying sediments on the subducting

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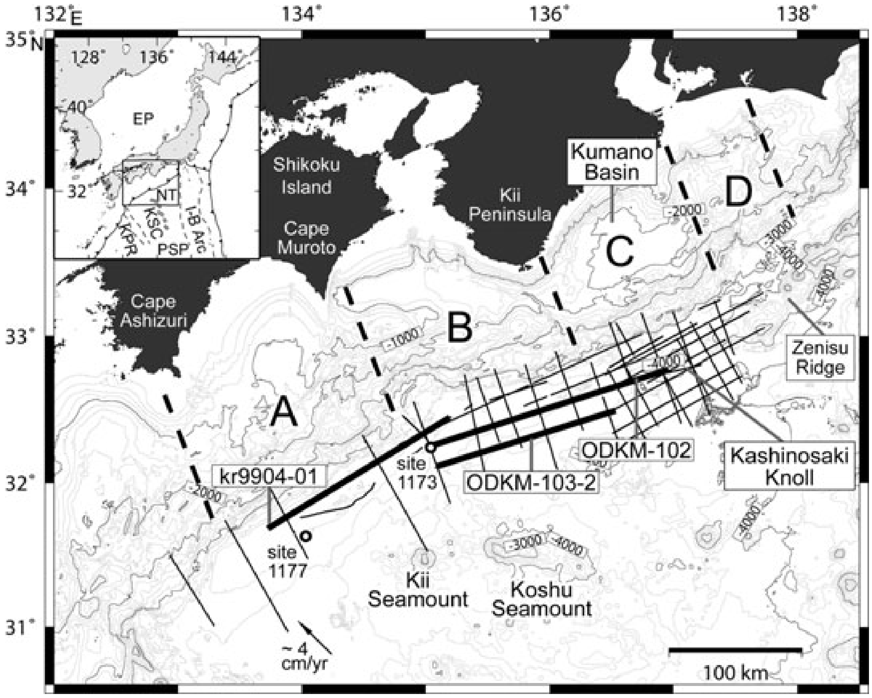

Fig. 1 Regional bathymetric map showing the location of seismic lines (solid lines) used in this study. Solid bold lines are the tracks of seismic sections presented in this paper (Figs 6–8). Contour intervals are 1000 m (bold) and 200 m (fine). Heavy dashed lines are the boundaries between earthquake segments A–D defined by Ando (1975), indicating the units of megathrust rupture along the Nankai Trough. Insert box is a tectonic map of the Philippine Sea Plate (PSP), and Japan Arcs. EP: Eurasian Plate, I–B Arc: Izu-Bonin Arc, IBVC: Izu–Bonin Volcanic Chain, KSC: Kinan Seamount Chain, KPR: Kyushu–Palau Ridge, NT: Nankai Trough.

oceanic plate control fluids entering the subduction zone (Underwood 2007). For instance, large contrasts in hydraulic impedance among different sediment types, such as the presence or absence of sandy/silty turbidites or hemipelagic mudstones, could affect the regional pressure gradient and fluid flow because sandy units are easier to dewater (Fisher *et al.* 1994; Sibson 1996; Giambalvo *et al.* 2000; Bourlange *et al.* 2003). The presence of thick sands deposited within isolated basement lows may create local compartments of excess pore pressure as they subduct if their dewatering pathways are restricted by surrounding impermeable units (Brown *et al.* 2003). Consequently, surface roughness of the subducting plate coupled with variations in fluid flux in the underthrusting sediment may affect the shallow dewatering processes that could, in turn, control interplate seismicity (e.g. Ruff 1989; Tanioka *et al.* 1997; Pritchard & Simons 2006).

The Nankai Trough, along the northern margin of the subducting Philippine Sea Plate (PSP) (Fig. 1), has been affected by destructive earthquakes and tsunami every *ca* 150 years (Ando 1975). The trough is characterized by a thick terrigenous trench-sediment section entering the subduction zone. Studies of ocean drilling program (ODP) drill cores across the northern PSP suggest that the Miocene turbidite unit identified within the lower Shikoku Basin facies in the western Nankai Trough (Ashizuri Transect, ODP Site 1177), is missing in the central Nankai Trough (Muroto Transect, ODP Site 1173) (Fig. 2). However, the regional variations in basement topography and sediment type have not yet been defined. Mapping the basement topography and the distribution of Miocene turbidites along the northern PSP provides a better understanding of the local relationship between fluid reservoir and seal facies within the sediments deposited on the PSP outboard of the Nankai Trough.

In this paper, we document along-strike variations in basement topography on sediment thickness and sediment type deposited in the northern Shikoku Basin during the Neogene. We focus on characterizing the wavelength, amplitude, and lineation of the basement relief as they affect the overlying sediments. We use 40 high-resolution multi-channel seismic (MCS) lines tied to ODP drill core data to discuss the implications of the basement relief for controlling the deposition of turbidites derived from the Japanese Islands and fed out onto the PSP, and the potential influence of these turbidites on the regional hydrostratigraphy on the PSP.

GEOLOGICAL SETTING

The PSP subducts beneath the Eurasian Plate at a rate that varies along the Nankai Trough, from about 5 cm/year at N52°W in the west to about

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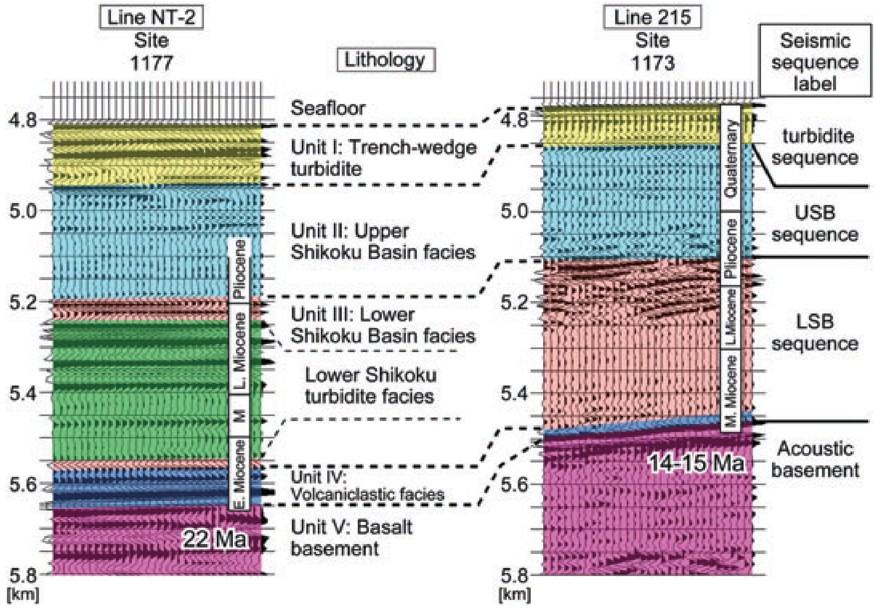

Fig. 2 Seismic stratigraphy of the Shikoku Basin sediments (scale in km) correlated with stratigraphy at ODP Sites 1173 and 1177.

4 cm/year at N48°W in the east (Seno *et al.* 1993). The latest phase of subduction is believed to have started at *ca* 15 Ma (Taira 2001). Changes in volcanic activity in western Japan have been used to suggest that the subduction either stopped or was very slow (<1 cm/yr) during 12–4 Ma, and increased to about 4–5 cm/yr since about 4 Ma (Taira 2001; Kimura *et al.* 2005). The marine sediments on the PSP have been sampled by ocean drilling in the western to central Nankai Trough off Shikoku Island (Karig *et al.* 1975; Taira *et al.* 1991; Moore *et al.* 2001a). A regional study of seismic reflection lines across the entire northern Philippine Sea led to a general definition of Cenozoic sediment stratigraphy and lithofacies classification (Higuchi *et al.* 2007). Our study, which uses newer seismic reflection data, is concentrated on the northernmost part of the Philippine Sea, which is not covered by data of Higuchi *et al.* (2007).

The Nankai Trough extends northeastward about 700 km from the Kyushu–Palau Ridge to the Izu–Bonin Arc. A large amount of terrigenous sediment is presently being channeled down the trench axis from the Izu–Honshu collision zone along the Suruga Trough into the Nankai Trough (Taira & Niitsuma 1986; Aoike 1999). These trench strata overlie the hemipelagic strata deposited on the Shikoku Basin crust before it reached the trench.

The basement structure of the Shikoku Basin, in the northern part of the PSP, was formed by the complex back-arc spreading history in the Izu–Bonin Island Arc (Kobayashi & Nakada 1978; Nakamura *et al.* 1984; Okino *et al.* 1994). The basement relief in the Shikoku Basin averages approximately 600 m (Chamot-Rooke *et al.* 1987). Sediments fill in deep basement lows that are interpreted to be fracture zones, probably formed during the last phase of seafloor spreading along the Kinan Seamount Chain (Le Pichon *et al.* 1987). Magnetic anomalies at the eastern and western sections of the basin trend dominantly NNW–SSE, reflecting the early seafloor spreading history (Okino *et al.* 1994; Kobayashi *et al.* 1995) that started *ca* 27 Ma (middle Oligocene), when the Kyushu–Palau arc was split by back-arc spreading. Lineated magnetic anomalies in the western half of the Shikoku Basin clearly correlate with magnetic anomalies 6 to 7, but the anomalies in the eastern basin are less distinct and their correlations are less certain (Okino *et al.* 1999). Spreading proceeded at about 2.3–4.7 cm/yr until anomaly 6B (*ca* 20–23 Ma). Seafloor spreading anomalies 5B and 6 (*ca* 15–20 Ma) indicate that the spreading direction changed to NE–SW during this time. Seafloor spreading between chrons 5B and 5E was the last true spreading phase in the Shikoku Basin (Okino *et al.* 1994, 1999), but late-stage rifting may have continued until 7–10 Ma with associated volcanism that formed the Kinan Seamount Chain (Chamot-Rooke *et al.* 1987; Ishii *et al.* 2000). The estimated ages of the youngest basalt dredge samples from the Kii Seamount are 10.1 ± 0.5 Ma, and 7.6 ± 0.5 Ma from the Dai-ichi Kinan Seamount (Ishii *et al.* 2000).

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DATA ACQUISITION AND PROCESSING

We used four seismic reflection data sets (Table 1), totaling 40 lines, collected by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) along the northern PSP. The first data set was collected from 1997 to 2001 on the R/V *Kairei* using a variety of sound sources and multichannel streamers. For data acquisition during the 1997 cruises, for example, an air-gun array of 50 L (3080 in^3) was used as the controlled-sound source and a 120-channel streamer (25 m group interval) was used as the sound receiver. During the 2001 cruises, a 160-channel steamer was used, with an untuned 196 L (~12 000 in^3) air-gun array as the sound source. Initial processing through stack was completed at JAMSTEC. We applied the second phase of data processing to this data set, including bandpass filters and post-stack time migration. The second data set was collected by a commercial contractor in the spring of 2003 using a 480-channel steamer and a tuned 70 L (4240 in^3) air-gun array as the sound source (Taira *et al.* 2005). We processed several of these lines through stack and post-stack time migration, and performed pre-stack depth migration (PSDM). The third data set was collected from 2003 to 2004 on the R/V *Kaiyo* in December 2003–January 2004 using an 18-channel streamer and a single 5 L (total 355 in^3) generator–injector (GI) gun as the sound source. We have also processed these lines through filter, stack, and post-stack time migration. We also used a 3D seismic data set that was collected by a US–Japan Collaborative Program off Muroto in 1999 using the R/V *Maurice Ewing* (Moore *et al.* 2001b). The acquisition parameters include a single 6 km streamer with 240 channels and a tuned 70 L (4270 in^3) air-gun array, and the resultant survey covered a region about 8 km wide and 80 km long.

We developed a regional velocity model based on the PSDM velocity analyses from lines ODKM-22 and ODKM-B, from the eastern part of the Shikoku Basin (Costa Pisani P, unpubl. data, 2005), and Muroto-3D-284 (from the central Shikoku Basin) (Costa Pisani *et al.* 2005), and used these velocities for depth conversion of the other seismic lines. In the Kumano area, where the topography is relatively flat, the velocity model has values of 1510 m/s at the seafloor followed by a gradient of 650 m/s^2 with increasing two-way travel time. The velocities over Kashinosaki Knoll have a smaller gradient of 550 m/s^2. In the Muroto area, the velocity model has values of 1510 m/s at the seafloor followed by a gradient of 900 m/s^2 for the trench wedge turbidites within the trench axis, whereas the gradient is 550 m/s^2 seaward of the trench axis. These velocities are accurate enough to identify regional sediment thickness trends, so we extend this velocity model throughout the data set along the Nankai Trough.

To supplement the digital seismic reflection lines, we also digitized the basement depth from

Table 1 Seismic reflection data acquisition and processing parameters

Acquisition parameters			
Survey initial	ODKM	ODKM	KR
Survey vessel	R/V *Kaiyo*	M/V *Polar Princess*	R/V *Kairei*
Recording year	2003–2004	2003	1997–2001
Seismic source	One GI gun	Tuned air-gun array	Non-tuned air-gun array
Gun volume (L)	5.7	70	~196
Shot interval (m)	25	50	50
Number of channels	18	480	160
Channel interval (m)	25	12.5	25
Processing sequence			
1.	Bandpass Filter (12–24–100–150 Hz)	Spiking Deconvolution	Bandpass Filter (3–5–100–120 Hz)
2.	Spiking/Predictive deconvolution	Bandpass Filter (8–12–72–80 Hz)	Deconvolution
3.	Spike & Noise Edit	Velocity analysis	Velocity analysis
4.	Velocity analysis	Dip moveout correction (DMO)	Normal moveout correction (NMO)
5.	NMO	NMO	Mute
6.	Mute	Mute	Stack (by JAMSTEC)
7.	Stack	Stack	F-K time migration
8.	F-K time migration	F-K time migration	Depth conversion
9.	Depth conversion	Depth conversion	

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the seismic lines collected by the Kaiko Project (Kaiko I Research Group 1986). We used the lines that are located in Box 6 of Le Pichon *et al.* (1987), south of Cape Muroto. We developed a constant velocity model for the sediment column (1900 m/s) that yields a reasonable correlation of the basement depth well with that in the other seismic data. The misfit of the basement depth measured from the Kaiko Project to the other seismic data is approximately 150 m, which increases as the basement deepens. This digitized data set is used only for describing the basement depth and total sediment thickness but we did not identify sediment sequences.

SEISMIC STRATIGRAPHY

We interpret and define four major seismic stratigraphic sequences that are correlated with the key lithostratigraphic units defined at the ODP Leg 131 and 190 drill sites (Taira *et al.* 1991; Moore *et al.* 2001a) (Fig. 2). The stratigraphic section of the northern Shikoku Basin is younger than early Miocene, and thus, corresponds to Units IV and V of Higuchi *et al.* (2007). The base of the stratigraphic sequence is a thin volcaniclastic unit that overlies oceanic crust (acoustic basement) (Moore *et al.* 2001a). The oldest mapped sediment unit is the lower Shikoku Basin (LSB) sequence that overlies the volcaniclastics. This sequence is characterized by discontinuous to moderately-continuous, hummocky reflections at the upper boundary, with very low-amplitude and very few coherent internal reflections in the lower portion. The LSB sequence is correlated with the middle Miocene to lower Pliocene hemipelagic mudstone sampled at the ODP drill sites (Moore *et al.* 2001a), and the seismic character is similar to Facies A of Higuchi *et al.* (2007). Within this sequence, there are laterally continuous, high-amplitude reflections correlated with Miocene turbidites (LSB-T unit) cored at ODP Site 1177. This unit has a terrestrial component characterized by plant detritus, pieces of wood, and 25–55% smectite content of the bulk mudstone (Moore *et al.* 2001a). The probable source of the sands within lower Shikoku turbidite facies of early to late Miocene age (*ca* 6–16 Ma) at ODP Site 1177 (Moore *et al.* 2001a) is suggested to be the inner zone of southwest Japan (Fergusson 2003). Hemipelagic clays interbedded with the Miocene turbidites have a strong volcanic component of suspended-sediment input, presumably from the Izu–Bonin arc (Underwood & Fergusson 2005). In the eastern part of the Shikoku Basin, we identify sections of low-amplitude reflections within the LSB-T unit. It is possible that in this region, the LSB-T unit may be thick-bedded turbidites, as at ODP Site 1177 (Moore *et al.* 2001a), although the loss of reflection amplitudes over short distances could be a result of disruption of layering due to deformation or fluid flow.

The boundary between the LSB sequence and the overlying upper Shikoku Basin (USB) sequence is diagenetically controlled, at least partially, by the breakdown of sparse ash layers and opal-to-quartz diagenetic reaction in the lower unit (Taira *et al.* 1991; Moore *et al.* 2001a). The USB sequence, characterized by low amplitude seismic reflections similar to Facies A of Higuchi *et al.* (2007) in the upper part of the sequence and few coherent reflections in the lower part, is correlated with a hemipelagic mudstone and an abundant ash and tuff unit that is Quaternary to Pliocene in age at ODP Site 1173. Sediment properties in the USB sequence at ODP Site 1173 do not follow a typical compaction profile in which porosity decreases uniformly with depth. Instead, porosity is nearly constant, about 55–65%, over a depth range of approximately 240 m (Moore *et al.* 2001a). A change in physical properties associated with the phase transition from cristobalite to quartz or dissolution of a weak opal cement may also be responsible for the reflections within the lower section of the USB sequence (Moore *et al.* 2001a; Spinelli *et al.* 2007). Note that the hummocky reflections at the top of LSB sequence in Muroto (Site 1173) and off Kumano Basin are not present off Ashizuri (Site 1177).

BASEMENT TOPOGRAPHY AND REGIONAL PROVINCES

Seismic reflection profiles across the northern PSP demonstrate large variations in basement relief that are not reflected in the regional bathymetry (Fig. 3) because of the thick sediment blanket. We divide the northern Shikoku Basin into three provinces based on its basement relief and associated sediment cover. Our boundaries follow closely those proposed by Kido and Fujiwara (2004) based on regional magnetic anomaly correlations, thus indicating that the primary basement character is controlled by the seafloor spreading history.

The Eastern Province of the Shikoku Basin is characterized by relatively rough basement relief, both lineated and isolated, associated with

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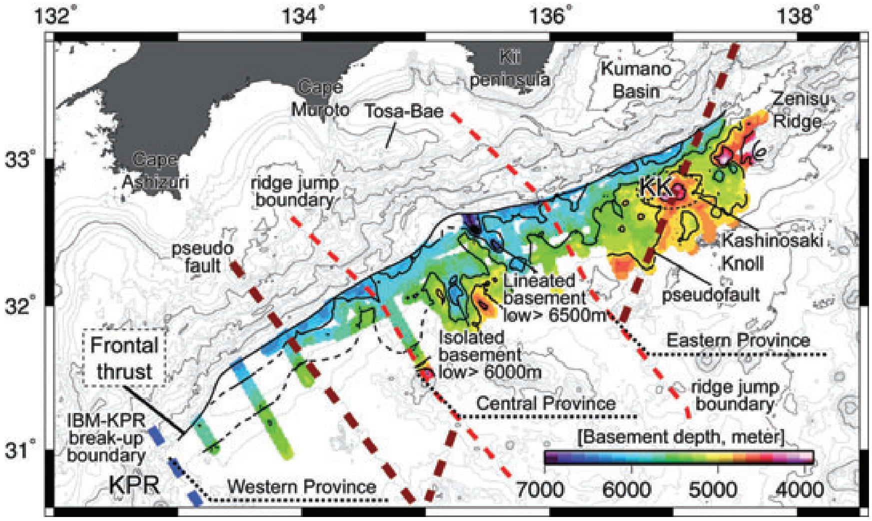

Fig. 3 Basement depth contour map based on the interpretation of seismic reflection data shown in Figure 1. A depth scale is shown at the bottom right; solid lines are thickness contours at 500 m intervals. Dashed lines indicate boundaries of magnetic zones (B. Taylor, pers. comm. 2006): pseudofaults; IBM-KPR break-up boundaries; ridge jump boundaries. Bathymetric map shown in the background has contour intervals of 1000 m (bold) and 200 m (fine). Regional basement/sediment provinces are also shown.

Kashinosaki Knoll (basement amplitude <1500 m) and other unnamed topographic highs (<600 m). The half-wavelength of the basement highs, parallel to the trench, ranges from about 10 to 20 km. The basement highs are generally about one half to one third as wide as the intervening basement lows. The Central Province has approximately 10–20 km wide, NW-trending basement lows that are about 1–2 km deeper than adjacent horst blocks along the Kinan Seamount Chain (Fig. 3). In most cases, the amplitude of the basement highs is about six times greater than that of the overlying seafloor topographic relief. Sdrolias *et al.* (2004) interpret the late stage sea floor spreading of the Shikoku Basin (*ca* 19 Ma) to have had a half spreading rate of about 2.0 cm/year, which is about 1.0 cm/year lower than the major spreading rate of the Shikoku Basin. The formation of large basement relief in the Central Province may relate to the major change in sea floor spreading to NE–SW, accompanied by a decrease in spreading rate, and young seamount eruption (Le Pichon *et al.* 1987). These basement lows in the Central Province have 3–5 times larger relief than those in the Western Province, which is characterized by relatively smooth basement relief (<200–400 m) associated with a few isolated basement highs. The basement relief is the smoothest along the trench-perpendicular seismic lines. In detail, the majority of the basement in this zone has relief of about 170 m perpendicular to the trench and 200–400 m parallel to the trench. Although the data coverage is less in the western part of the Shikoku Basin compared with other areas, the trench-perpendicular basement relief on the Western Province has lower amplitude than the Eastern Province. The basement relief in the Eastern Province is <600 m, midway in between that of the Western and Central Provinces. The basement depth is shallower than the Western Province that has a similar crustal age. Oceanic crust in the Eastern Province may have formed by seafloor spreading associated with volcanic intrusions from the spreading axis or the nearby volcanic arc.

TOTAL SEDIMENT THICKNESS

Isopachs of sediment thickness, determined by subtracting the depth of the seafloor from depth of the basement on the seismic lines and extrapolated between lines, are shown in Figure 4. The incoming sediment blanketing the basement relief shows local variations in total thickness. For instance, the maximum total sediment thickness seaward of the deformation front is approximately 2000–2200 m in the central Shikoku Basin. The minimum thickness is less than 300 m over the topographic highs, such as Kashinosaki Knoll and near the Kinan Seamount Chain. The total sediment thickness in the Western Province ranges mostly between 500 and 750 m, in the basement lows seaward of the Nankai Trough, without much variation parallel to the trough. On the other hand, the total sediment thickness in the Central and Eastern Provinces exceeds 1000 m in the basement lows seaward of Nankai Trough.

Previous studies indicated that the total sediment thickness generally increases towards the trench and the Izu–Bonin arc (Ludwig & Houtz 1979; Nemoto *et al.* 1995). Our observations generally follow the same trend. A plot of basement

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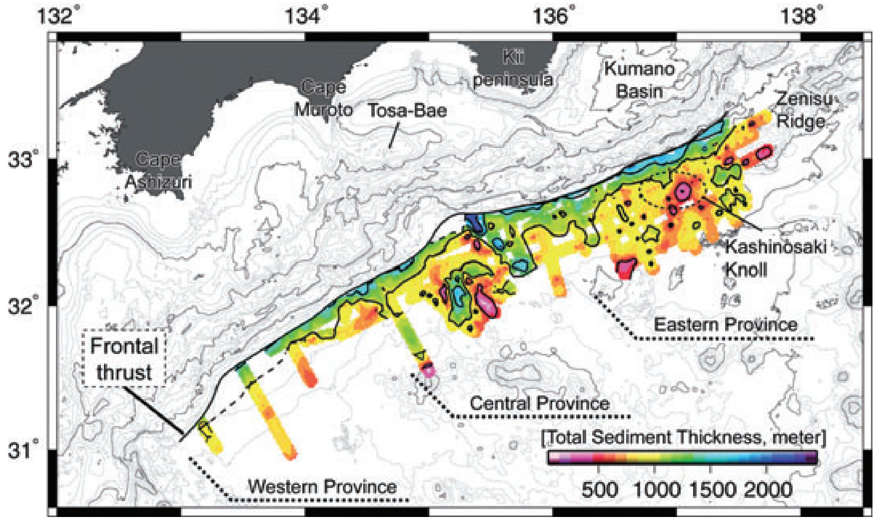

Fig. 4 Total sediment isopach map along the northern Shikoku Basin. A scale for each isopach is shown at the bottom right. Within the shaded isopach, solid lines are the thickness contour with 500 m intervals. Bathymetric map shown in the background has a 200 m contour interval. KK: Kashinosaki Knoll, ZR: Zenisu Ridge.

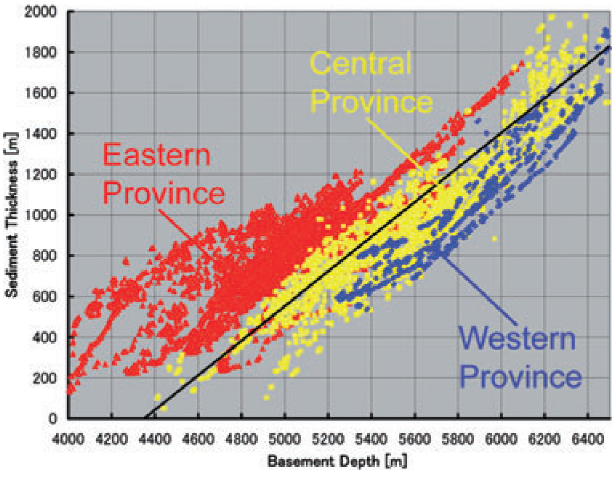

Fig. 5 Total sediment thickness *vs* Basement depth in the Western, Central, and Eastern Provinces of the Shikoku Basin. Black line indicates the best fit for the central part.

depth versus total sediment thickness shows that the two parameters are linearly related with a slope of 0.83 (Fig. 5), indicating that turbidites are channeled into the basement lows. We note that there is a significant variation in sediment thickness (600–800 m) for a given basement depth (Fig. 5).

LOCAL STRATIGRAPHIC VARIATIONS

We divide the seismic sequences into four classes based on regional and sedimentary characteristics. The most important stratigraphic feature of the incoming section is the presence or absence of the LSB-T unit in the LSB sequence.

CLASS I: SPATIALLY UNIFORM SEDIMENTS OVER SUBDUED BASEMENT RELIEF

Class I is characterized by the presence of the LSB-T unit associated with relatively smooth basement lows in the Western Province of the Shikoku Basin (Fig. 6). The sediment sequences in this class are correlated with those at ODP Site 1177 (Fig. 2). The LSB-T unit, in general, has high-amplitude continuous reflections and is generally sub-parallel to the basement (Fig. 7a, shot point (S.P.) 7000–8200, shaded area), although in some areas, the LSB-T unit shows low-amplitude reflections in the lower section. The thickness of the high-amplitude reflection section, LSB-T unit, ranges from about 200 to 350 m (Fig. 7b). The LSB-T unit mostly laps onto basement highs whose summits exceed 400 m height above the adjacent basement lows seaward of the Nankai Trough. Class I is restricted to the Western Province of the Shikoku Basin (Fig. 6) and part of the Central Province (Fig. 7a). The LSB-T sequence in the Eastern Province (Fig. 7c) differs from that in the central and western regions by the presence of the low-amplitude reflections in the upper part of the LSB-T unit.

CLASS II: ABSENCE OF LSB-T UNIT OVER RELATIVE BASEMENT HIGHS

Class II is characterized by basement highs associated with the absence of the LSB-T unit. A region characteristic of Class II is the Muroto area in the central part of the Shikoku Basin, where the sediment sequences were drilled at ODP Site 1173 (Fig. 2). The total sediment thickness in this class

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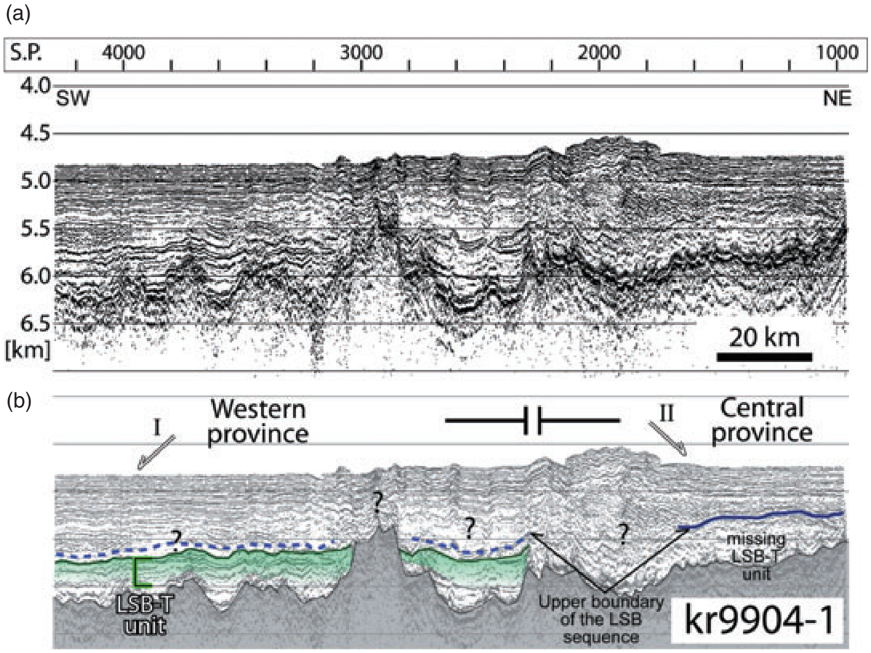

Fig. 6 (a) Seismic depth section kr9904-01, (b) Interpreted seismic stratigraphy. Bold line is the upper boundary of the LSB sequence (dashed where less certain), and the upper boundary of the LSB-T unit. Shading represents the area of high-amplitude reflections that form the LSB-T unit. Vertical axis is depth in km. S.P. = shot point, interval = 50 m. Vertical exaggeration is ~ 20x.

ranges from about 500 to 800 m, a value that represents the minimum thickness in the northern Shikoku Basin.

In this class, the basement highs have three characteristics in common: (i) they are at least approximately 400–600 m higher than the adjacent basement lows; (ii) their maximum slope angle is about 20–25 degrees; and (iii) their width is about 5–10 km parallel to the trench. Major basement highs are located off Cape Muroto, off Kii peninsula (Fig. 7a), and a few in the western part of the Shikoku Basin (Fig. 6).

CLASS III: SEDIMENTS IN NW-TRENDING BASEMENT LOWS ALONG THE KINAN SEAMOUNT CHAIN

Class III is characterized by a thick section of the LSB-T unit within deep basement lows. This class occurs mostly near the Kinan Seamount Chain, along the extinct spreading center of the Shikoku Basin (Figs 7a,8a). In this class, a section of low-amplitude reflections characterizes the bottom portion of the LSB sequence (e.g. Fig. 8a, S.P. 3200–4000). This unit thins from approximately 500 m thick in the deepest parts of the basins to less than seismic resolution on the basin flanks (e.g. Fig. 8b, S.P. 3200–4000). This distinct transparent character is indicative of a homogeneous section containing no significant acoustic impedance contrasts which were probably formed mostly of hemipelagic sediments, and which were originally deposited on the adjacent topographic highs then slumped into the intervening lows. Overlying the transparent layer, the LSB-T unit is 450–800 m thick and exhibits high-amplitude, continuous reflections. On the flanks of the basins, where the underlying hemipelagics become very thin, the LSB-T unit onlaps the basement of the adjacent topographic highs. The LSB-T unit is folded in some of the basins due to differential compaction of the underlying hemipelagic strata (e.g. Fig. 7a, S.P. 6200–6600 and Fig. 8a, S.P. 1250–1750, 3200–4000). Thus, Class III is characterized by thick (>1000 m) hemipelagic and terrigenous sediments within deep basement lows.

CLASS IV: LOW-AMPLITUDE REFLECTIONS IN THE LSB-T UNIT

Class IV is restricted to the Eastern Province and is characterized by variations in reflection amplitude within the LSB-T unit. The lower section of the LSB-T unit is mostly characterized by high-amplitude laterally-continuous reflections that lap onto the basement highs, similar to the LSB-T unit in Class I (Fig. 7c). The thickness of this section ranges from 100 to 350 m, depending on the basement relief. Locally, this section is characterized by very low-amplitude discontinuous reflections (e.g. Fig. 7a, S.P. 3000–5000) that are no different from the transparent character found in Class III (Fig. 8a, S.P. 4000–6300). These very low-amplitude reflections are geographically restricted to the region south of the Kii peninsula (e.g.

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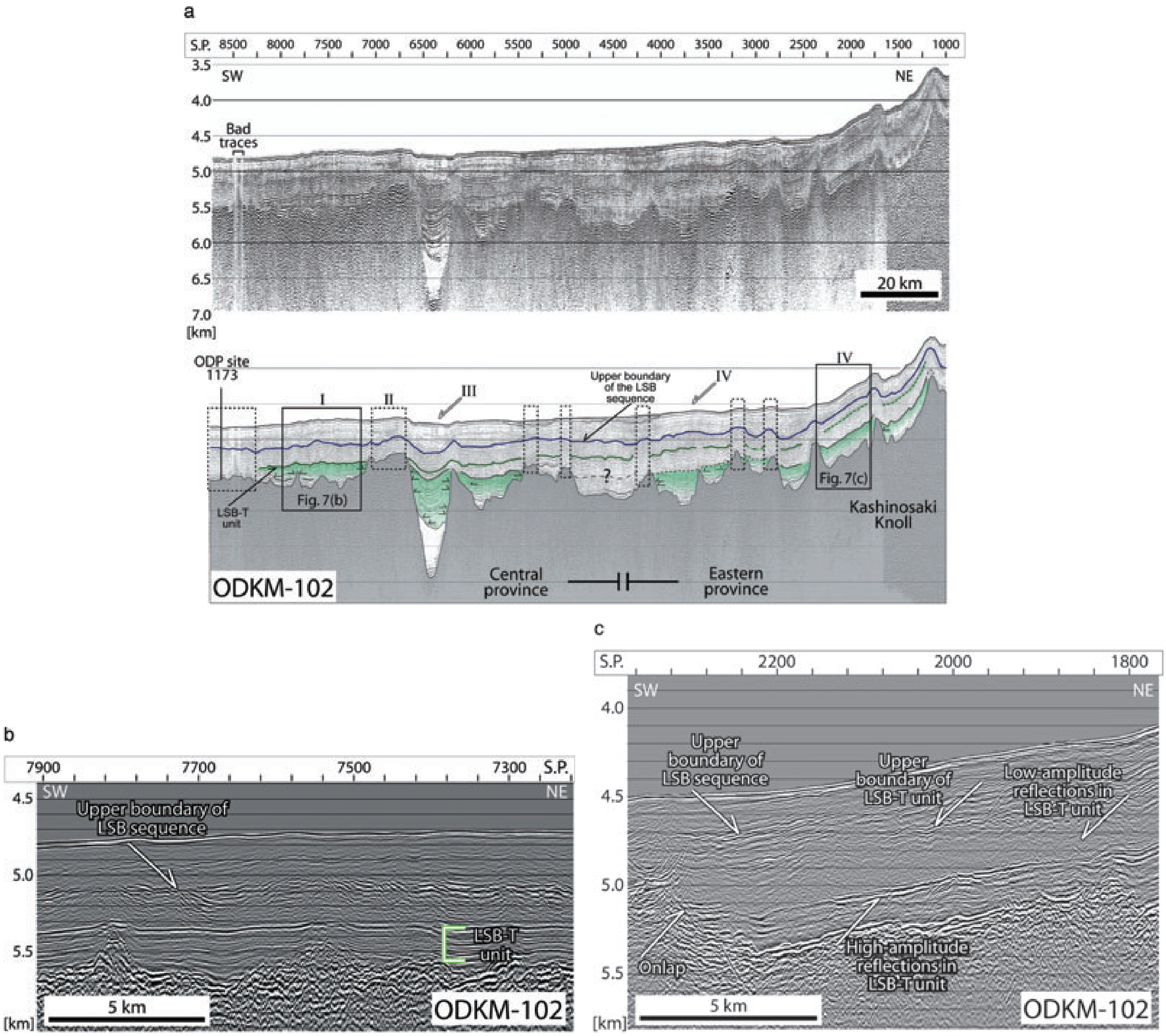

Fig. 7 (a) Upper: Seismic depth section ODKM-102 that crosses through Site 1173 and Kashinosaki Knoll showing along-strike variations of basement topography associated with sediment thickness and type. Lower: Interpretation showing stratigraphic boundaries. Small black arrows indicate onlap structure. Roman numerals indicate sediment sequence classes. Bold line is the upper boundary of the LSB sequence (dashed where less certain); and the upper boundary of the LSB-T unit. Shading represents the area of high amplitude reflections that form the LSB-T unit. Vertical axis is depth (km). S.P. = shot point, interval = 25 m. Vertical exaggeration is ~20x. (b) Enlarged portion of seismic depth section ODKM-102 showing the relationship between the relative basement low and sediment sequences of Class I. Vertical exaggeration is 5x. (c) Enlarged portion of seismic depth section ODKM-102 showing the relationship between the basement relief and sediment sequence of Class IV. Vertical exaggeration is ~5x.

Fig. 8c). The upper section of the LSB-T unit is characterized by low-amplitude, discontinuous reflections indicative of small changes in acoustic impedance. The thickness of the low-amplitude section ranges from 100 to 380 m (Fig. 7a). The total thickness of the LSB-T unit is midway between that of Classes I and III. In this class, the upper boundary of the LSB-T unit is defined by high-amplitude continuous reflections similar to Classes I and III.

The seismic character of the LSB-T unit does not change over the Kashinosaki Knoll (Fig. 7c). The LSB-T unit occurs over the Kashinosaki Knoll where the basement has relatively low dip on its landward margin. We define the eastern boundary of Class IV at the eastern edge of the Kashinosaki Knoll because the sediment sequence is affected by Quaternary turbidites and debris flows that are not common to other Classes toward the west.

UPPER BOUNDARY OF THE LSB SEQUENCE

A second-order heterogeneity in the incoming sediment is the change in seismic character along

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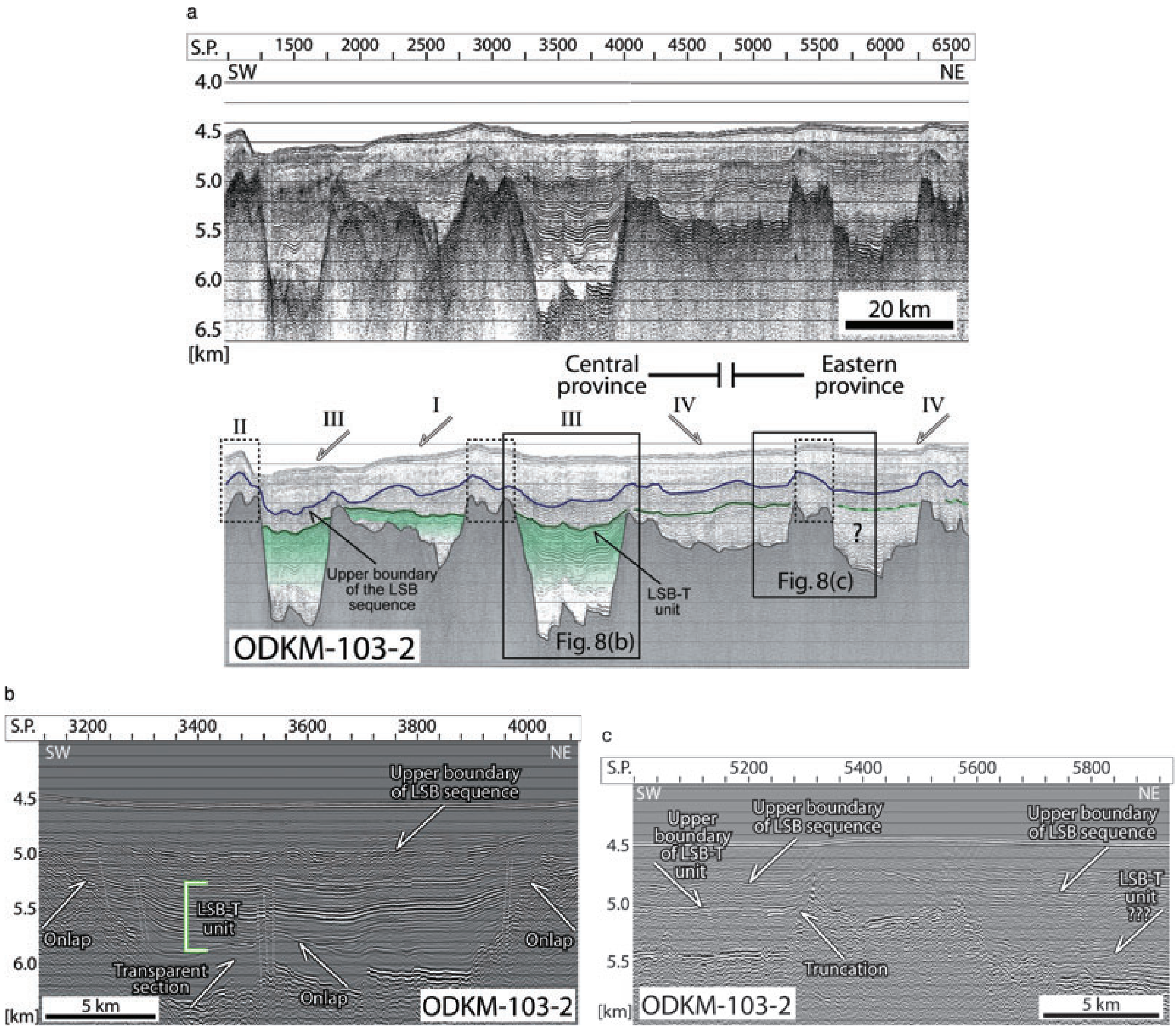

Fig. 8 (a) Upper: Seismic depth section ODKM-103 that runs near ODP Site 1177 in the Western Province of the Shikoku Basin, along the Nankai Trough. Lower: Interpretation showing regional stratigraphic boundaries. Bold line is the upper boundary of the LSB sequence (dashed where less certain), and the upper boundary of the LSB-T unit. Shading represents the area of high amplitude reflections that form the LSB-T unit. Vertical axis is depth in km. S.P. = shot point, interval = 25 m. Vertical exaggeration is ~20x. Roman numerals correlate indicate sediment sequence classes. (b) Enlarged portion of seismic depth section ODKM-103-2 showing the relationship between the basement low and sediment sequences of Class III. Vertical exaggeration is ~ 5x. (c) Enlarged portion of seismic depth section ODKM-103-2 showing the relationship between the basement relief and sediment sequence of Class II & IV. Vertical exaggeration is ~5x.

the upper boundary of the LSB sequence. The acoustic response from the boundary between the LSB and USB sequences is believed to be controlled by diagenetic reactions such as the breakdown of sparse ash layers (Taira *et al.* 1991; Moore *et al.* 2001a). The hummocky reflection that is the classic characteristic of this boundary is not clearly shown in the Western Province (Fig. 6). To the east, the hummocky reflections clearly appear near ODP Site 1173 (344 m below seafloor), in the Central Province (Fig. 7a). The lateral continuation of these reflections shows one of two seismic characteristics: either (i) they are parallel to the basement relief; or (ii) they are parallel to the upper boundary of the LSB-T unit. The first case appears in the central Shikoku Basin (Fig. 8a, S.P. 2000–3000). The upper boundary of the LSB sequence shows concave-up morphology over the basement lows (Fig. 8b, S.P. 3200–4000). Its relief is more parallel with the reflections in the LSB-T unit than the sea floor relief. The second case appears in the Eastern Province (Fig. 8a, S.P. 4300–5200). In this area the upper boundary of the LSB sequence is located approximately 290–380 m

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beneath the seafloor. Therefore, the acoustic response from the boundary between LSB and USB sequence varies along the Nankai Trough, and this boundary may not be solely controlled by diagenesis but may be affected by other lithofacies transitions.

DISCUSSION

Our high resolution seismic data illustrate a complex interaction between the Shikoku Basin basement relief and sedimentation that produces regionally variable sediment thickness and facies that, in turn, likely affect the physical properties of the subducting section along the northern PSP. Comparisons of basement relief, sediment thickness, sediment type, and extent of diagenesis lead us to divide the northern Shikoku Basin into three distinct provinces. Variations in the above factors could contribute to regional variations in the rupture process of earthquakes, seismic segmentation, and the frictional properties along the subducting plate interface (Sibson 1986; Prawirodirdjo *et al.* 1997; Liu-Zeng *et al.* 2005).

TECTONIC AND BASEMENT CONTROLS ON SHIKOKU BASIN SEDIMENTATION

We have shown that our different sediment classes are closely correlated with basement morphology in each province. For example, it is apparent from the seismic profiles that lateral variations in the basement relief had significant control on the deposition of turbidites within the LSB sequence. The present distribution of the LSB-T unit is highly variable, with most occurrences being within topographic lows, and locally over relative basement highs associated with gentle slopes. This suggests that turbidity currents flowing from the Japanese Islands were deflected around topographic highs and flowed into the topographic lows in the Shikoku Basin. This led to significant variations in sediment thickness and type across the width of the Shikoku Basin in the LSB section. Here, we examine the effect of basement relief on the formation of LSB-T unit. We focus on the presence or absence of the LSB-T unit (Miocene turbidites) because of the importance of the turbidites as dewatering conduits, thus potentially affecting overall physical properties of the underthrusting sediment section along the Nankai prism.

The presence of turbidite units within the lower to upper Miocene deposits of the Shikoku Basin and the absence of turbidite units in the upper Miocene to Pliocene USB sequence implies a major change in sedimentation in the Shikoku Basin at the end of the late Miocene. Turbidites coming from the Japanese Islands are not currently able to flow out into the Shikoku Basin, except for the region around the Kashinosaki Knoll and the Zenisu Ridge, because they are trapped in either the forearc basins, in basins on the accretionary prism, or in the trench. The most likely significant difference was the lack of a forearc basin, trench slope basins along the continental slope, and a bathymetric trench. All of these would have trapped sediments derived from the Japanese Islands, thus allowing the sediments to flow out into the Shikoku Basin in the early Miocene. This is consistent with the inference of extremely low subduction rates during this time (Kimura *et al.* 2005), which would have meant that the rate of growth of any accretionary prism must have been very slow, even though there were thick sediments at the base of the continental slope that could have been accreted. In addition, the young Shikoku Basin crust probably did not have significant flexure, similar to the Cascadia Basin (Underwood *et al.* 2005), so the plate was probably relatively flat without a large trench. At the end of the late Miocene, rejuvenated subduction led to rapid building of the present accretionary prism, thus forming accommodation space within and seaward of the prism, and cutting off the supply of turbidites to the Shikoku Basin.

In addition, the difference in the seismic character of the LSB-T unit between Class I (Western Province) and IV (Eastern Province) indicates a regional change in turbidite sedimentation during the formation of the LSB sequence. The appearance of low-amplitude reflections in the upper part of the LSB-T unit is limited to the Eastern Province of the Shikoku Basin. In this province, a high hemipelagic sedimentation rate is expected in the middle Miocene period because of the region's close proximity to the Izu–Bonin Island Arc which, after a volcanic minimum in the early Miocene, led to increased production of volcaniclastic sediments in the middle Miocene (*ca* 17 Ma, Taylor 1992) that were likely dispersed by bottom currents (Underwood & Fergusson 2005).

IMPLICATION FOR PHYSICAL PROPERTIES ALONG PLATE BOUNDARY

We have defined the basement morphology and its effect on sedimentation in each province. Here, we discuss the possible effect of basement relief and

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incoming sediment properties on the plate boundary. We focus on sediment classes because each class should have distinct controls on compaction and dewatering that could also affect friction properties as the sediments enter the subduction/ seismogenic zone.

The significant variations in sediment thickness and type along the subducting northern Shikoku Basin described above will likely have associated major mechanical effects on the shallow levels of the subduction zone. For example, the décollement in the central and western Nankai Trough apparently localizes at nearly the same stratigraphic level within the upper part of the LSB sequence (Moore *et al.* 2001a). Thus, most of the LSB sequence is subducted beyond the toe of the accretionary prism and this is the section that has the most variability in thickness and sediment type across the Shikoku Basin.

In our analysis above, we have defined the basement morphology and its effect on sedimentation in each province. Here, we discuss the possible effect of basement relief and incoming sediment properties on the plate boundary. We focus on our defined sediment classes because each class should have distinct controls on compaction and dewatering that could also affect friction properties as the sediments subduct.

Sediments may play an important role in the locking and rupturing at the plate boundary as well as tsunamigenic earthquakes (Okal 1988; Tanioka *et al.* 1997; Wang & Hu 2006). Different sediment types, such as terrigenous turbidites and hemipelagic clay, could cause regional variations in permeability of several orders of magnitude (Giambalvo *et al.* 2000). The Nankai Trough plate boundary has been shown to rupture in regional segments (e.g. Ando 1975) and local variations in earthquake characteristics have been correlated with similar magnitudes of basement relief in other subduction zones (e.g. Bilek & Lay 2002; Bilek *et al.* 2003). In addition, the rupture area of tsunami generation for the 1944 and 1946 events are reasonably well understood (Baba & Cummins 2005). Our study has demonstrated that regional variations in both basement structure and sediment thickness/type on the subducting PSP occur on both regional (100–200 km) and local (~5–20 km) scales that might correlate with the segments defined by previous studies.

The Western Province of the Shikoku Basin has the smoothest basement relief in the Shikoku Basin (<200–400 m) and has a relatively homogeneous sediment section (Class I). Mudstones in the lower Shikoku Basin turbidite facies and volcaniclastic-rich facies, at ODP Site 1177, are enriched by much higher percentages of smectite in the basement lows (Steurer & Underwood 2003), which could affect the generation of fluids as well as the pore fluid pressure (Moore & Vrolijk 1992). The least variation in sediment thickness occurs in the Western Province, with total sediment thickness ranging from about 500 to 1300 m (Nemoto *et al.* 1995; Yoshioka & Ito 2001).

In the Central Province, along the extinct spreading center of the Shikoku Basin, large seamounts and ridges and intervening deep basement lows alternate in both strike and dip directions. The inter-connected basement lows associated with sediment Class III contain the thickest sediment sections and the thickest turbidite sequences. The turbidites likely are areas of relatively more rapid drainage because of the relatively more porous nature of the turbidites compared with areas dominated by mudstones. Where the turbidites pinch out against the flanks of topographic highs (seamounts or horst blocks), local compartments of excess pore pressure may be generated because fluid escape would be inhibited (e.g. Brown *et al.* 2003; Underwood 2007). This could generate regions of lowered effective stress, perhaps facilitating rupture over these areas when they enter the seismogenic zone (Scholz 1990). In addition, the relatively higher heat flow associated with the Kinan Seamounts in the Central Province initiates clay mineral transformations (smectite to illite) outboard of the deformation front, whereas this reaction takes place under the accretionary prism to the east and west (Steurer & Underwood 2003; Spinelli & Underwood 2004).

The Eastern Province has less basement relief than the Central Province, but considerably more than the Western Province, with correspondingly greater variations in sediment thickness than in the west, but less than in the Central Province.

Turbidite-rich sections should dewater more rapidly than clay-rich sections. Where turbidites onlap basement highs, dewatering is inhibited because the onlap point forms a seal, preventing the migrating fluid from escaping, so pore pressures should increase. Areas where turbidite sections onlap the basement should have relatively more rapid lateral changes in physical properties of the subducting section such as in the Eastern and Central Provinces of the Nankai Trough where the basement relief is rough, than in the Western Province where the relief is smoother.

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These phenomena may be commonplace wherever seafloor topography with linear ridges, horst–graben structures, and areas of a high rate of terrigenous sedimentation intersect a margin. For example, off northern Chile, subduction of a thick sediment section appears to increase the maximum depth of seismicity (Zhang & Schwartz 1992; Pritchard & Simons 2006). In the Cascadia margin, the deep grabens of the Juan de Fuca spreading system channel turbidites from western North America, leading to highly variable sediment sections entering the subduction zone (Underwood 2002; Underwood *et al.* 2005). The lineated relief in the Eastern Province may create variations in the effective hydrologic seal and drainage or hydrogeologic conversion of basement and sediment seal. We propose that both regional and local variations in basement relief and sediment thickness/type cause lateral heterogeneities on the incoming material, and thus, control physical properties over the underthrusting plate.

CONCLUSIONS

Our seismic reflection data sets across the northern Philippine Sea Plate (PSP) suggest the following conclusions:

1. The subducting Shikoku Basin crust can be divided into three provinces depending on the morphology of the basement relief and tectonic setting. Irregularities in the basement relief (>1500 m) of the Central Province are 3–5 times larger than those in the Western and Eastern Provinces. The basement topography in the Eastern Province is characterized by relatively more rough geometry (<600 m average) than the Western Province (<200–400 m).
2. The basement depth and total sediment thickness are linearly related because turbidites are channeled into basement lows, thus increasing sediment thickness in the lows at the expense of the basement highs.
3. Four distinct classes of sediments are recognized on the subducting Shikoku Basin crust. The classes, distinguished on the basis of the sediment thickness and type within the LSB sequence, allow us to delineate local (~5–20 km) sediment variations. Within the LSB sequence, the seismic character of the LSB-T unit indicates regional variations in turbidite sedimentation during the middle Oligocene to the middle Miocene. In addition, the turbidites are generally absent where the basement highs have relief exceeding 500–600 m, except over the Kashinosaki Knoll, which has a relatively shallow dip on its landward margin, allowing the turbidites to climb up towards its flank.

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