Geochemistry Geophysics Geosystems G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 10
29 December 2009
Q0AD01, doi:10.1029/2009GC002713
ISSN: 1525-2027

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Interactions between deformation and fluids in the frontal thrust region of the NanTroSEIZE transect offshore the Kii Peninsula, Japan: Results from IODP Expedition 316 Sites C0006 and C0007

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[1] Integrated Ocean Drilling Program (IODP) Expedition 316 Sites C0006 and C0007 examined the deformation front of the Nankai accretionary prism offshore the Kii Peninsula, Japan. In the drilling area, the frontal thrust shows unusual behavior as compared to other regions of the Nankai Trough. Drilling results, integrated with observations from seismic reflection profiles, suggest that the frontal thrust has been active since ~0.78–0.436 Ma and accommodated ~13 to 34% of the estimated plate convergence during that time. The remainder has likely been distributed among out-of-sequence thrusts further landward and/or accommodated through diffuse shortening. Unlike results of previous drilling on the Nankai margin, porosity data provide no indication of undercompaction beneath thrust faults. Furthermore, pore water geochemistry data lack clear indicators of fluid flow from depth. These differences may be related to coarser material with higher permeability or more complex patterns of faulting that could potentially provide more avenues for fluid escape. In turn, fluid pressures may affect deformation. Well-drained, sand-rich material under the frontal thrust could have increased fault strength and helped to maintain a large taper angle near the toe. Recent resumption of normal frontal imbrication is inferred from seismic reflection data. Associated décollement propagation into weaker sediments at depth may help explain evidence for recent slope failures within the frontal thrust region. This evidence consists of seafloor bathymetry, normal faults documented in cores, and low porosities in near surface sediments that suggest removal of overlying material. Overall, results provide insight into the complex interactions between incoming materials, deformation, and fluids in the frontal thrust region.

Components: 8172 words, 4 figures.

Keywords: subduction zone; Nankai; fluid flow; frontal thrust; IODP; seamount.

Index Terms: 8170 Tectonophysics: Subduction zone processes (1031, 3060, 3613, 8413); 8010 Structural Geology: Fractures and faults; 8045 Structural Geology: Role of fluids.

Received 1 July 2009; **Revised** 13 October 2009; **Accepted** 20 October 2009; **Published** 29 December 2009.

Screaton, E., et al. (2009), Interactions between deformation and fluids in the frontal thrust region of the NanTroSEIZE transect offshore the Kii Peninsula, Japan: Results from IODP Expedition 316 Sites C0006 and C0007, *Geochem. Geophys. Geosyst.*, *10*, Q0AD01, doi:10.1029/2009GC002713.

Theme: Mechanics, Deformation, and Hydrologic Processes at Subduction Complexes, With Emphasis on the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) Drilling Transect
Guest Editors: D. Saffer, P. Henry, and H. Tobin

1. Introduction

[2] Subduction zones account for 90% of global seismic moment release, generating damaging earthquakes and tsunamis with potentially disastrous effects on heavily populated coastal areas [e.g., *Lay et al.*, 2005]. Understanding these plate boundary fault systems is a crucial step toward evaluating earthquake and tsunami hazards and is the objective of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE). NanTroSEIZE includes in situ measurements, direct sampling, allied laboratory and numerical modeling studies, and long-term monitoring along a transect through the Kumano Basin region, offshore of the Kii Peninsula, Japan. The Nankai Trough subduction zone offshore the Kii Peninsula was selected for NanTroSEIZE multidisciplinary investigation of seismogenic processes due to its well-documented history of large earthquakes, well-constrained rup-

ture area in the most recent (1944) earthquake, and accessibility by ocean drilling [*Kinoshita et al.*, 2009].

[3] The first stage of NanTroSEIZE drilling focused on the shallow portion of a major out-of-sequence thrust fault, termed the megasplay, and the deformation front. Characterization of the frontal sedimentary wedge is relevant to the seismogenic zone for several reasons. The incoming crust, sediments, and fluids observed at the deformation front will eventually comprise the seismogenic zone. As a result, heterogeneities of the incoming plate and sediments or variations in deformation during early subduction may influence the genesis and propagation of slip at seismogenic depths. This influence may result directly from the frictional properties of the materials themselves, or indirectly as lithology impacts pore pressures through its effect on permeability and the volume of water carried within pore spaces or minerals [e.g., *Underwood*, 2007]. In particular, seamounts and ridges may create strong asperities amidst weaker sediments [*Bilek et al.*, 2003; *Cloos*, 1992; *Scholz and Small*, 1997], allow fluid flow sufficient to perturb the thermal regime [e.g., *Harris et al.*, 2004; *Spinelli and Saffer*, 2004], and influence sedimentation patterns, as turbidity currents preferentially fill basement lows and basement highs dam turbidite flows [e.g., *Ike et al.*, 2008a, 2008b]. Furthermore, the distribution and timing of slip within the frontal wedge provide information about the properties of the shallow plate boundary and potentially impact tsunamigenesis. Simulations by *Wang and He* [2008] suggest that coseismic slip can extend to the trench even if the shallow fault zone material is slightly velocity strengthening (i.e., the frictional resistance against slip increases with increasing slip rate); surprisingly, rupture that fully breaks the trench was simulated to create less seafloor uplift than slip that stops short of the trench [*Wang and He*, 2008].

[4] Although lithology is an important control on permeability and fluid expulsion, deformation also plays a significant role in developing fluid pressures and controlling fluid migration pathways in subduction zones. Porosity data and inferences from seismic velocity have provided evidence for undercompaction beneath fault zones, suggesting elevated pore pressures [e.g., *Screaton et al.*, 2002; *Tobin and Saffer*, 2009], and pore water geochemical results have suggested focused flow from depth along fault zones [e.g., *Kastner et al.*, 1993]. Numerical models of subduction zones integrate drilling and seismic reflection data; results consistently indicate that fault zones provide an important fluid escape path [*Saffer and Bekins*, 1998; *Spinelli and Saffer*, 2004].

[5] Deformation due to subducting seamounts has been suggested to enhance pore pressures in overlying materials, decreasing strength [*von Huene*, 2008] and also to transfer fine-grained, fluid-rich sediments to deeper in the complex, where they would elevate pore pressures and inhibit coseismic rupture [*Bangs et al.*, 2006]. Deformation also rearranges sediments, truncating permeable horizons and altering the distribution of fluids. For example, the location of the décollement, and thus the partitioning between subducted and accreted sediments, controls the length of flow paths for fluid escape. The impact on pore pressure may persist to seismogenic depths [*Screaton*, 2006].

[6] Offshore the Kii peninsula, the outer accretionary wedge is a strongly deformed fold and thrust belt above the presumed aseismic portion of the plate boundary. An unusual feature of the accretionary prism in the NanTroSEIZE drilling area is that frontal imbrication appears to have ceased until recently, and the frontal thrust extends 6 km landward [*Moore et al.*, 2009]. Furthermore, the taper angle at the toe is the largest in the Nankai Trough [*Kimura et al.*, 2007] and similar to those in erosive margins [*Clift and Vannucchi*, 2004]. This contrasts with the Muroto and Ashizuri transects in the Nankai Trough [*Moore et al.*, 2001] and other accretionary margins such as the Barbados and Aleutian margins in which the deformation front is characterized by in-sequence thrusts that propagate systematically seaward [e.g., *Moore et al.*, 1990; *von Huene et al.*, 1998]. *Moore et al.* [2009] suggest that the anomalous conditions in this region may be related to recent subduction of a seamount evidenced by an indentation in the deformation front to the west of the NanTroSEIZE transect.

[7] Observations from IODP Expedition 316 drilling provide the opportunity to examine the distribution of slip offshore the Kii peninsula. Comparison of frontal thrust slip rates and estimated plate convergence rates allow assessment of the percent of slip that has propagated to the trench. Core-scale observations also provide understanding as to the nature of slip in this region and the interaction between deformation and fluid flow. Furthermore, drilling results provide the opportu-

nity to view the internal response of sediments to a significant perturbation.

2. Study Area

[8] The Nankai Trough is formed by subduction of the Philippine Sea plate to the northwest beneath Japan (Figure 1). The convergence direction is approximately normal to the trench, with estimates of convergence rate varying from ~40 [*Seno et al.*, 1993] to >60 km/my [*Miyazaki and Heki*, 2001]. The Nankai Trough has been selected as a focus site for studies of subduction zone seismogenesis based on a >1300 year historical record of great (M > 8.0) earthquakes [e.g., *Ando*, 1975], and direct societal relevance of understanding tsunamis and earthquakes near heavily populated coastal areas. Previous drilling investigations of the Nankai Trough have focused on the Muroto and Ashizuri transects (Figure 1). IODP Expedition 316 took place December 2007 to February 2008 and was the third NanTroSEIZE drilling expedition [*Kinoshita et al.*, 2009].

[9] Information from seismic reflection studies and seafloor bathymetry provides the context for interpreting the deformation in this region. Seafloor bathymetry indicates a large embayment to the west of the Kumano transect. This slump scar possibly reflects indentation by a recently subducted seamount (Figure 1). Irregular bathymetry seaward of this embayment is inferred to be mass movement debris. The trench channel has been deflected significantly seaward of the deformation front, likely due to blockage of axial flow by the seafloor mass wasting deposits [*Moore et al.*, 2009]. The seismic reflection data (Figure 2) indicate that the frontal thrust in the Kumano transect extends much further landward (~6 km, as compared to a more typical 2–3 km) and is lower angle than frontal thrust faults in other regions of the Nankai subduction zone [e.g., *Moore et al.*, 1990]. As a result, a large block has been thrust over the trench deposits. Beneath and seaward of this frontal thrust, a protothrust region is visible (Figure 2), suggesting that the region may currently be returning to more normal seaward imbrication.

3. Expedition 316 Observations

[10] Although Site C0006 was successfully drilled with Logging while Drilling (LWD) during Expedition 314 [*Expedition 314 Scientists*, 2009], coring at Site C0006 was unable to reach the frontal thrust. Drilling conditions in the frontal thrust region were difficult due to heavily fractured sediments, as well as abundant unconsolidated sand and gravel. To reach the frontal thrust at a shallower depth than at Site C0006, drilling moved to Site C0007, located closer to the deformation front (Figure 2b). At this site, holes were grouped in two areas ~215 m apart; the second location was necessitated by gravel that stopped drilling at the first. The combined information from Sites C0006 and C0007 provide a comprehensive picture of the deformation front.

3.1. Stratigraphy

[11] The uppermost sediments in the frontal thrust region (Unit I, Figure 3a) consist of a fining upwards succession of silty clay, sand, silty sand, and rare volcanic ash layers, extending from the seafloor to a depth of 27.23 m below seafloor (mbsf) at Site C0006 and 33.94 mbsf at Site C0007. These sediments are interpreted to have been deposited by hemipelagic settling, turbidity currents, and soft sediment slumping on an oversteepened slope. At Site C0006, slope sediments dip westward, whereas at Site C0007, bedding dips to the southeast (Figure 3). This difference likely reflects that Site C0006 slope deposition occurred in a basin deepening landward and created by the uplifting by the frontal thrust, whereas the slope sediments at Site C0007 are deposited on the slope down to the trench (Figure 2b). Calcareous nannofossil dates suggest an age between 0.436 and 0.9 Ma at the base of these sediments at Site C0006. Magnetostratigraphy places the Brunhes/Matuyama Chron boundary (0.78 Ma) at 32.75 mbsf (Figure 3). At Site C0007, the oldest nannofossil age for slope sediments is 0.436 Ma; observed repetitions of the nannofossil sequence suggest reworking and/or disturbance, possibly by slumping.

[12] A coarsening upwards succession from fine-grained mud to sand- and gravel-rich deposits comprises Unit II, the accreted trench wedge. The top of the accretionary prism is defined by the frequent occurrences of sand beds; at Site C0007, these sediments include gravel. These upper prism sediments are interpreted to reflect increasing proximity to the axial portion of the trench up-section, with the fine-grained sediments at the base representing basinal deposition and the sand- and gravel-rich sediments at the top representing trench sediments.

[13] The lower portion of the prism (Shikoku Basin facies, Unit III, Figures 2b and 3a) consists of silty clay with some interbedded dolomite-cemented

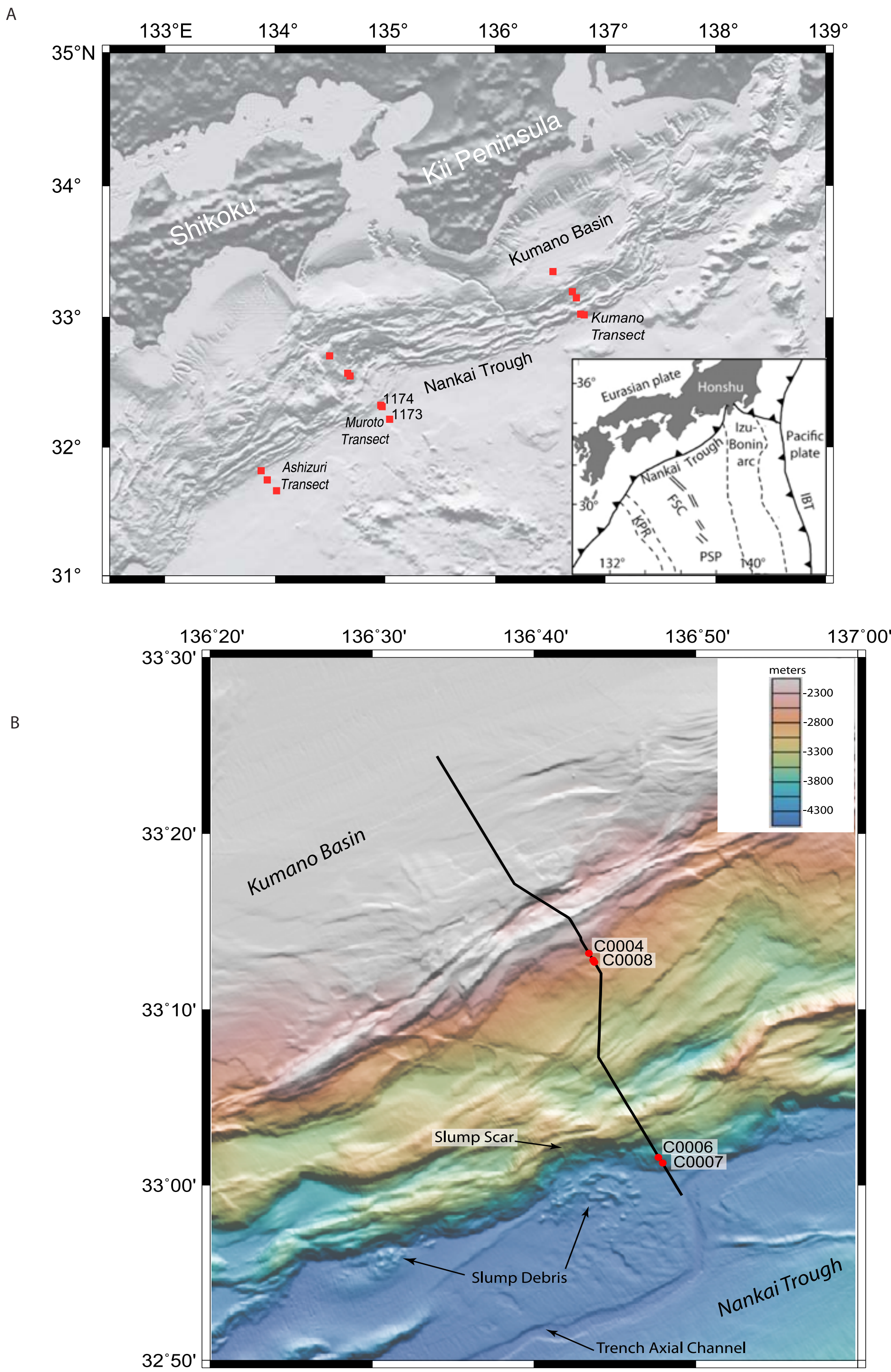

Figure 1. (a) Regional bathymetry of the northern Shikoku Basin and Nankai Trough showing the previous and current ODP/IODP transects. Red squares show the locations of ODP/IODP drill sites. The inset is a tectonic map showing the plate tectonic setting of the region. IBT, Izu-Bonin Trench; KPR, Kyushu-Palau Ridge; FSC, fossil spreading center; PSP, Philippine Sea Plate. (b) Location of IODP Expedition 316 drill sites (modified from *Moore et al.* [2009]). Solid line indicates location of seismic profile in Figure 2.

and calcite-cemented ash, interpreted to have been deposited by hemipelagic settling in a deep marine basin. A significant age transition from Pleistocene (1.24 Ma) and younger sediments above to Miocene (2.5 Ma and older) below marks the boundary between the coarsening upwards sediments of the accreted trench wedge (Unit II) and the underlying fine-grained hemipelagic sediments of the Shikoku

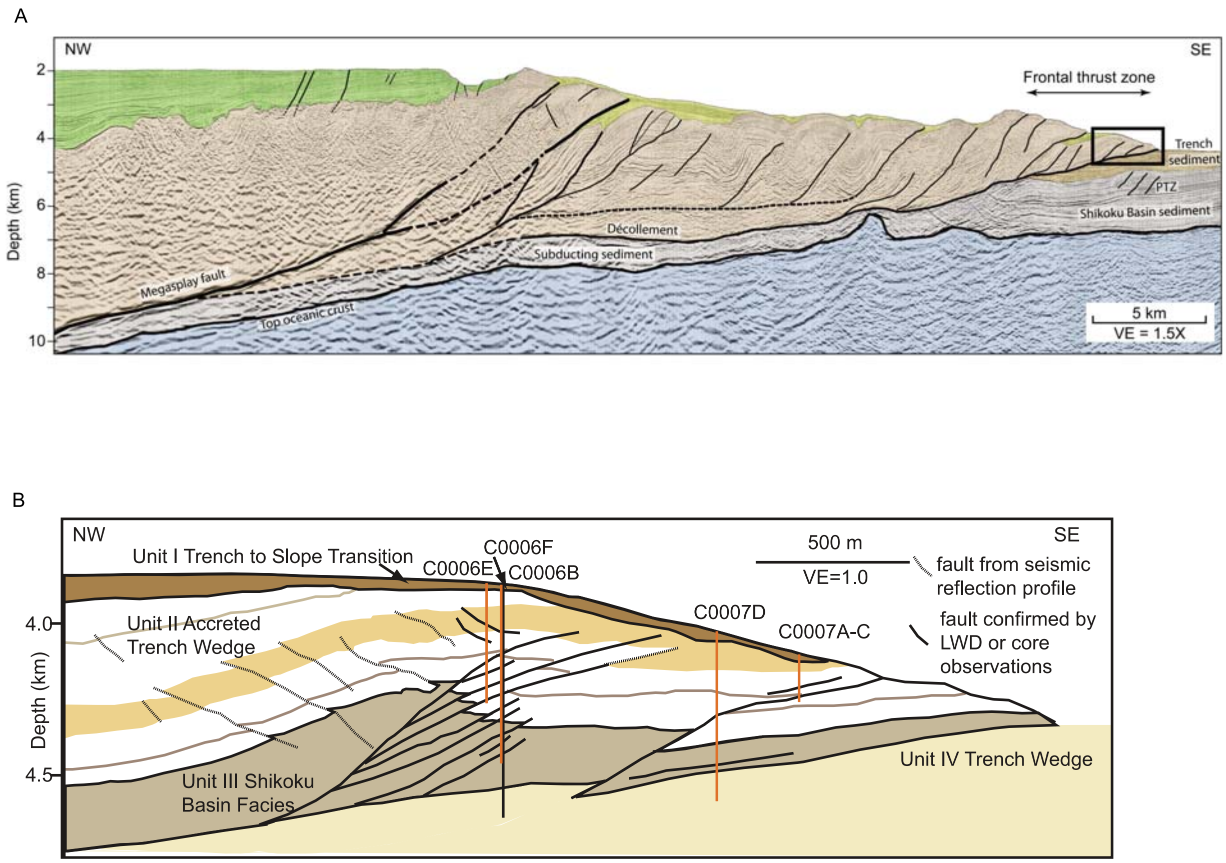

Figure 2. (a) Interpreted cross section of Kumano transect (modified from *Moore et al.* [2009]). The green shading indicates Kumano Basin sediments, and yellow shading indicates slope sediments. PTZ, protothrust zone. The distance of frontal thrust movement (6 km) was estimated from extent of underthrust trench sediments. The black box indicates location of Figure 2b. (b) Interpretation of frontal thrust region showing Expedition 316 sites. Stratigraphy and structure are greatly simplified, with only the largest and most obvious faults shown. A traceable horizon within Unit II (tan shading) is distinguished to illustrate structure. At Site C0006, Hole C0006B (black line) was drilled with LWD during Expedition 314 but not cored. Holes C0006E and F (red lines) were cored during Expedition 316, and results are combined in Figure 3a. At Site C0007, no LWD hole was drilled. Holes C0007A–C are at the same location (red line). Information from Holes C0007A–C and deeper intervals of Hole C0007D is combined in Figure 3B.

Basin facies (Unit III). At Site C0007, this lithologic change and age gap coincide with evidence of a fault zone observed in the cores from 341.5 to 362.3 mbsf; in contrast, no evidence of coincident faulting was observed at Site C0006.

[14] Although coring at Site C0006 did not reach the underthrust trench sediments, LWD results from this site, particularly the natural gamma ray (NGR), indicate a lithologic change to sand- or silt-rich sediments [*Expedition 314 Scientists*, 2009]. Coring of the corresponding sediments at Site C0007 resulted in extremely poor recovery of dark gray sand of the trench wedge (Unit IV). The sand is fine to medium grained and consists of abundant black lithic fragments, metamorphic rock fragments, ferromagnesian minerals, and quartz, feldspar and opaque grains.

3.2. Deformation

[15] The accretionary prism in the frontal thrust region is deformed by thrusting, as visible on the seismic profiles and LWD data (Figure 2) [*Expedition 314 Scientists*, 2009; *Moore et al.*, 2009]. During Expedition 316, many of the thrusts inferred from the seismic profile and LWD were confirmed by age reversals, fault zones sampled in cores, and/or repetition of specific strata; some additional faults were also defined during Expedition 316 drilling (Figures 2b and 3). The character of faulting in the frontal thrust region at Sites

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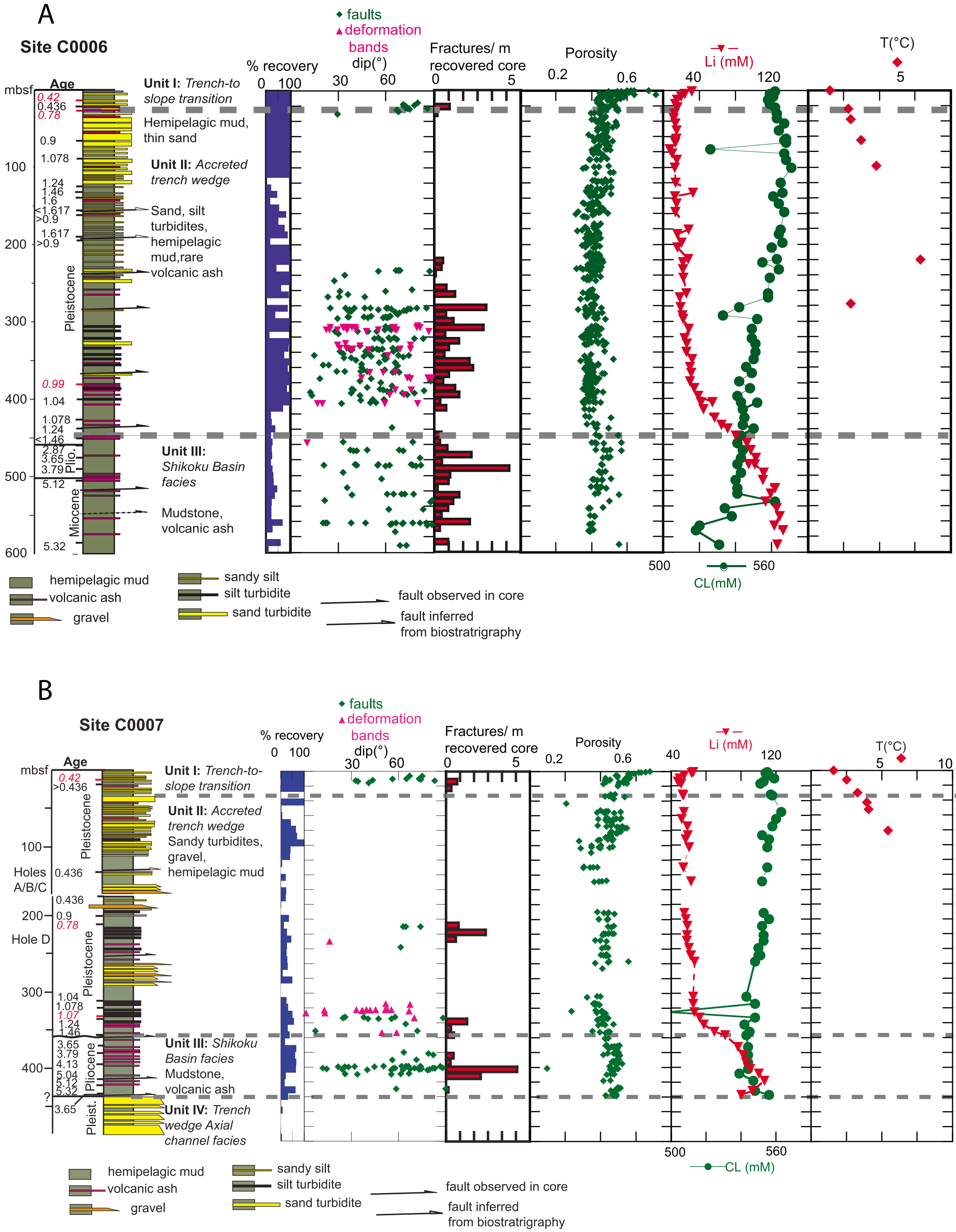

Figure 3. Lithostratigraphy, recovery percent, dip angles of faults and deformation bands, observed fractures per meter recovered in cores, porosity, pore water chloride and lithium, and temperature at Sites (a) C0006 and (b) C0007. Ages shown in black are from biostratigraphy, and ages shown in red italics are from magnetostratigraphy. The observed fractures per m recovered cores includes faults and joints that could be distinguished from drilling induced damage. Total number per core were divided by the meters recovered in a core.

Figure 4. Examples of (a) fractured mudstone (351.14 to 351.41 mbsf, Hole C0007D) and (b) fault breccia and fault gouge (double arrow) (362.06 to 362.20 mbsf, Hole C0007D) [from *Kinoshita et al.*, 2009]. (Photo provided by the Integrated Ocean Drilling Program.)

C0006 and C0007 is considerably more complex than observed in the Muroto and Ashizuri transects [*Moore et al.*, 2001].

[16] At Site C0006, cores are strongly fractured, striated or polished planes are common, and tectonic breccias are observed in a broad zone from 230 to 545 mbsf. Deformation bands, defined by bedding-oblique dark bands with a reverse sense of shear that typically develop in argillaceous sediments [e.g., *Ujiie et al.*, 2004], are observed in cores between 300 and 460 mbsf. Between 300 and 405 mbsf, five concentrated zones of deformation, containing greater densities of deformation bands, fractures, and tectonic breccias were tentatively identified as faults (Figure 3). In general, these zones transition from coherent material through fractured rock and protobreccias, consisting of angular to subangular fragments with little matrix, to breccias and microbreccias, consisting of small fragments embedded in a clayey matrix. In some locations, fault gouge, consisting of fine-grained clayey material, was observed (Figure 4). The lowermost fault zone (526–545 mbsf) contains a progression from tectonic breccia to microbreccia and then fault gouge. At Site C0007, several fault zones were described, with the deepest recovered fault zone observed at 398.5–446.0 mbsf in the basal part of the prism above the frontal thrust (Figure 3). This fault zone is marked by a heterogeneous distribution of fractures, commonly with polished and slickenlined surfaces, and brecciation. A foliated fault gouge was observed at 418.83 to 418.94 mbsf with a shear sense consistent with thrust faulting. The lowermost part of the fault

zone at 438.28 to 438.57 mbsf is intensely brecciated into fragments approximately 1 to 10 mm in size. Nannofossil biostratigraphy indicates an age reversal of 1.67 My across this 29 cm interval. This breccia exhibits a foliated aspect arising from an anastomosing network of polished and striated surfaces. At the base of this zone, a 2 mm thick dark layer sharply separates intensely brecciated hemipelagic mudstone above from unbroken hemipelagic mudstone and ash below.

[17] X-ray computed tomography (CT) images were used to estimate sense of displacement of minor faults observed in cores at Site C0006. Of the 220 observed faults, normal faults were the most frequent (42%), followed by reverse faults (12%) and left-lateral (10%) or right-lateral (10%) faults. The remaining faults (26%) have undetermined or ambiguous displacement. Predominantly steeply dipping normal faults were found between 545 and 603 mbsf at Site C0006. No preferred orientation of fault plane directions could be recognized.

3.3. Sediment Physical Properties and Fluid Flow

[18] Porosities are quite low at shallow depths below the surface, reaching 48% at 5 and 34 mbsf at Sites C0006 and C0007, respectively (Figure 3). In contrast, porosities of fine-grained sediments do not decrease to <50% until ~150 to 200 mbsf, at other sites drilled in the Kumano transect during Expedition 316 (Site C0004 and slope basin Site C0008). The observed low porosities at shallow depths suggest that a considerable thickness of material has been removed from the surface at Sites C0006 and C0007. Porosity profiles indicate gradual downhole decreases, with only a slight increase at the lithologic boundary between Unit II (the accreted trench wedge) and Unit III (Shikoku Basin facies). This lithologic boundary coincides with an age gap of >1 My at Sites C0006 and C0007, and an observed fault at Site C0007. An increase in clay content at this lithologic boundary suggests that the porosity change may reflect an increase in interlayer water. Interlayer water can cause artificially high porosity values, because the shipboard porosity measurements cannot distinguish between pore and interlayer water [*Brown and Ransom*, 1996]. Pore fluid geochemical profiles, as illustrated by chloride and lithium (Figure 3) are relatively smooth through most of the multiple fault zones penetrated at Site C0006 (Figure 3); negative excursions of chloride concentrations occur at 77 at 292 mbsf, but are considered an artifact of gas hydrate dissociation on core recovery.

[19] Downhole temperature and laboratory thermal conductivity measurements yield heat flow estimates of 33 and 53 mW/m^2 at Sites C0006 and C0007, respectively. These values are anomalously low relative to seafloor measurements ranging from 70 to 200 mW/m^2 in the frontal thrust region and incoming plate offshore the Kii peninsula region [*Yamano et al.*, 2003]. Although temperature measurements in sand-rich sediments are vulnerable to contamination and cooling by borehole seawater, the observed profiles are generally linear with the exception of the deepest measurement at Site C0006 (Figure 3), The linearity of the profiles argues against contamination, which would be expected to produce more random variations in estimated temperature.

4. Discussion

4.1. Distribution of Slip and Frontal Thrust History

[20] The lithologic transition from slope deposits (Unit I) to the accreted wedge (Unit II) at Site C0006 records the uplift due to movement of the frontal thrust. This transition lies ~5.5 m above the Brunhes/Matuyama Chron boundary (0.78 Ma). Thus, the age of this transition is estimated between 0.436 and 0.78 Ma (Figure 3), and provides a constraint on the initiation of frontal thrust activity. During this time, it appears that the frontal thrust has overridden ~6 km of the underlying sediments (Figure 2a). Assuming a relative plate motion velocity between the overriding Japanese islands and the Philippine Sea Plate of about ~40–60 km/my [*Seno et al.*, 1993; *Miyazaki and Heki*, 2001], the total plate convergence would be 17–26 and 31–47 km for 0.436 and 0.78 Ma, respectively. This suggests that the frontal thrust system accommodated at least ~13 to 34% of the plate convergence. If frontal thrust activity recently slowed or ceased due to resumption of seaward propagation of the décollement, this percentage would have been higher in the past. These results indicate that a significant component of slip approached the seafloor along the frontal thrust. Detailed fault zone studies will be needed to assess the rate of this slip. Modeling by *Wang and He* [2008] suggests that coseismic slip can reach the trench even if the shallowest portion of the fault is slightly velocity

strengthening. If the slip occurred rapidly, it could contribute to tsunamigenesis.

[21] Within the frontal thrust region, the inferred 6 km of slip was distributed among multiple faults. For example, the fault observed at 438.28–438.57 mbsf at Site C0007 exhibits an age reversal of 1.67 My. Assuming sedimentation rates of the Shikoku Basin facies off the Kii Peninsula are similar to those off the Muroto Peninsula (2.7×10^{-5} m/yr [*Shipboard Scientific Party*, 2001]), approximately 45 m thickness of sediment has been repeated. For an estimated fault angle of 10°, this would imply a displacement of 260 m. Thus, this fault provided ~4% of the total frontal thrust displacement of 6 km. Several thin dark shear zones are present between 438.28 and 438.57 mbsf that could accommodate this displacement.

4.2. Pore Pressures and Fluid Flow

[22] Development of elevated pore pressures very near the deformation front has been well documented from previous drilling of accretionary prisms, including the Muroto transect of the Nankai Trough [*Screaton et al.*, 2002; *Saffer*, 2003]. In contrast, porosity data from Sites C0006 and C0007 have quite low values near the surface, and profiles show no porosity increases across fault zones that would indicate undercompaction. This suggests that local dewatering was able to keep pace with increased stresses due to fault displacement, including both increased overburden due to thrust faulting and lateral stresses. Within the frontal thrust region of the Kumano transect, the high number of faults observed within the prism would have distributed the slip among multiple faults, making it easier for fluid escape to keep pace than if slip occurred on fewer faults. Nonetheless, the rate of burial due to individual faults is moderately high. The estimated 45 m of repetition across the fault observed at 438.28–438.57 mbsf at Site C0007 yields an estimated burial rate of 58 to 100 m/My to the footwall sediments if this fault were active for 0.436 to 0.78 My. While this value is less than that generally considered sufficient for maintenance of excess pore pressures (on the order of 500 m/My for sedimentary basins [*Bredehoeft and Hanshaw*, 1968]), it is likely that that the individual fault was not active for the entire frontal thrust history; thus the rate could be significantly higher. Furthermore, within the prism, lateral stress will exceed overburden stress, further increasing loading rates. Dewatering within the frontal thrust region is likely aided by fluid flow through the underthrust coarse-grained trench sediments (Figure 2b) as well as uplifted trench sediments within the prism. Although fault cores, with fine-grained gouges and microbreccias, are expected to have low permeability, surrounding fractured zones could potentially allow fluid escape [*Wibberly et al.*, 2008].

[23] Another difference between results from the Kumano transect and those of previous drilling is the lack of geochemical evidence for focused deeply sourced fluid flow within the frontal thrust region. At the Muroto transect, low-chlorinity fluids suggest flow from depth; after correction for in situ dehydration, the anomaly is centered on the décollement [*Saffer and McKiernan*, 2009]. Lack of evidence for focused flow of deeply sourced fluids within the hanging wall of the Kumano transect frontal thrust suggests that deeply sourced fluids escaped upward through the prism before reaching the frontal thrust region, fluid escape occurred (or is occurring) deep within the underthrust sediments or basement (below the depth penetrated by drilling), or that outflow in the frontal thrust region is too diffuse to be detected. Heat flow data also provide no indication of flow of warm fluids from depth in the frontal thrust region. On the contrary, anomalously low heat flows estimated for Sites C0006 and C0007 allow the possibility of cooling by seawater circulation. Sand-rich sediments, such as found within the accreted and underthrust trench deposits, have permeabilities similar to that of crustal basalt (10^{-12} to 10^{-9} m^2 [*Freeze and Cherry*, 1979]), in which convection is driven by small thermal differences [e.g., *Fisher*, 2005].

[24] Delineation of timing and location of discrete slip has the potential to improve numerical models of excess pore pressures and fluid flow. A common modeling approach considers the incoming sediments to enter the prism at the rate of plate convergence plus prism outgrowth [e.g., *Screaton et al.*, 1990; *Bekins and Dreiss*, 1992; *Saffer and Bekins*, 1998]. The sediments are assumed to continually decelerate with distance from the deformation front as the prism thickens and sediments compact. These simulations yield broad regions of near-lithostatic pore pressures. In contrast, discrete slip will result in localized regions in which thrusting rapidly increases total stresses, potentially raising pore pressures, with intervening regions experiencing more diffuse application of stresses, and thus more gradual increases, or perhaps even decreases, of pore pressure.

[25] Given an average frontal thrust dip of 7° [*Moore et al.*, 2009] and estimated slip rate of 0.77 to 1.38 cm/year, sediments beneath the frontal thrust would have experienced a burial rate of 740 to 1700 m/My. Although these estimated burial rates beneath the frontal thrust are extremely high, the underthrust coarse-grained trench sediments would provide permeable pathways for fluid escape to the nearby seafloor, allowing pore pressures within this unit to remain low. Finer grained, lower permeability sediments within the more deeply buried Shikoku Basin facies would drain more slowly and could possibly build excess pressures. Local increases in burial rate would also occur where plate convergence was accommodated along out of sequence thrusts such as that observed ~5 km landward of the deformation front (Figure 2) or by the megasplay fault [*Moore et al.*, 2007; *Strasser et al.*, 2009]. As a result, locations beneath these out of sequence thrusts may host localized elevated pore pressures if total stress increased more rapidly than fluid expulsion reduced pore pressures.

4.3. Implications

[26] Sites C0006 and C0007 are located to the east of a disturbed zone that *Moore et al.* [2009] suggest is caused by a recently subducted seamount. If this interpretation is correct, the observed disruptions to the frontal imbrication could be directly or indirectly related to nearby seamount subduction. Sandbox models have shown temporary stepping up of the décollement zone over a subducting seamount, followed by downstepping following seamount passage [*Dominguez et al.*, 2000]. The uplift and associated deformation could produce the greater complexity of faulting at this transect relative to the Muroto transect [e.g., *Moore et al.*, 2001]. Alternatively, the perturbation observed at the Kumano transect could be indirectly related to an incoming seamount by changes in sedimentation patterns due to disruption of flow in the trench channel. If the unusual structure at the toe of the Kumano transect is a response to seamount subduction, drilling observations suggest that the dewatering allowed by underthrusting of coarse-grained trench deposits and faulting within the prism may counteract the weakening effect of seamounts that has been previously suggested [*Bangs et al.*, 2006].

[27] Regardless of the cause of the perturbation, the Kumano transect illustrates the interplay between deformation, sediment inputs, and fluid flow. The temporary cessation of frontal accretion caused trench fill sediments to be carried at least 6 km under the frontal thrust. Because trench deposits at Sites C0006 and C0007 are coarse grained and apparently uncemented, drainage will be efficient, resulting in higher strength than poorly drained overpressured sediments. Furthermore, the frictional strength of quartz-rich sediment is greater than smectite-rich hemipelagic sediments [e.g., *Marone and Saffer*, 2007]. As a result, the presence of well-drained sand beneath the frontal thrust should result in high fault strength and contribute to the observed large taper angle near the toe [*Kimura et al.*, 2007].

[28] Development of a protothrust zone suggests a recent return to frontal imbrication [*Moore et al.*, 2009]. As the décollement propagates into the Shikoku Basin facies, the lower frictional coefficient of presumably smectite-rich sediments would favor a lower taper angle. The Shikoku Basin sediments have been rapidly buried by the hanging wall of the frontal thrust; unless these sediments could drain quickly to overlying trench sediments or through deeper turbidite units, pore pressures could build and contribute to weakness of the propagating décollement. Slope failures in the frontal thrust region are evidenced by mass wasting deposits evident in the bathymetry as well as low porosities measured in near-surface sediments. These slope failures may be a response to reduced fault strength.

[29] The unusual geometry of the frontal thrust has also affected incoming sediments. The slope failure and resulting mass transport deposits have deflected the axial trench channel significantly seaward (~10 km [*Moore et al.*, 2009]). As a result, incoming sediments in the near future will likely be poorly sorted and rapidly deposited, and thus potentially poorly drained. If these observed morphological and geological features reflect recurring or cyclical processes, perhaps related to variations in basement topography, then repeated subduction of packages of alternating well-drained and poorly drained sediments and their attendant impacts on fluid flow and pore pressure will comprise an integral component of accretionary prism development.

5. Summary

[30] Results of IODP Expedition 316, integrated with seismic reflection and bathymetric observations, document anomalous conditions at the deformation front of the Kumano transect. The frontal

thrust apparently acted as the plate boundary fault as frontal imbrication temporarily ceased. The frontal thrust has accommodated ∼13 to 34% of the plate convergence during ∼0.436 to 0.78 My of activity. The remainder of the plate convergence must be accommodated by diffuse shortening and/or out of sequence thrusts, including the megasplay. Within the frontal thrust region, displacement appears be distributed along many faults observed within seismic profile and cores; investigation of an individual fault with significant gouge development suggests a few hundred meters of displacement.

[31] Currently, development of a protothrust zone seaward of the frontal thrust suggests that the main décollement is returning to its previous level, accompanied by slope failures in the overlying prism. At the core scale, low porosities measured in near-surface sediments suggest removal of overlying material. Observed normal faults are also consistent with observed slope failures.

[32] The unusual structure of the Kumano transect frontal thrust region may help to explain why fluid behavior appears to differ significantly from that other subduction zones that have been drilled, including the Nankai Trough Muroto transect. High permeability stratigraphic horizons, such as the underthrust coarse-grained trench sediments, could aid dewatering. In addition, fractures related to a high frequency of faults within the prism may also enable fluid escape and help to explain the lack of observed porosity shifts beneath faults. Multiple fluid escape paths also diminish the likelihood of focused flow from depth, consistent with lack of pore water geochemical evidence for deeply derived fluid flow. Efficient dewatering of coarse-grained sediment below the frontal thrust, as well as the frictional properties of these sediments, would have contributed to frontal thrust strength and allowed the observed large taper angle. As frontal imbrication resumes and the décollement propagates into weaker sediments of the Shikoku Basin facies, reduction of the taper angle would be expected. Recent reduction of taper angle due to fault weakness provides a possible explanation for evidence of slope failure consisting of debris on the seafloor, porosity data indicative of removal of overlying sediments, and normal faults.

Acknowledgments

[33] The authors thank the ship and drilling personnel, staff, and technicians aboard the D/V *Chikyu* and at the Center for Deep Earth Exploration (CDEX) for their work that allowed the overall success of this expedition. The authors also thank NanTroSEIZE chief project scientists (H. Tobin and M. Kinoshita), specialty coordinators (T. Kanamatsu, D. Saffer, M. Underwood, and G. Wheat), and the scientists of Expeditions 314 and 315 (J. Ashi, J. H. Behrmann, B. Boeckel, S. Bourlange, T.Byrne, G. Calves, C. Chang, V. Famin, P. Gaillot, F. E. Girault, S. Gulick, J. Guo, Y. Hashimoto, H. Hayashi, P. Henry, T. Hirono, S. M. Hulme, A. H. Kaksonen, K. Kanagawa, A. Kopf, S. Lallemant, W. J. Likos, K. M. Martin, H. Masago, L. McNeill, A. Miyakawa, J. C. Moore, J. Pares, M. Conin, H. Saito, F. Schmidt-Schierhorn, S. Saito, D. S. Sawyer, M. Kyaw Thu, H. Tomura, A. Tsutsumi, J. Tudge, K. Ujiie, Y. Yamada, A. Yamaguchi, and W. Zhu). Comments by Demian Saffer and two anonymous reviewers greatly improved this manuscript. This research used samples and data provided by the Integrated Ocean Drilling Program (IODP).

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