Clay-mineral assemblages across the Nankai-Shikoku subduction system, offshore Japan: A synthesis of results from the NanTroSEIZE project

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ABSTRACT

The Integrated Ocean Drilling Program, as part of the Nankai Trough Seismogenic Zone Experiment, recovered samples of mud and mudstone from the Kumano forearc basin, the inner and outer accretionary prisms, the overlying slope apron, and the Shikoku Basin (subduction inputs). This unprecedented suite of cores and cuttings captures an unusually complicated history of subduction-zone tectonics, erosion and dispersal of suspended sediment from multiple sources, and sedimentation in diverse environments. Our X-ray diffraction analyses of 1567 samples show that clay-mineral assemblages shifted gradually throughout the subduction system, from a smectite-rich assemblage during the Miocene to a more illite- and chlorite-rich assemblage during the Pliocene and Quaternary. Miocene clays in the Shikoku Basin (Sites C0011 and C0012) originated primarily from weathering of anomalous, near-trench felsic-volcanic rocks along a broad swath of the Outer Zone of Japan. The middle Miocene, however, was also a time of sediment transport into the Shikoku Basin by turbidity currents emanating from the East China Sea (Kyushu Fan). Interfingering of clays from those two sources resulted in considerable compositional scatter. Our results also reveal large discrepancies in contents of smectite between Miocene mudstones from the inner accretionary prism (Sites C0001 and C0002) and coeval mudstones from the Shikoku Basin. We suggest that frontal accretion during the early-late Miocene was a product of Pacific plate subduction rather than subduction of the Philippine Sea plate. Routing of sand through the East China Sea was effectively cut off by ca. 7 Ma due to rifting of the Okinawa Trough and the buildup of topography along the Ryukyu arc-trench system. Subduction of Shikoku Basin restart at ca. 6 Ma, and denudation of the Outer Zone continued through the Pliocene and Quaternary. Those adjustments in weathering, from volcanoes to exposures of plutons and metasedimentary rocks, gradually increased the concentrations of illite and chlorite. By the late Pliocene, multiple sources, including the rapidly uplifted Izu-Honshu collision zone, supplied suspended sediment through a combination of transverse and trench-parallel (axial) routing. At the same time, the northeast-directed Kuroshio Current intensified at ca. 3.5 Ma. That regional-scale oceanographic transition probably resulted in more illitic clays moving from offshore Taiwan through the Okinawa Trough, although its compositional signal is masked by simultaneous enrichment of illite from the Outer Zone sources. Accreted trench-wedge deposits in the frontal prism (Sites C0006 and C0007) originated mostly from the Izu-Honshu collision zone, and most were transported down the axis of the trench by sediment gravity flow. Hemipelagic deposits in the Kumano Basin (Site C0002) were homogenized from a combination of transverse gravity flows, northeast-directed surface current, and thermohaline bottom currents. Slope-apron and slope-basin deposits (including mass-transport deposits) likewise show uniform clay-mineral assemblages indicative of northeast-directed transport by the Kuroshio Current, transverse resedimentation, and bottom-water circulation. Collectively, these differences in sediment composition in both time and space set the Nankai-Shikoku depositional system apart from other subduction zones, and they are important to consider when assessing the margin’s hydrogeology and frictional and/or geotechnical properties.

INTRODUCTION

Clay-mineral assemblages in marine environments are widely known to change in response to the types of detrital source rocks, tectonic influences on the distribution of such sources, the conditions of weathering and climate in the source areas, and the physical mechanisms and special patterns of transport and dispersal once suspended sediments enter the ocean (e.g., Naidu and Mowatt, 1983; Petschick et al., 1996; Fagel et al., 2001). As general rules, smectite tends to track volcanic sources, chlorite tends to increase toward higher latitudes, kaolinite is more prevalent in tropical latitudes (where chemical weathering is more intense), and illite is a typical product of physical weathering on continental landmasses (e.g., Biscaye, 1965; Thiry, 2000). To a first approximation, those general rules for clay provenance also apply to suspended sediments in subduction zones.

Some subduction zones (mostly intraoceanic examples) display relatively simple histories and spatial patterns of sedimentation dominated by steady pelagic to hemipelagic settling (Underwood and Moore, 1995; Spinelli and Underwood, 2004; Underwood, 2007; Kimura et al., 2012; Kameda et al., 2015a,
The majority of regional-scale dispersal systems, however, are much more complicated and diverse. That diversity is caused by different levels of influence among several governing factors: distribution of widely spaced point sources (i.e., submarine canyons), diffuse transverse delivery through slope gullies and by unconfined gravity flows, margin-parallel routing by both ocean currents and gravity flows, and progradation of large submarine fans or channel-levée complexes onto adjacent (subducting) abyssal plains (e.g., Karlin, 1980; Emmel and Curraw, 1985; Kolla and Courmes, 1985; Underwood and Moore, 1995; Spinielli and Field, 2001; Noda and Tsuzino, 2007; Noda et al., 2008; Alexander et al., 2010; Gulick et al., 2015; Meridith et al., 2017). In fact, imbalanced competition between transverse and margin-parallel routing can result in compositional decoupling between coarser gravity-flow deposits and finer-grained hemipelagic muds (e.g., Underwood, 1986; Hathon and Underwood, 1991). Essentially, the time-honored paradigm of a predictable upward-thickening and upward-coarsening stratigraphic succession (Piper et al., 1973) is usually violated by, rather than supported by, individual case studies.

The connections of cause-and-effect between subduction-zone sedimentation and tectonics are also multifaceted, and they work in both directions. Proportions of common clay minerals are known to affect tectonic processes in several fundamental ways (Underwood, 2007). Mineralogy of the clay-size fraction, for example, often dictates the shear strength and permeability of mudstone (Saffer et al., 2001; Brown et al., 2003; Kopf and Brown, 2003; Saffer and Marone, 2003; Ikari and Saffer, 2011; Ikari et al., 2013). Expandable clays of the smectite group are mechanically weaker and often dominate mineral assemblages in subduction-zone sediments because of their proximity to volcanic sources (Vrolijk, 1990), although some notable exceptions to that standard do exist (Naidu and Mowatt, 1983; Hathon and Underwood, 1991). Unusually high concentrations of smectite are thought to control the stratigraphic position of the frontal décollement in some systems (e.g., Deng and Underwood, 2001; Kameda et al., 2015b). Flips in fault verge within some accretionary prisms have been attributed to along-strike changes in clay mineralogy and clay diagenesis, and their effects on frictional properties and shear strength (Underwood, 2002). Release of interlayer water and silica, as reaction products of smectite-to-illite diagenesis (Bruce, 1984; Colten-Bradley, 1987), modulate the freshening of pore water and increase the likelihood of having pore-fluid pressures rise above hydrostatic, especially in areas where drainage is retarded (Bekins et al., 1995; Saffer and Bekins, 1998, 2006; Saffer and McKiernan, 2009; Saffer and Tobin, 2011). Accordingly, the dehydration of smectite, if the minerals are volumetrically significant, probably helps regulate the down-dip transition from aseismic (stable sliding) to seismogenic (stick slip) behavior along megathrust faults (Hyndman et al., 1995; Wang et al., 1995; Olesekevich et al., 1999; Moore and Saffer, 2001; Spinelli and Saffer, 2004). Other scientists have suggested that zones of fluid overpressure contribute to occurrences of slow-slip events along some plate interfaces (Kodaira et al., 2004; Schwartz and Rokosky, 2007; Bell et al., 2010; Saffer and Wallace, 2015). Thus, we recognize many ancillary reasons to scrutinize the spatial and temporal changes in clay mineralogy within subduction zones.

The Nankai-Shikoku system provides an ideal natural laboratory to study subduction-zone sedimentation and tectonics; it is arguably the best studied example in the world. Located offshore south-central to southwest Japan (Fig. 1), this particular margin has received considerable attention over five decades of scientific ocean drilling, largely because of its 1300-year historical record of great earthquakes and tsunamis (Ando, 1975; Cummins and Kaneda, 2000; Cummins et al., 2001). With that history in mind, the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) was designed and implemented to improve our collective understanding of Nankai fault-slip phenomena (Tobin and Kinoshita, 2006). Twelve sites have been cored along the NanTroSEIZE transect by the Integrated Ocean Drilling Program (IODP). Most of those sites are within the confines of a 3D seismic-reflection survey (Moore et al., 2009). The tectonostratigraphic environments sampled along the transect include the Kumano forearc basin, the inner and outer accretionary prisms, and subduction inputs that were deposited seaward of the trench in the Shikoku Basin (Ashi et al., 2009; Screaton et al., 2009a; Expedition 319 Scientists, 2010; Underwood et al., 2010; Expedition 333 Scientists, 2012a; Strasser et al., 2014a; Tobin et al., 2015a; Kopf et al., 2017).

This paper provides a synthesis of X-ray diffraction (XRD) results from 1567 specimens of mud and mudstone, covering virtually all of the Nankai-Shikoku depositional environments. Our data compilation demonstrates that clay-mineral assemblages fluctuated over time throughout the regional system, largely in response to: (1) gradual changes in proportions of parent rocks exposed to weathering within detrital source areas; and (2) reorganisations of the plate boundaries. Understanding how, when, and where the budget of suspended sediment changed carries important implications relative to the specific goals of NanTroSEIZE (Tobin and Kinoshita, 2006), especially with regard to predictions and modeling of such phenomena as fault-slip behavior and intrapram hydrogeology. We believe those fundamental connections between cause and effect are also exportable to other subduction zones around the world.

GEOLOGIC SETTING

Structure and Bathymetry

The Nankai Trough currently forms the boundary between the subducting Philippine Sea plate and the overriding Eurasia plate (Fig. 1). The trench axis is <5000 m below sea level, and the gradient of the trench-floor dips gently to the northeast end of the Nankai Trough (Le Pichon et al., 1987; Nakamura et al., 1987). The Nankai deep-sea channel meanders down the axis of Nankai Trough to a termination point offshore from the Kii Peninsula (Shimamura, 1989). Several more through-going submarine canyons (e.g., Tenryu Canyon) are incised into the accretionary prism offshore Shikoku Island, the Kii Peninsula, and central Honshu (e.g., Soh and Tokuyama, 2002; Underwood et al., 2003a; Kawamura et al., 2009; Tsuji et al., 2014).
Located immediately seaward of the trench, the Shikoku Basin (Fig. 1) initially formed behind the Izu-Bonin island arc during a phase of backarc spreading that persisted from 26 Ma to 15 Ma (Chamot-Rooke et al., 1987; Kobayashi et al., 1995; Okino et al., 1994, 1999; Sdrolias et al., 2004). The Kyushu-Palau Ridge on the basin’s western edge (Fig. 1) represents the remnant arc (Ishizuka et al., 2011). The northern (proximal) part of the basin includes several bathymetric complexities (Fig. 2): four cross chains of en echelon seamounts (in the vicinity of IODP site U1437); Zenisu Ridge and associated fault fragments; a large canyon-channel complex (Zenisu channel); and the Kinan seamount chain, which runs down the axis of the basin (Lallemant et al., 1989; Ishii et al., 2000; Sato et al., 2002; Wu et al., 2005; Machida et al., 2008). Kashinosaki Knoll, another prominent bathymetric high within the NanTroSEIZE transect area (Figs. 2 and 3), is thought to have formed by reorientation of the backarc spreading center and off-axis volcanism during the Miocene (Ike et al., 2008a). Total sediment thickness across the Shikoku Basin ranges from 300 m to 2200 m, with pronounced thinning toward the south and above the larger basement highs (Higuchi et al., 2007; Ike et al., 2008b).

The lower trench slope of Nankai Trough (outer or frontal accretionary prism) is dominated by a fault-controlled ridge-and-trough landscape (Ashi and Taira, 1992; Okino and Kato, 1995; Moore et al., 2001, 2011; Bangs et al., 2004; Gulick et al., 2004). The outer accretionary prism is characterized by a critical taper that varies along strike, by internal deformation via folds and in-sequence, seaward-vergent thrusts, and by an aseismic décollement (Kimura et al., 2007). In the vicinity of the NanTroSEIZE transect, frontal imbrication appears to have been dormant until recently, and the frontal fault can be traced landward (down-dip) from the base-of-slope to its intersection with the basal décollement (Moore et al., 2009; Scraeton et al., 2009b). The taper angle of the prism is unusually large in that area (Kimura et al., 2007), and the anomalous structural architecture was probably induced by recent subduction of a seamount (Moore et al., 2009). Integration of seismic, logging, and coring results confirms the existence of many subparallel thrusts within the frontal prism, as evidenced by age reversals, repetition of distinctive stratigraphic intervals, and localized core-scale deformation (Scraeton et al., 2009b).
Moving farther landward, the most prominent structural element is an out-of-sequence thrust (Fig. 3), usually referred to as the megasplay fault (Park et al., 2000, 2002; Moore et al., 2007; Strasser et al., 2009; Kimura et al., 2011; Yamada et al., 2013). Similar faults exist along many subduction margins (e.g., Barnes et al., 2002; Collot et al., 2008; Hsu et al., 2013; Lauer and Saffer, 2015), and some such faults are thought to be responsible for destructive earthquakes and tsunamis (e.g., Sibuet et al., 2007; Waldhauser et al., 2012; Melnick et al., 2012). The Nankai megasplay marks the boundary between the inner accretionary prism and the outer prism (Fig. 3). The inner prism is characterized by a consistently narrow taper, weakly deformed internal structure, and a seismogenic megathrust along its base (Kimura et al., 2007). The prism’s geologic makeup is poorly documented but thought to consist of old accreted sediments (Nakanishi et al., 2002). Analysis of 3D seismic data provides clear evidence of thrust-fault reactivation after the overlying forearc basin formed (Boston et al., 2016). In addition, deformation of the inner prism is heterogeneous and locally intense, and the prism’s semitransparent acoustic character is indicative of a generally uniform lithology with steep bedding dips (Boston et al., 2016). Slip along the Nankai megasplay started ca. 1.95 Ma, and the thrust has remained active in the eastern domain of the 3D survey since 1.24 Ma (Kimura et al., 2011). Subsurface fault traces correlate with clusters...
of low-frequency tremor, very low frequency earthquakes, and co-seismic slip during great earthquakes (Cummins and Kaneda, 2000; Cummins et al., 2001; Ito and Obara, 2006; Obana and Kodaira, 2009).

The seaward edges of several forearc basins (e.g., Kumano Basin, Muroto Basin) are positioned close to the landward edge of the transition zone between the inner and outer prisms (Fig. 2) (Kimura et al., 2007). Accordingly, many workers have suggested that initial formation and subsequent infilling of the basins by turbidites were triggered by offset along the megasplay (e.g., Gulick et al., 2010; Hayman et al., 2012; Moore et al., 2015; Ramirez et al., 2015). On the other hand, numerical modeling indicates that infilling of such basins results in emergence or reactivation of out-of-sequence thrusts (Mannu et al., 2016), rather than the other way around; so the links between cause and effect are probably more complicated.

As documented along many other subduction zones (Moore and Karig, 1976; Underwood and Moore, 1995), slope-apron and slope-basin environments are ubiquitous across the landward slope of Nankai Trough. The sediment carapace overlies the accretionary prism and records complicated local histories of sedimentation that have been tempered by changes in sediment supply, mass wasting, and bathymetric adjustments to accretion-related deformation (Underwood et al., 2003a; Strasser et al., 2011). Slope basins within the NanTroSEIZE transect area host several prominent mass-transport complexes (MTCs), as well as erosional features that have been linked to episodes of offset along the megasplay fault (Strasser et al., 2011; Alves et al., 2014; Kaminatsu et al., 2014; Moore and Sawyer, 2016; Laberg et al., 2017).

**Lithostratigraphy of the NanTroSEIZE Transect**

In this paper, we group the many lithologic units and subunits recognized by NanTroSEIZE shipboard scientists into six tectonostratigraphic domains: (1) subduction inputs of Shikoku Basin; (2) the frontal thrust zone of the accretionary prism; (3) the carapace of slope-apron and slope-basin deposits (including mass-transport complexes); (4) the shallow hanging wall to the megasplay fault (inner accretionary prism); (5) deeper (intermediate) levels of the inner accretionary prism; and (6) the Kumano forearc basin. This grouping into domains is a modification of the Stage 1 summary by Underwood and Moore (2012); it is more fundamental in terms of the depositional environments and takes into account the most recent drilling results (Underwood et al., 2010; Expedition 333 Scientists, 2012a; Strasser et al., 2014a; Tobin et al., 2015a).

**Subduction Inputs**

Subduction inputs were cored at Sites C0011 and C0012 (Underwood et al., 2010; Expedition 333 Scientists, 2012a). The two sites are located seaward of the trench on the northwest flank and near the summit of Kashinosaki Knoll (Figs. 2 and 3). Basaltic basement at Site C0012 is older than 18.9 Ma (Underwood et al., 2010) and overlain by a thin interval of pelagic claystone (Fig. 4). A unit of tuff mixed with volcaniclastic-siliciclastic turbidites overlies the claystone and grades upsection into a silty turbidite facies. Pickering et al. (2013) named those turbidite deposits the Kyushu Fan (Figs. 4 and 5). Turbidite deposition near Kashinosaki Knoll ceased ca. 12.5 Ma to 12.2 Ma, after which hemipelagic mud dominated until 9.2 Ma to 9.1 Ma (Underwood et al., 2010). An overlying volcanic turbidite facies comprises interbeds of hemipelagic mudstone, volcaniclastic and siliciclastic sandstone, ignimbrites, mud turbidites, and mass-transport deposits (Schindlbeck et al., 2013; Kutterolf et al., 2014). Pickering et al. (2013) named that interval the Zenisu Fans (Figs. 4 and 5). The youngest lithologic unit in Shikoku Basin is a hemipelagic-pyroclastic facies that ranges from late Miocene (7.6 Ma to 7.8 Ma) to Holocene in age (Underwood et al., 2010; Expedition 333 Scientists, 2012a). As analyzed in more detail (i.e., basin-wide) by Underwood and Pickering (2018), the unit boundaries described above are diachronous, and some units cannot be correlated across the width of the basin.

**Figure 3. Composite seismic-reflection profile crossing the NanTroSEIZE transect with locations of Integrated Ocean Drilling Program (IODP) drill sites. See Figure 2 for geographic context.**
Figure 4. Simplified stratigraphic columns for Integrated Ocean Drilling Program (IODP) drill sites along the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) transect with lithofacies designations and key positions of age control.
Drilling at Sites C0006 and C0007 (Figs. 2 and 3) showed that the frontal thrust domain comprises three stratigraphic components: accreted Shikoku Basin deposits (hemipelagic-pyroclastic facies), accreted trench-wedge facies, and slope-apron deposits (Fig. 4). Frontal accretion molded the trench-wedge and upper Shikoku Basin deposits into a complicated system of imbricate thrust slices (Moore et al., 2009; Screaton et al., 2009b). Within the hanging wall to the frontal thrust, an unconformity separates the hemipelagic-pyroclastic facies (maximum age of 5.32 Ma) from Quaternary gravity-flow deposits (Screaton et al., 2009a). The associated hiatus spans from 2.87 Ma to 1.46 Ma at Site C0006 and from 3.65 Ma to either 2.06 Ma or 1.46 Ma at Site C0007.

Figure 5. X-ray diffraction (XRD) results for subduction inputs at Site C0011, Shikoku Basin. See Underwood et al. (2010) for stratigraphic overview. Data are from Expedition 322 Scientists (2010a), Expedition 333 Scientists (2012b), and Underwood and Guo (2013, 2017).
(Screaton et al., 2009a) (Fig. 4). The accreted trench-wedge deposits range in age from 1.46 Ma to 0.44 Ma and display an overall upward coarsening trend with abundant sand and gravel (Screaton et al., 2009b; Underwood and Moore, 2012).

**Trench-Slope Deposits**

Slope-apron and slope-basin deposits were recovered from seven sites (Fig. 3). Above the frontal accretionary prism, a thin carapace of fine-grained slope-apron facies is less than 0.44 Ma in age (Screaton et al., 2009a) (Fig. 4). The equivalent facies at Site C0001 (Fig. 3) is ~200 m thick and consists of hemipelagic mud with scattered interbeds of fine sand, silt, and volcanic ash; the maximum age there is 2.06 Ma (Ashi et al., 2009). Matsuzaki et al. (2014) compiled a detailed age-depth model for those slope deposits using radiolarian biostratigraphy and oxygen-isotope stratigraphy. Comparable recoveries from Site C0008, located just seaward of the megasplay, include a lower sand-rich unit (accreted trench-wedge facies), a mass transport complex (MTC) with an age range of 2.9 Ma to 1.6 Ma, and Quaternary slope-basin deposits (Expedition 333 Scientists, 2012a; Strasser et al., 2014a).

Sites C0018 and C0021 (Fig. 4) were drilled in a nearby slope basin (Fig. 3) to investigate the timing and emplacement mechanisms of MTCs. Hemipelagic mud is the dominant lithology, but thin interbeds of silty- to sand-size volcanic ash are abundant, as are silt to fine-sand turbidites (Fig. 4). The ages of deposition, based on nannofossil and paleomagnetic datums, are less than 1.46 Ma (Expedition 333 Scientists, 2012a; Strasser et al., 2014a). Mesoscale evidence for mass transport (i.e., debris flow and submarine slide mechanisms) includes convolute and tilted strata, intervals with remobilized mud clasts overlying tilted strata, and discrete shear zones. Thicker MTCs comprise a mixture of mud-rich debris-flow deposits, intact hemipelagic beds, and contorted layers that evidently resulted from extensive deformation within the interior of the failure.

**Inner Accretionary Prism**

Shallow portions of the inner accretionary prism (hanging wall to the megasplay) were sampled at three sites. Coring successfully penetrated the megasplay fault at Site C0004 (Fig. 3). The footwall to the thrust is typical slope-apron facies (Fig. 4), as described above, with an age of ca. 1.6 Ma (Screaton et al., 2009a). The fault zone, itself, contains a thin sliver of Pliocene mudstone with numerous interbeds of volcanic ash (age 3.65 Ma) (Screaton et al., 2009a), superficially similar to the hemipelagic-pyroclastic facies of Shikoku Basin (Underwood et al., 2010). That fault sliver, however, is not present at Site C0010, which was drilled along strike for installation of a borehole observatory (Kopf et al., 2017). The hanging wall at Site C0004 includes a Pliocene subunit of deformed mudstone and a Pliocene–Pleistocene subunit of synsedimentary mudstone breccia (Screaton et al., 2009a). An unconformity separates the breccia from overlying slope-apron deposits (age <1.6 Ma) (Screaton et al., 2009a).

Farther upslope at Site C0001 (Fig. 3), accreted Pliocene mudstone yields a maximum age of 5.32 Ma (Fig. 4) (Ashi et al., 2009). An angular unconformity at the top of the accretionary prism has a time gap that extends from 3.79 Ma to 2.06 Ma (Ashi et al., 2009). Acoustic character below the unconformity is semi-transparent, which is indicative of relatively homogeneous lithologies. Cores display abundant small faults, shear zones, vein structures, and steepened bedding dips (Ashi et al., 2009). Shipboard scientists during Expedition 315 were perplexed by the enigmatic, mudstone-dominated character of the accretionary prism, which is in stark contrast to the coarse-grained Quaternary trench-wedge deposits in the frontal prism (Screaton et al., 2009b; Underwood and Moore, 2012); they speculated that the trench (and/or spillover into Shikoku Basin) during latest Miocene to early Pliocene time was isolated for some unspecified reason from influx by sandy sediment gravity flows (Ashi et al., 2009). The lithologic match to coeval deposits within Shikoku Basin (i.e., the hemipelagic-pyroclastic facies) is dubious, however, judging from the ubiquity of discrete volcanic ash beds in one (C0011 and C0012) and the paucity of similar beds in the other (C0001). Furthermore, correlation between accreted mudstones and the older hemipelagic facies at Sites C0011 and C0012 fails completely because of their disparate ages (Underwood et al., 2010). Thus, facies relations documented at Site C0001 point to a depositional environment quite unlike the setting for coeval subduction inputs on the Philippine Sea plate (Underwood, 2018).

Farther landward, the uppermost accretionary prism at Site C0002 (Fig. 3) also contains deformed Pliocene–Miocene mudstone with scattered beds of sandstone and siltstone, yielding a maximum age of 5.9 Ma (Ashi et al., 2009). Those strata are similar to core recoveries of the accretionary prism at Site C0001. The hiatus along the angular unconformity at the top of the prism extends from 5.0 Ma to 3.8 Ma (Fig. 4) (Ashi et al., 2009). The basal unconformity is covered by mudstone deposits (starved slope or slope-basin facies) that are Pliocene to Pleistocene in age (3.8 Ma to 1.6 Ma) (Ashi et al., 2009). At Site C0009 to the north (Fig. 3), the boundary between slope deposits and the accretionary prism is more complex, as is the transition from trench-slope to turbidite facies within the overlying Kumano forearc basin (Hayman et al., 2012; Ramirez et al., 2015; Boston et al., 2016).

Interpreting facies relations within older and deeper portions of the inner prism at Site C0002 (Fig. 3) is hampered by the paucity of core and the reliance on analysis of cuttings that were sampled during riser drilling (Strasser et al., 2014a; Tobin et al., 2015a). A unit boundary at ~1665 mbsf (Hole C0002N) is based on a significant down-hole reduction in the proportion of sandstone to mudstone in the cuttings (Fig. 4). The underlying, mudstone-dominant unit displays increases in clay-size content with depth. Age control is sparse, but nannofossil datums range from >5.59 Ma to <10.73 Ma (Strasser et al., 2014a; Tobin et al., 2015a).

The cored interval in Hole C0002P provides a better indicator of the finescale lithologic diversity within the accretionary prism. The most common lithology is hemipelagic mudstone, with thin interbeds of siltstone to fine sandstone and scattered laminae of pyrite. Bedding dips are steep, with angles of 60°
to 90° (Tobin et al., 2015b). Correlations between these fine-grained rocks and lithofacies in the Shikoku Basin are questionable (Underwood, 2018). The oldest nannofossil datum from the inner prism (ca. 10.7 Ma) (Tobin et al., 2015b) falls within the age brackets of the mudstone-dominant hemipelagic facies of Shikoku Basin (12.5 Ma to 9.1 Ma) (Underwood et al., 2010). The overlying accreted sandstone, however, is quartzose, with relatively few lithic fragments or volcanic glass shards (Tobin et al., 2015b), in stark contrast to the distinctive volcanic and tuffaceous sandstones that typify the Zenisu Fans at Sites C0011 and C0012 (Pickering et al., 2013; Kutterolf et al., 2014). Thus, facies relations for accreted sediments at Sites C0002 and C0001 both point to a depositional environment dissimilar to the setting for coeval subduction inputs (Underwood, 2018).

**Forearc-Basin Deposits**

At Site C0002, rapid accumulation of silty and sandy turbidites in the forearc basin commenced at ca. 1.6 Ma, with an overall trend of thickening and coarsening upward (Ashi et al., 2009; Strasser et al., 2014a). Kumano Basin shifted to that phase of rapid sedimentation in response to a combination of uplift at the basin’s seaward edge, which created more accommodation space (Strasser et al., 2009; Gulick et al., 2010), and incision of slope gullies and submarine canyons near the shoreline, which enhanced the sediment supply to that growing accommodation space (Guo et al., 2013). The basin traps sediment gravity flows emanating from small canyons and slope gullies along the upper slope, even during the Holocene highstand of sea level (Blum and Okamura, 1992; Omura and Ikehara, 2010; Shirai et al., 2010; Shirai and Hayashizaki, 2013). Proximal areas of the basin also contain thick deposits of channelized turbidite sand and sheet-like sand that act as reservoirs for gas hydrates (Noguchi et al., 2011; Egawa et al., 2013). Deformation of those sand bodies attests to complex tectonic reorganization of the forearc, perhaps in response to subduction of seamounts. In addition, 3D seismic-reflection data from the distal basin show evidence of buried landslides, rotational slumps, and disintegrative slides (Moore and Strasser, 2016).

**RESULTS**

**Shikoku Basin Subduction Inputs**

Among the tectonostratigraphic domains sampled during this study, Sites C0011 and C0012 (Figs. 3 and 4) display the largest amounts of compositional variability over the longest range of depositional ages. The depth distributions of mineral abundances define a general trend of decreasing smectite and increasing illite and chloride upsection, particularly within the hemipelagic-pyroclastic facies (Figs. 5 and 6). The relative abundance of smectite within that uppermost facies ranges from 12 wt% to 81 wt%, with a mean value (μ) of 44.6 wt% and a standard deviation (σ) of 13.2 (Table 1). The proportion of illite in the clay-size fraction ranges from 18 wt% to 49 wt% (μ = 34.7; σ = 6.3). Percentages of chloride range from 2 wt% to 29 wt% (μ = 13.5; σ = 5.8). Percentages of clay-size kaolinite and quartz average 4.2 wt% (σ = 3.4) and 3.0 wt% (σ = 3.5), respectively. For the older lithologic units (depositional ages >72 Ma to 74 Ma), the relative abundance of smectite ranges from 23 wt% to 100 wt% (μ = 64.2; σ = 13.6); 41 of those samples are bentonites, with smectite contents greater than or equal to 80 wt%. The scatter of values is particularly large within the Kyushu Fan and Zenisu Fan intervals (Figs. 5 and 6). The specific variety of smectite is consistently dioctahedral, probably montmorillonite. The proportion of illite ranges from 0 to 50 wt% (μ = 23.7; σ = 7.9), and percentages of chloride range from 0 to 18 wt% (μ = 6.3; σ = 3.4). Average values for kaolinite and clay-size quartz are 1.8 wt% and 4.3 wt%, respectively.

Figure 7A shows 502 values of %-smectite within the clay-size fraction plotted as a function of depositional age, up to a maximum of 15 Ma. The ages were extrapolated from each sample’s depth position on the integrated age-depth models for Sites C0011 and C0012 (Expedition 322 Scientists, 2010a, 2010b; Expedition 333 Scientists, 2012b, 2012c). Linear regression yields a correlation coefficient of 0.88 for the entire data set, and the slope of the regression line indicates ~2.8 wt% decrease in the amount of smectite for each 1 m.y. of younging. The slope of the regression line is steeper when data are limited to the past 9 m.y., with a decrease of 4.1 wt% for each 1 m.y. (Fig. 7B). Underwood and Pickering (2010) presented similar plots for each site using calculated values of %-smectite within the bulk mud or mudstone.

**MATERIALS AND METHODS**

Sample preparation, XRD protocols, and error analysis have been thoroughly described in a series of IODP data reports (Underwood et al., 2003b; Guo and Underwood, 2012; Underwood and Guo, 2013, 2017; Underwood and Song, 2016a, 2016b; Underwood, 2017a, 2017b, 2017c). The vast majority of our specimens are from “clusters” of collocated specimens used to characterize whole-round intervals that were extracted from the dominant lithology by other shipboard scientists, ostensibly for coordinated studies of interstitial water geochemistry, frictional and/or geotechnical properties, and hydrogeochemistry. Accordingly, our data set targets the dominant background lithology rather than interbeds of volcanic ash or turbidites.

Our calculated values of mineral abundance in the glycol-saturated clay-size fraction (<2 μm) utilized a matrix of normalization factors derived from singular value decomposition (SVD). We used the saddle/peak method (Rettke, 1981) to calculate the percent expandability of smectite and illite/smectite (I/S) mixed-layer clay. The proportion of illite in the I/S mixed layer is calculated by the position (d-value) of the (002/003) peak (Moore and Reynolds, 1989). To discriminate between dioctahedral and trioctahedral varieties of smectite, we determined the d-value of the (006) reflection using randomly oriented powders of the <2 μm size fraction (Brindley, 1980). Values of illite crystallinity index are based on peak width at half-height for the illite (001) reflection (Blakenship, 1988; Kisch, 1990).

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**Nankai-Shikoku clay-mineral assemblages**

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Figure 6. X-ray diffraction (XRD) results for subduction inputs at Site C0012, Shikoku Basin. See Underwood et al. (2010) for stratigraphic overview. Data are from Expedition 322 Scientists (2010b), Expedition 333 Scientists (2012c), and Underwood and Guo (2013, 2017).

### Table 1. Statistical Comparison of Clay Mineral Assemblages from Nankai Trough and Shikoku Basin

<table>
<thead>
<tr>
<th>Tectonostratigraphic setting</th>
<th>IODP sites</th>
<th>Age (Ma)</th>
<th>Number analyzed</th>
<th>Smectite</th>
<th>Illite</th>
<th>Chlorite</th>
<th>Kaolinite</th>
<th>Quartz</th>
<th>Total clay minerals#</th>
<th>Bulk sediment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope apron, slope basin, MTDs</td>
<td>C0001, C0004, C0008, C0018, C0021, C0006, C0007</td>
<td>0.0–2.87</td>
<td>384</td>
<td>36.4</td>
<td>4.2</td>
<td>20.0</td>
<td>3.6</td>
<td>5.1</td>
<td>3.0</td>
<td>46.1</td>
</tr>
<tr>
<td>Forearc basin</td>
<td>C0002</td>
<td>0.0–3.79</td>
<td>88</td>
<td>35.6</td>
<td>2.9</td>
<td>20.8</td>
<td>4.1</td>
<td>4.7</td>
<td>2.8</td>
<td>12.0</td>
</tr>
<tr>
<td>Frontal (outer) prism</td>
<td>C0006, C0007</td>
<td>0.90–5.32</td>
<td>206</td>
<td>35.4</td>
<td>4.3</td>
<td>22.9</td>
<td>5.6</td>
<td>4.5</td>
<td>2.3</td>
<td>7.5</td>
</tr>
<tr>
<td>Inner prism (shallow)</td>
<td>C0001, C0002, C0004</td>
<td>3.65–5.9</td>
<td>123</td>
<td>35.9</td>
<td>3.3</td>
<td>16.5</td>
<td>3.7</td>
<td>6.5</td>
<td>2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Inner prism deep (unit IV)</td>
<td>C0002 (cuttings)</td>
<td>5.9–7.3</td>
<td>53</td>
<td>34.2</td>
<td>4.4</td>
<td>17.5</td>
<td>5.3</td>
<td>3.2</td>
<td>3.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Inner prism deep (unit V)</td>
<td>C0002 (above 2220 m)</td>
<td>7.3–10.7</td>
<td>90</td>
<td>35.6</td>
<td>6.5</td>
<td>19.3</td>
<td>5.7</td>
<td>5.0</td>
<td>3.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Inner prism (overprinted)</td>
<td>C0002 (below 2200 m)</td>
<td>7.3–10.7</td>
<td>93</td>
<td>37.4</td>
<td>6.9</td>
<td>24.6</td>
<td>6.2</td>
<td>7.3</td>
<td>3.4</td>
<td>10.0</td>
</tr>
<tr>
<td>Subduction inputs (unit I)</td>
<td>C0011</td>
<td>0.0–7.6</td>
<td>210</td>
<td>34.7</td>
<td>6.3</td>
<td>13.5</td>
<td>5.8</td>
<td>4.2</td>
<td>3.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Subduction inputs (units II–V)</td>
<td>C0012</td>
<td>0.0–7.8</td>
<td>298</td>
<td>37.7</td>
<td>7.9</td>
<td>6.3</td>
<td>3.4</td>
<td>1.8</td>
<td>1.6</td>
<td>4.3</td>
</tr>
</tbody>
</table>

^Smectite + illite + chlorite + kaolinite + quartz = 100%.

#Total clay minerals + quartz + feldspar + calcite = 100%.

Abbreviations: IODP—Integrated Ocean Drilling Program; S.D.—standard deviation; MTD—mass transport deposit.
Values of the illite crystallinity (Kubler) index for the subduction inputs range from 0.84 $\Delta^2\theta$ to 0.27 $\Delta^2\theta$, with a majority of results falling within the confines of anchizone metamorphism; as a frame of reference, we follow Warr and Mahlmann (2015) on the anchizone limits of 0.32 $\Delta^2\theta$ and 0.52 $\Delta^2\theta$. The scatter of values is unusually large, and a significant number of data plot in the diagenetic zone (Figs. 5 and 6). We see no systematic gradient in illite crystallinity as a function of burial depth, although the upper portion of the section shows less scatter. The values of expandability for illite/smectite mixed-layer clays also display an unusually large range, from 49% to 100%. The average value for Site C0011 is 72.1% ($s = 8.3$), and the average for Site C0012 is 73.8% ($s = 7.8$). In addition, I/S expandability decreases upsection by an average of ~10% within the hemipelagic-pyroclastic facies (Fig. 5 and 6), in the sense opposite to normal burial diagenesis.

Frontal (Outer) Accretionary Prism

The accreted trench-wedge facies at Sites C0006 and C0007 (Fig. 3) display an overall upward-coarsening trend accentuated by progressive increases in silt and sand turbidites. Contents of total clay minerals in the bulk mud tend to decrease upsection in response to those changes in texture (Fig. 8). Overall, illite is the dominant clay mineral ($\mu = 35.4$ wt%, $s = 4.3$), followed by smectite ($\mu = 29.7$ wt%, $s = 8.2$), chlorite ($\mu = 22.9$ wt%, $s = 5.6$), kaolinite ($\mu = 4.5$ wt%, $s = 2.3$), and quartz ($\mu = 7.5$ wt%, $s = 3.3$) (Table 1). We see a decrease in smectite content upsection, especially across the unconformity between the trench-wedge facies and the inferred Shikoku Basin hemipelagic-pyroclastic facies (Fig. 8). Contents of smectite below the unconformity match favorably with the results from coeval strata at Sites C0011 and C0012 (Figs. 5 and 6); that close correspondence reinforces the interpretation of thrust slices displacing subducted Shikoku Basin sediments (e.g., Screaton et al., 2009b). Values of illite crystallinity consistently straddle the boundary between anchizone and epizone metamorphism (Fig. 8), and values of I/S expandability are uniformly between 60% and 70%.

Inner Accretionary Prism

Shallow levels of the inner accretionary prism (hanging wall to the megasplay) were sampled at Sites C0004, C0001, and C0002 (Figs. 3 and 9). The most abundant clay mineral at Site C0004 is illite ($\mu = 38$ wt%) followed by smectite ($\mu = 28$ wt%) and chlorite ($\mu = 21$ wt%). Mudstones from the fault-bounded package (2.87 Ma to 3.65 Ma) (Screaton et al., 2009a) contain more smectite ($\mu = 36$ wt%) and are similar in composition to the hemipelagic-pyroclastic facies of the Shikoku Basin (Figs. 5 and 6). At Site C0001, accreted strata consists mostly of deformed mudstone, with ages ranging from 3.79 Ma to 5.32 Ma (Ashi et al., 2009). Proportions of illite and smectite there are roughly equal, at ~35 wt% each (Fig. 9). The top of the accretionary prism is slightly older at Site C0002, ranging in age from 5.0 Ma to 5.9 Ma (Ashi et al., 2009), and detrital smectite increases by a few wt% relative to Sites C0001 and C0004, with a maximum value of 60 wt% (Fig. 9); scatter for those abundances also increases.
Figure 8. X-ray diffraction (XRD) results for accreted units at Sites C0006 and C0007, frontal accretionary prism of Nankai Trough. See Screaton et al. (2009a) for stratigraphic and structural overview. Data are from Expedition 316 Scientists (2009b, 2009c) and Guo and Underwood (2012).
When results from the three sites are grouped (Table 1), the shallow hanging wall contains roughly equal proportions of smectite ($μ = 35.7$ wt%, $s = 6.8$) and illite ($μ = 35.9$ wt%, $s = 3.3$), followed in rank order by chlorite ($μ = 16.5$ wt%, $s = 3.7$), kaolinite ($μ = 6.5$ wt%, $s = 2.3$), and clay-size quartz ($μ = 5.4$ wt%, $s = 3.1$). Values of illite crystallinity index fall consistently near the anchizone–epizone boundary, and values of I/S expandability are consistently between 60% and 70% (Fig. 9).

Our XRD results from deeper levels of the inner accretionary prism come mostly from analysis of cuttings, and we see clear evidence of a progressive smectite-to-illite diagenetic overprint with depth. Diagenetic reaction progress below the cored interval of Hole C0002P (2163 mbsf to 2216 mbsf) is consistent with temperature gradients derived from borehole and observational measurements (e.g., Sugihara et al., 2014), with temperatures documented elsewhere for the onset of illitization (e.g., Freed and Peacor, 1989), and with kinetic modeling (e.g., Pytte and Reynolds, 1989). Below 2220 mbsf, proportions of smectite in the clay-size fraction steadily decrease with depth, balanced by steady increases in the proportion of illite (Fig. 10). In addition, the proportion of illite in I/S mixed-layer clays increases monotonically with depth to a maximum of 68%, and the scatter among those values shrinks (Fig. 10). Values of illite crystallinity increase over the same depth range (i.e., the peaks broaden) due to enrichment of the poorly crystalline diagenetic illite. Thus, we see four interrelated indicators of progressive smectite-to-illite conversion over one common depth interval (Fig. 10).

Figure 9. X-ray diffraction (XRD) results for strata in the shallow hanging wall to the megasplay fault.

Data from above 2220 mbsf retain the sediment’s primary detrital signatures (Fig. 10), and the proportion of smectite in the clay-size fraction varies from an average of 41.7 wt% in unit IV to an average of 34.5 wt% in unit V (Table 1). Average values for the other minerals in units IV and V, respectively, are: illite = 34.2 wt% and 35.6 wt%; chlorite = 17.5 wt% and 19.3 wt%; kaolinite = 3.2 wt% and 5.0 wt%; and quartz = 3.4 wt% and 5.7 wt%. We note a small but progressive decrease in smectite down-hole between 1100 and 2220 mbsf (Fig. 10). Values of smectite within the cored interval (Underwood and Song, 2016b) show considerably more variability (11 wt% to 98 wt%); the larger range is due partly to differences in total clay minerals within the bulk sediment (38 wt% to 73 wt%) among thin interbeds of mudstone, siltstone, and fine sandstone, together with scattered occurrences of altered volcanic ash (bentonite). Mean values for the core samples, however, are nearly identical to the cuttings results from Hole C0002N over the same depth interval. As expected, the mixing of cuttings tends to homogenize small-scale compositional differences among interbeds.

The depth interval between 2220 mbsf and 1100 mbsf (i.e., above the diagenetic overprint) coincides with a span of depositional ages between 10.5 Ma and 6 Ma (Fig. 4). In the Shikoku Basin, coeval Miocene mudstones contain dramatically higher percentages of smectite, typically between 50% and 62% of the clay-size fraction (Fig. 7). Those compositional contrasts, moreover, inflate steadily as the depositional ages get older; they are too large (especially for unit V) for us to explain in any way other than a difference in detrital provenance and depositional setting (Underwood, 2018).

Kumano Basin

The inner accretionary prism at Site C0002 is buried beneath forearc-basin deposits (Figs. 3 and 4). Figure 11 shows that illite in the fill of Kumano Basin is consistently the most abundant clay-size mineral ($μ = 35.6$ wt%, $s = 2.9$) followed by smectite ($μ = 26.9$ wt%, $s = 6.9$), chlorite ($μ = 20.8$ wt%, $s = 4.1$), quartz ($μ = 12.0$ wt%, $s = 3.1$), and kaolinite ($μ = 4.7$ wt%, $s = 2.8$). The average proportion of total clay minerals in the bulk sediment is 46 wt% (Table 1).
Inner accretionary prism - deep riser drilling

Figure 10. X-ray diffraction (XRD) results for strata from intermediate levels of the hanging wall to the megasplay at Site C0002, inner accretionary prism of Nankai Trough. Most of the samples were recovered as cuttings during riser drilling. See Strasser et al. (2014a) and Tobin et al. (2015a) for stratigraphic and structural overview. Data are from Strasser et al. (2014b), Tobin et al. (2015b), Underwood and Song (2016a, 2016b), and Underwood (2017b, 2017c).
The starved-basin facies at the base of the forearc section contains proportions of smectite modestly higher than the overlying turbidites (Fig. 11), with small corresponding reductions of illite and chlorite. All of those values are similar to the results from broadly coeval slope-apron and slope-basin deposits (see below). The expandability of I/S mixed-layer clay minerals does not change significantly downsection, averaging ~60%, and values of illite crystallinity index are mostly between 0.30°2θ and 0.40°2θ (Fig. 11), consistent with detrital source rocks exposed to anchizone-to-epizone metamorphism.

Slope-Apron and Slope-Basin Deposits

As we discovered in the Kumano Basin, detrital illite is the most abundant clay mineral in the slope-apron and slope-basin deposits at all sites; detrital smectite is consistently second in abundance (Fig. 12). There are no obvious differences in composition between the MTCs and intact hemipelagic deposits at Sites C0018 and C0021 (Fig. 12). The relative abundance of illite throughout the slope cover ranges from 32 wt% to 52 wt%, with a mean value of 36.4 wt% and a standard deviation of 4.2 (Table 1). The proportion of smectite in the clay-size fraction ranges from 8 wt% to 39 wt% (μ = 29.0; s = 6.9). Percentages of chlorite range from 9 wt% to 36 wt% (μ = 20.0; s = 3.6). Clay-size kaolinite and quartz are subordinate, averaging 5.1 wt% (s = 3.0) and 9.5 wt% (s = 4.0), respectively. Values of the illite crystallinity index range from 0.21°2θ to 0.42°2θ, straddling the anchizone-epizone boundary (Fig. 11). I/S expandability values display a considerable amount of scatter, from 48% to 68%, usually with no systematic changes as a function of burial depth. At Site C0001, however, I/S expandability increases downsection within the slope apron (Fig. 12), which is opposite to the trend expected with conventional burial diagenesis.

DISCUSSION

Our interpretations of hemipelagic sediment dispersal and paleogeography for the Nankai-Shikoku depositional system have been influenced heavily by refinements to the region’s reconstructed history of plate interactions (e.g., Wu et al., 2016). Our considerations of specific detrital sources for suspended sediment entering the Nankai-Shikoku system also include localities both close to and outside of the immediate geographic area of the NanTroSEIZE transect (e.g., Clift et al., 2013; Pickering et al., 2013). Transport of suspended sediment in most deep-marine environments is governed by a dynamic combination of surface currents, thermohaline bottom currents, sediment gravity flows, and biologic resuspension (e.g., Gorsline, 1984). Therefore, the likely impact of ocean circulation on sedimentation across the Nankai-Shikoku system also needs to be incorporated into the interpretations. To set the stage, we summarize below some of the key studies to date.

Plate Boundary Reconstructions

The consensus among recent plate-tectonic reconstructions (e.g., Hall, 2012; Seton et al., 2012; von Hagke et al., 2016; Wu et al., 2016) is that subduction of the Pacific plate dominated across southwest Japan prior to ca. 16 Ma, creating a trench that extended from Hokkaido in the north to Kyushu and beyond to the southwest (Fig. 13A). The Shikoku Basin during that time probably was separated from Japanese landmasses by a salient of the Pacific plate (Hibbard and Karig, 1990). The Philippine Sea plate evidently initiated its descent beneath the proto–Nankai Trough just before the Shikoku Basin spreading center went extinct at ca. 15 Ma.

The most dramatic response to subduction of young and unusually warm lithosphere (including the extinct spreading center) was anomalous near-trench magmatism across the Outer Zone of Japan (Kimura et al., 2005) (Fig. 13A). The compilation of age data by Kimura et al. (2014) shows that the oldest of those magma bodies is 16.8 ± 0.8 Ma, and most radiometric ages cluster around 15 Ma.
Slope apron, slope basin, and mass-transport deposits

Figure 12. X-ray diffraction (XRD) results for Quaternary slope-apron and slope-basin deposits at Sites C0001, C0004, C0006, C0007, C0008, C0018, and C0021, Nankai Trough. See Ashi et al. (2009), Screaton et al. (2009a), Expedition 333 Scientists (2012a), and Strasser et al. (2014) for stratigraphic overview. Data are from Expedition 315 Scientists (2009a), Expedition 316 Scientists (2009a, 2009b, 2009c, 2009d), Expedition 333 Scientists (2012d), Strasser et al. (2014c), Guo and Underwood (2012), and Underwood (2017a). MTCs—mass-transport complexes.
The near-trench volcano-plutonic complex included I-type granites, S-type granites, rhyolitic lavas, and rhyolitic ignimbrites. Intrusions are surrounded by accreted sedimentary rocks (Shimanto Belt) and associated forearc-basin deposits. Overprints of paleothermal structure within those country rocks have been documented using such techniques as vitrinite reflectance (e.g., Chijiwa, 1988; Underwood et al., 1992).

By 14 Ma to 13 Ma, magmatism shifted north of the Median Tectonic Line (Fig. 13A) and became better organized along the Setouchi Belt of high-magnesium andesites (Kimura et al., 2005; Tatsumi, 2006). Overlapping that time period (17 Ma to 11 Ma), the triple junction among the Pacific, Philippine Sea, and Eurasia plates appears to have migrated toward the northeast, as indicated by a crude spatial pattern for the ages of anomalous near-trench magma bodies (Kimura et al., 2014). Once that phase concluded, Kyushu and Shikoku experienced a long period of quiescence in subduction-related volcanism (Fig. 13B); the absence of magmatism from 10 Ma to 6 Ma has been attributed to either sinistral strike-slip motion or pronounced deceleration of subduction due to highly oblique plate convergence along the proto-Nankai margin (Kamata and Kodama, 1994; Mahony et al., 2011). How far the sinistral boundary extended to the northeast remains uncertain, but the entire strike-length of the proto-Nankai margin was probably in transcurrent slip from 10 Ma to 6 Ma (Fig. 13B).

Motion of the Philippine Sea plate changed dramatically ca. 6 Ma, when subduction rates increased and/or the convergence vector reestablished its direction to roughly trench-normal (e.g., Wu et al., 2016). Studies of mantle tomography reinforce this interpretation; seismic slab-subduction depths for the Philippine Sea plate extend only to ~60 km, whereas the Pacific plate slab can be traced to depths of ~500 km beneath Hokkaido and northern Honshu (Honda and Nakanishi, 2003; Nakajima and Hasegawa, 2007; Zhao, 2012; Zhao et al., 2012). Re-establishment of near-orthogonal convergence along the proto-Nankai Trough resulted in a series of collisions between bathymetric highs along the Izu-Bonin arc and the Honshu arc (Niihama and Kodama, 1994; Mahony et al., 2011). How far the sinistral boundary extended to the northeast remains uncertain, but the entire strike-length of the proto-Nankai margin was probably in transcurrent slip from 10 Ma to 6 Ma (Fig. 13B).

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At the present time, the Ryukyu Trench, islands of the Ryuku volcanic arc, and the Okinawa Trough separate the East China Sea from the northeastern edge of the West Philippine Basin and the northwest corner of the Shikoku Basin (Fig. 1). Those bathymetric obstructions, however, did not exist during the early to middle Miocene (e.g., Letouzey and Kimura, 1986; Sibuet et al., 1995). To the north of the Okinawa Trough, the continental margin of the East China Sea shows widespread evidence for extensional faulting (Cukur et al., 2011; Gungor et al., 2012). Rifting of the shelf began in the Late Cretaceous and resulted in the creation of several sedimentary basins separated by buried continental ridges or rifted remnants of proto-Ryukyu arc basement (Sibuet et al., 1987). Multiple phases of uplift (basin inversion) also affected the shelf (Yang et al., 2004; Lee et al., 2006; Cukur et al., 2011; Yang et al., 2011). The timing of initial rifting and seafloor spreading in the Okinawa Trough remains a point of debate. Estimates vary considerably from <2.6 Ma (Kimura, 1985; Park et al., 1998), 7 Ma to 2 Ma (Sibuet et al., 1998), 10 Ma to 6 Ma (Miki, 1995), and 13 Ma to 7 Ma (Sibuet et al., 1987). Gungor et al. (2012) described the formation of a small rift basin (Ho Basin) between a basement high (Longwan Ridge) and the proto-Ryukyu Trench during the middle Miocene (15.9 Ma to 11.6 Ma); according to their reconstructions, the Okinawa Trough did not open and the Ryukyu islands did not grow to elevations above sea level until the late Miocene (ca. 7 Ma).

Ryukyu volcanoes (Kimura et al., 2005) erupted above a basement of accreted sedimentary and metamorphic rocks that are broadly correlative with the Shimanto Belt of southwest Japan (Kizaki, 1986; Ujiie, 1997; Schoonover and Osozawa, 2004). Detailed bathymetry and analysis of magnetic anomalies indicate that the volcanic front shifted toward the west ca. 2.1 Ma (Sato et al., 2014), which is approximately the same time as the change in subduction vector for the Philippine Sea plate (Wu et al., 2016). Currently, the deep Ryukyu Trench floor and the seaward slope of the trench (Hsu et al., 2013) provide additional impediments to sediment transport from the East China Sea all the way into the Shikoku Basin.

Prospective Parent Rocks on the Japanese Islands

The onland bedrock geology of central and southwest Japan comprises a wide variety of Mesozoic and early Cenozoic accretionary complexes (Maruyama et al., 1997; Taira, 2001; Isozaki et al., 2010). The Inner Zone to the north of the Median Tectonic Line (Fig. 13A) contains low-pressure, high-temperature metamorphic rocks of the Ryoke Belt and related granitic rocks (Nakajima, 1997). The Outer Zone, to the south (Fig. 13A), consists of parallel bands of high-pressure metamorphic rocks and low-grade metasedimentary strata—the Sanbagawa, Chichibu, and Shimanto Belts (Toriumi and Teruya, 1988; Taira et al., 1988; Higashino, 1990). All of those accreted terranes are potential sources for detrital illite and chlorite.

We need to critique several volcanic arcs around the rim of Shikoku Basin as potential sources for detrital smectite, including the anomalous Outer Zone ignimbrites and welded tuffs, and the Setouchi high-Mg andesites (Fig. 13A) (Kimura et al., 2005). In addition, the Honshu Arc to the northeast (Figs. 13B and 13C), a product of Pacific plate subduction, has been erupting nearly continuously since the late Miocene (Cambray et al., 1995; Kimura et al., 2005; Accocella et al., 2008; Uto and Tatsumi, 1996). On Kyushu, the Hohi volcanic zone initiated at 6 Ma to 5 Ma, whereas calderas and ignimbrites dominated after 2 Ma (Figs. 13B and 13C); active volcanoes from that system also extended westward into the islands of the Ryuku Arc (Kamata and Kodama, 1999; Mahony et al., 2011).

The Izu-Bonin Arc (Honza and Tamaki, 1985) borders Shikoku Basin to the northeast (Fig. 1) and provides another potential source of both coarser volcaniclastic sediment (Marsaglia, 1992) and smectite-rich clays. The initial phases of backarc spreading in the Shikoku Basin were accompanied by reduced arc volcanism, but bimodal lava flows and explosive silicic eruptions have continued along the island arc from the middle Miocene to Holocene (Taylor, 1992; Gill et al., 1994; Bryant et al., 2003; Straub, 2003; Tamura et al., 2009). Ash layers recovered from the Shikoku Basin (distal tephra fallout) record several discrete pulses of explosive Izu-Bonin volcanism (Cambray et al., 1995; Straub, 2003).

Incipient collisions between bathymetric highs along the Izu-Bonin Arc and the Honshu Arc (Fig. 13B) evidently started ca. 12 Ma, with three subsequent phases of collision-accretion from 9 Ma to 7 Ma, 5 Ma to 3 Ma, and during the past 1 m.y. (Niitsuma, 1989; Amano, 1991). The Quaternary phase of collision has been especially important because it dramatically changed the regional paleogeography (Kitazato, 1997; Hashima et al., 2016). The transformed topography rerouted the primary pathways for sediment gravity flows into the Nankai Trough, to a system dominated by southwest-directed funneling through Suruga Trough (Fig. 2). The watersheds of the collision zone are unusually diverse in their bedrock and surficial geology (Fig. 13A), with older Cenozoic and Cretaceous accretionary complexes, Neogene plutonic, volcanic, and sedimentary rocks, and a cover of active Pleistocene–Holocene volcanoes that include Mount Fuji (e.g., Ogawa et al., 1985; Sato and Amano, 1991; Soh et al., 1991, 1998; Kitazato, 1997; Saito et al., 1997, 2007). Exposures of Miocene tephra (Fig. 13A) are proof of rapid uplift from intermediate levels of the crust (Kawate and Arima, 1998). We infer that individual watersheds such as the Fuji River have probably changed significantly through time, in terms of their aerial extent, their geometry, and sediment composition as they adjusted to uplift, denudation, and the growth of large stratovolcanoes.

Ocean Currents

A warm-water western boundary current, the Kuroshio Current (Fig. 1), dominates surface-water circulation off the coast of central Japan (Taft, 1972; Andres et al., 2015). The Kuroshio Current flows northward past the Philippines, enters Okinawa Trough through the Yonaguni Depression east of Taiwan (Fig. 1), bifurcates to feed the Tsushima Current into the Sea of Japan (Moriyasu, 1972), and returns to the Philippine Sea through the Tokara Strait south of Kyushu.
ich has profoundly affected shipboard operations at all of the NanTroSEIZE drill sites (Fig. 2), reaching speeds as high as 5 knots (~250 cm/s) (Nagata et al., 1999). The circulation system is quite complicated over short periods of time, with alternating phases of large meanders and straighter-path courses (Fig. 13), generation of mesoscale eddies, countercurrents, interaction with seamounts, and significant subannual changes in both speed and direction (Worthington and Kawai, 1972; White and McCreary, 1976; Taira and Teramoto, 1981; Nagata et al., 1999; Ebuchi and Hanawa, 2000; Kimura and Sugimoto, 2000; Endoh et al., 2011; Shen et al., 2014; Katsumata, 2016). When averaged over scales of geologic time, however, sediment suspended in the surface water off central Japan follows a net transport direction toward the northeast (Fig. 13).

At water depths greater than ~500 m, thermohaline circulation involves south-directed North Pacific Deep Water (NPDW), which enters the Shikoku Basin through gaps in the Izu-Bonin Arc (Fig. 1). More buoyant north-directed Antarctic Intermediate Water (AAIW) enters the Philippine Sea through the Yap gateway south of the Mariana Arc. Based on sparse measurements along the Izu-Bonin Ridge, the boundary between the two water masses is positioned at a water depth of ~2000 m (Lee and Ogawa, 1998). Local ageostrophic perturbations are created by internal tides and steep seafloor topographies associated with submarine canyons and seamounts (Okada and Ohta, 1993; Nagano et al., 2013). The bathymetric obstructions that surround Shikoku Basin on all sides (Fig. 1) allow for very limited exchange with abyssal water masses. Abyssal circulation is largely inferred, but nepheloid suspensions evidently rotate counterclockwise at speeds of 5 cm/s to 10 cm/s, with southwest-directed transport along the margins of the Nankai Trough (Fukasawa et al., 1986; Lee and Ogawa, 1998). The deep currents, however, are also sensitive to depth-dependent variations and the straight versus large-meander cycles that develop in the overlying Kuroshio Current (Fukasawa and Teramoto, 1986). We expect this deep-water circulation to enhance sustained suspension, repeated resuspension, and long-distance transport of fine-grained sediment within the near-bottom nepheloid layer, thereby homogenizing the compositional signals of multiple potential sources.

The oceanographic behaviors outlined above have, of course, changed over time. One particularly transformative event occurred ca. 3.5 Ma, when the Central America Seaway closed at the isthmus of Panama (Maier-Reimer et al., 1990; Coates et al., 1992; Ibaraki, 1997; Molina-Cruz, 1997; Tsuchi, 1997). The Kuroshio Current intensified at that time as part of the overall strengthening of the North Pacific subtropical gyre. The Tsushima Current likewise strengthened at the end of the Pliocene, as evidenced by increases of continental (illite-rich) sediment passing from the East China Sea and Taiwan through the Korea Strait into the Sea of Japan (Fagel et al., 1992). There is also considerable evidence for increased sensitivity of the western Pacific and Nankai Trough to obliquity forcing of climate change during the Plio-Pleistocene (Ito and Horikawa, 2000; Chiyonobu et al., 2012; Venti et al., 2013; Matsuzaki et al., 2015; Iwatanai et al., 2012, 2016; Ujiie et al., 2016). The 41 k.y. obliquity cycles have amplified the eustatic responses to glacial-interglacial oscillations.

The main effects of lowered sea level near the Japanese Islands have been to impede ventilation of the Okinawa Trough, to focus Kuroshio circulation outboard of the Ryukyu Islands (Fig. 1), and to shift the balance of sediment delivery into the Okinawa Trough toward continental sources bordering the East China Sea. Conversely, the core of the Kuroshio Current migrates into the Okinawa Trough during interglacial highstands (Fig. 1), which increases the contribution of sediment from Taiwan into the Ryukyu backarc (Ujiie and Ujiie, 1999; Kao et al., 2006; Lee et al., 2013; Shi et al., 2014; Amano and Itaki, 2016; Nishina et al., 2016). Under both sets of eustatic circumstances, however, the dominant direction of surface-water transport across the Nankai Trough and the northern Shikoku Basin should have been toward the northeast. Our interpretations of detrital provenance and routing have taken that dominant pathway into account (Fig. 13).

Temporal and spatial changes in the behavior of thermohaline bottom currents are more difficult to evaluate than surface currents, but studies of middle to late Miocene and Plio-Pleistocene sedimentary rocks bordering the northeast side of the Izu-Honshu collision zone (Fig. 13B) show clear evidence of strong bottom-water circulation within forearc-basin and slope-basin environments (Ito, 1996, 1997; Ito and Horikawa, 2000; Stow et al., 2002). The sandy contourites were deposited at paleowater depths of 400 m to 1500 m; their paleocurrent indicators are variable in orientation but dominated by slope-parallel and upslope directions (Ito, 2002). Movement of sand toward the south and southwest was probably induced by circulation of NPDW through the Izu-Bonin forearc, and those currents likely contributed to the downstream transport of suspended sediment in the Shikoku Basin. We surmise that the main role of bottom currents was to homogenize suspended sediment entering the Nankai-Shikoku system from multiple sources.

Regional Trends in Clay Composition

Our interpretations of sediment dispersal for the NanTroSEIZE transect area build upon an extensive foundation of compositional data generated by previous workers. Those earlier results from Nankai Trough and Shikoku Basin include Leg 31 of the Deep Sea Drilling Project (DSDP) (Cook et al., 1975; Underwood et al., 2003b), DSDP Legs 58 and 87 (Chamley, 1980; Chamley et al., 1988), Leg 131 of the Ocean Drilling Program (ODP) (Underwood et al., 1993a, 1993b; Underwood and Pickering, 1996; Masuda et al., 1996, 2001), and ODP Leg 190 (Steuer and Underwood, 2003; Underwood and Steuer, 2003; Underwood and Fergusson, 2005). Direct quantitative comparisons among those data sets are unreliable because of differences in instrumentation, analytical methods, and weighting factors. All of the results, however, reinforce one first-order tendency: proportions of detrital smectite decrease significantly in younger strata, regardless of the site of deposition, and those decreases are balanced by increases in detrital illite and chlorite. Below, we explore the reasons behind that important temporal trend, and we consider the geologic, tectonic, and oceanographic causes for a list of second-order complications.
Composition and Provenance of Subduction Inputs

X-ray diffraction data from Sites C0011 and C0012 (Figs. 5–7) provide an unprecedented record of the gradual temporal shifts in clay-mineral assemblages entering the Shikoku Basin. Minor inputs of eolian dust are to be expected (e.g., Miyazaki et al., 2016) as documented by others in the pelagic realm of the central Philippine Sea (Mahoney, 2005; Wan et al., 2012; Seo et al., 2014; Xu et al., 2015). The rates of sedimentation and proximity of Sites C0011 and C0012 to continental watersheds, however, both point to marine processes (surface currents, bottom currents, turbidity currents, etc.) as the dominant mechanisms of suspended sediment influx and resedimentation.

Underwood and Fergusson (2005) recognized from studies associated with ODP Leg 190 that fine-grained suspended sediments had been eroded and transported from multiple sources; competition among those sources and dispersal routes had changed steadily over time. They attributed the depletion of detrital smectite, with commensurate increases in illite and chlorite, to four factors: (1) intensification of the northeast-directed Kuroshio Current after closure of the Central America seaway ca. 3.5 Ma (e.g., Molina-Cruz, 1997); (2) strengthening of ocean bottom currents ca. 6 Ma, in response to buildup of Antarctic ice and enhanced circulation of Antarctic Bottom Water (AABW) (e.g., Lee and Ogawa, 1998); (3) shifts in centers of active volcanism, as well localities with widespread exposures of weathered volcanic rock (e.g., Cambray et al., 1995); and (4) progressive uplift and erosion of accreted sedimentary rocks across the Outer Zone of Japan (e.g., Hasebe and Tagami, 2001). Our refinements of those interpretations have been influenced by improved reconstructions of regional plate-tectonic history (e.g., Wu et al., 2016), better mapping and dating of time-space patterns for magma bodies (e.g., Kimura et al., 2014), expanded records of regional and local denudation history (e.g., Yamada and Tagami, 2008), consideration of some new geochemical indicators of detrital provenance for coeval sand deposits in the Shikoku Basin (e.g., Clift et al., 2013), and superior reconstructions of regional paleoceanography (e.g., Diekmann et al., 2008). We argue below that the effects of tectonics and bedrock geology have dominated over the effects of oceanography.

The most likely source of the detrital smectite that dominated sedimentation during the Miocene was the broad swath of anomalous near-trench magmatic centers that migrated across the Outer Zone of Japan from 16 Ma to 12 Ma (Kimura et al., 2005; Kimura et al., 2014) (Fig. 13A). The felsic caldera eruptions left regionally extensive ignimbrite deposits, with abundant, chemically unstable volcanic glass (e.g., Danhara et al., 2007; Iwano et al., 2007; Miura and Wada, 2007). Studies completed elsewhere lead us to suggest that subtropical chemical weathering of the ignimbrites and associated lava flows produced soils with high concentrations of smectite (e.g., Parra et al., 1985; Hodder et al., 1990; Fagel et al., 2001; Wan et al., 2012). In addition, sub-seafloor alteration of the marine ash layers and dispersed volcanic glass probably resulted in the development of interbedded bentonites (e.g., Hein and Scholl, 1978; Hodder et al., 1993; Naish et al., 1993). At the same time, the deeper-seated granitic rocks now exposed across the Outer Zone (Fig. 13A) experienced rapid cooling, uplift, and exhumation, as indicated by apatite fission-track ages (Hasebe and Hoshino, 2003; Hasebe et al., 2000). We suggest that 15 m.y. of progressive denudation stripped away the weathered volcanic cover and gradually exposed more of the deeper-seated intrusions and surrounding country rocks.

Denudation across the Outer Zone of Japan was uneven and has resulted in diverse exposures of the parent-rock lithologies. Fission-track studies have highlighted several examples of local differential uplift and exhumation along the strike-length of the Shimanto Belt, with younger (ca. 10 Ma) cooling ages in the Muroto Peninsula (Hasebe et al., 1993; Hasebe and Tagami, 2001; Hasebe and Hoshino, 2003; Hasebe and Watanabe, 2004). The Izu-Honshu collision zone (Fig. 13) followed a similar history, with rapid exhumation bringing tonalities to the surface from midcrustal (7 km to 12 km) depths (Yamada and Tagami, 2008). Even though uplift and weathering trends were not entirely uniform along strike, the first-order response was consistent: progressive exposure of more granitic plutons, accreted sedimentary rocks, and associated metasedimentary rocks to chemical and physical weathering. The weathering products, therefore, shifted gradually toward a clay-mineral assemblage that became progressively more enriched in illite and chlorite.

Another important observation from Shikoku Basin is the unusual amount of scatter in the compositional trend, especially for intervals older than 7 Ma where the hemipelagic deposits are interbedded with numerous sand and silt turbidites (Fig. 7). Underwood and Pickering (2018) discussed the evidence for entrance of sandy sediment gravity flows into Shikoku Basin from the East China Sea during Kyushu Fan deposition. Their reconstruction is consistent with the U-Pb dates of detrital zircons (Clift et al., 2013), which correlate with a Yangtze River watershed. If the coarser components of the basin’s sediment budget followed that dispersal route from 16 Ma to 7 Ma, then some clay-size suspended sediment must have tracked the same path within the entrained layers of turbidity currents. Thus, the likelihood of finding interlayered muds derived from disparate sources seems strong. The best direct test of that idea would have been to sample the fine-grained tops of Shikoku Basin turbidites and compare their clay-mineral assemblages with overlying and underlying hemipelagic muds. The sampling strategy during NanTroSEIZE did not have that goal in mind.

A more indirect way to fingerprint the East China Sea source is through clay mineral abundances in near-surface muds. Numerous studies show those muddy sediments to be highly enriched in detrital illite (>50%) with relatively low percentages of smectite, typically <30% of the total clay (Doy et al., 2010; Xu et al., 2014, 2017; Wang et al., 2015). Diekmann et al. (2008) showed a comparable dominance by detrital illite in Quaternary deposits at ODP Site 1202, which is located closer to Taiwan on the western edge of southern Okinawa Trough (Fig. 1). Deposits to the south of Taiwan are similarly dominated by illite (Liu et al., 2008).

If we assume that bulk-sediment compositions derived from kindred sources were similar during the Miocene, then any pulses of suspended...
sediment emanating from mainland China (via East China Sea) and/or farther west from Taiwan should have been distinctly illite-rich. Their contrast to documented concentrations of smectite within the Shikoku Basin is enormous; thus we conclude that the dominant route for suspended sediment during the Miocene was probably not through the East China Sea. Instead, we surmise that the steady background of smectite-rich hemipelagic transport from the Outer Zone sources was interrupted periodically by sediment gravity flows that contained higher concentrations of detrital illite in their entrained layers. Our XRD evidence to support these conclusions comes mostly from the scatter of %-smectite values in deposits older than ca. 7 Ma (Fig. 7). We see roughly two times as many examples of smectite-depleted specimens (relative to the regression line) over the time span of 7 Ma to 15 Ma as compared to smectite-enriched specimens. A similar increase in scatter is also evident through the Kyushu Fan interval at ODP Site 1177, Ashizuri transect (Fig. 2) (Steurer and Underwood, 2003; Underwood and Pickering, 2018). The route for those sandy turbidity currents from China was terminated at ca. 7 Ma (Underwood and Pickering, 2018), but trapping of gravity flows behind the Ryukyu Arc did not necessarily force a permanent and total cutoff of suspended-sediment exchange. Some exchange of surface water probably persisted through gaps and sills between the volcanic islands (e.g., Nishina et al., 2016), especially during highstands of sea level. During lowstands, a nearly continuous land bridge evidently impeded such exchanges of water masses and their dilute concentrations of suspended sediment (Ujiie and Ujiie, 1999).

Complementary evidence for a mixed mud provenance comes from Sr-Nd-Pb isotope compositions of upper Shikoku Basin sediments (i.e., the hemipelagic-pyroclastic facies) (Saitoh et al., 2015). Figure 14 illustrates convincingly that mixing occurred between two sources over the past 7 m.y.—the East China Sea source and a Japan margin source (Saitoh et al., 2015). The mixing line shows progressive temporal decreases in the influx of sediment from continental China, especially between 4.4 Ma and 2.9 Ma (Fig. 14). In addition to the role of bathymetric and/or topographic obstructions mentioned above, reductions of sediment routing toward the south from the shallow shelf of East China Sea were probably enhanced by intensification of the Kuroshio and Tsushima Currents, which now push surface water into the Okinawa Trough and the Sea of Japan (Fig. 1) (Diekmann et al., 2008; Chen et al., 2011; Xu et al., 2014, 2017; Dou et al., 2010, 2012, 2016). Migration of the paleoposition of depositional sites (C0011 and C0012) relative to the core of the current also needs to be considered (Saitoh et al., 2015).

To complicate matters, we emphasize that the mixing trend of Saitoh et al. (2015) should have been accompanied in the clay-mineral budget by contemporaneous decreases in the proportion of detrital illite relative to smectite (i.e., from 4.4 Ma to present); instead, we see the opposite trend in XRD results from the Shikoku Basin (Fig. 7). Moreover, the inverted trend for I/S expand-
ability (i.e., less expandable I/S moving upsection) is consistent with the idea of tapping into higher levels of diageneis and metamorphism over time in the sedimentary and metasedimentary parent rocks. Thus, while endorsing the idea of increasing proportions of suspended-sediment influx from the Japan margin over time (Fig. 14), we argue that those increases must have been accompanied by gradual changes in the proportions of parent rock types within detrital source areas across the Outer Zone, particularly the sources of smectite (Figs. 13B and 13C).

To summarize, the time period of ca. 9 Ma marks the onset of gradual and irreversible smectite depletin in the suspended sediments entering Shikoku Basin, particularly in the vicinity of the NanTroSEIZE transect (Fig. 7). That episode in the margin’s geologic history represents the turning point when widespread exposures of weathered Miocene ignimbrites across the Outer Zone began to shrink at the expense of uplifted granitic intrusions and metasedimentary rocks. Several subordinate sources, including a small component of elion-dust input (e.g., Mahoney, 2005; Xu et al., 2015), certainly complicated the picture. Sporadic delivery of illitic clays by turbidity currents moving through the East China Sea (Kyushu Fan) helps explain the scatter in %smectite values (Fig. 7). Similarly, tuffaceous gravity flows (Zenisu Fans) likely resulted in punctuated increases in the delivery of detrital ssmectite from the Izu-Honshu collision zone (Kutterolf et al., 2014) during the late Miocene (Fig. 7).

As time progressed into the late Pliocene and early Pleistocene, strengthening of the Kuroshio Current would logically have dampened transport of smectite from weathered volcanic islands of the Izu-Bonin chain (Fig. 13C). Stronger Kuroshio circulation reinforced the evolving Outer Zone illite-chlorite assemblage by adding more illite-rich mud from Taiwan and East China Sea sources. To support that idea, we note that IODP Site U1437, at the northeast edge of the Shikoku Basin (Fig. 2), yields evidence for unusually high rates of sedimentation for tuffaceous mud and/or mudstone deposits, consistent with long-term delivery of mud by a strong northeast-directed current (Tamura et al., 2015). Our NanTroSEIZE results, however, indicate that the oceanographic effect remained subsidiary to the effects of the evolving source areas on the Japanese Islands.

Provenance of the Inner Accretionary Prism

Several uncertainties surround geologic interpretations of the inner Nan-kai prism (e.g., Tsuji et al., 2015). The seaward extent of Miocene magmatic bodies, for example, remains poorly constrained (Kimura et al., 2014), as does the distribution of coeval volcaniclastic deposits and/or cemented sandstone (Tsuji et al., 2015). The paleogeography and depositional environment for strata at Sites C0001 and C0002 remain cryptic. Shipboard scientists (Ashi et al., 2009; Strasser et al., 2014b; Tobin et al., 2015b) drew vague references to the trench or the Shikoku Basin as sites of deposition for inner prism strata. As scrutinized by Underwood (2018), however, those links to modern or Quaternary analogs fail apart because of glaring mismatches in age, facies, and/or sediment composition. The most striking discrepancy occurs between proportions of smectite in bulk mudstones from the inner prism (smectite poor) compared to coeval deposits in the Shikoku Basin (smectite rich). Within the Miocene part of the record, such numerical differences in bulk mudstone composition increase over time from ~10 wt% to 13 wt% (at 6 Ma) to ~25 wt% to 27 wt% (at 10.5 Ma). From a sedimentological perspective, it stands to reason that accreted Miocene mudstones were initially deposited somewhere other than the proto–Nankai Trough or the Shikoku Basin (Underwood, 2018). In addition, seismic and logging data (Boston et al., 2016) show evidence for large-scale reactivation of thrust faults, steep rotation of older folds and faults, and multiple fracture populations within the inner prism. We further suggest that the younger structural fabric is a product of Philippine Sea plate subduction, but it is superseded on an older fabric imparted by Pacific plate subduction.

If plate-tectonic reconstructions for the Philippine Sea region (Mahony et al., 2011; Hall, 2012; Wu et al., 2016) are correct in paleogeographic detail, then the subduction zone at 15 Ma offshore central Honshu (Kii Peninsula) was one of convergence between the Pacific plate and the Eurasia plate (Fig. 15A). It follows that deposition of inner-prism strata during the Miocene must have occurred on the Pacific plate rather than the Philippine Sea plate (Underwood, 2018). A rigorous regional-scale test of this hypothesis would require strategic sampling of Pacific plate deposits to the north of Sagami Trough. The closest drilling transect across the Japan Trench (DSDP Legs 56 and 57) is located near 40°N latitude (Mann and Muller, 1980). Sediments in the forearc of the Japan Trench contain higher percentages of biogenic silica; so proportions of total clay within the bulk sediment are much smaller than what we find in the Shikoku Basin. Accepting those caveats, however, we note that proportions of smectite within the clay-size fraction are roughly equal to the proportions of illite (~40:40), and the ratio does not change significantly over time (Mann and Muller, 1980). Compositional uniformity over time is consistent with the relatively slow rates of erosion in the Tohoku catchments of northern Honshu (Korup et al., 2014). More to the point, smectite-to-illite ratios in the Japan Trench (Mann and Muller, 1980) are roughly equal to those in the deep inner accretionary prism of Nankai Trough (Fig. 10). We therefore contend that a shared detrital provenance is more than just a remote possibility.

By ca. 10 Ma, sinistral slip along the transcurrent margin of southwest Japan appears to have brought the triple junction between Pacific, Eurasia, and Philippine Sea plates closer to the geographic corridor of the NanTroSEIZE transect (Fig. 15B). The inferred paleolocation of Site C0002 deposition, however, was still to the northeast of the Izu-Bonin volcanic arc; so accretion of Shikoku Basin sediments seems unlikely at that time. Instead, late Miocene sedimentary rocks currently within the inner prism probably were deposited near the triple junction, in a setting that drew most of its suspended sediment from watersheds in northern to central Honshu rather than from Shikoku and Kyushu (i.e., similar to present-day Suruga Trough). That pattern of sediment routing seems to have held until 6 Ma, when near-orthogonal subduction reinitiated along the proto–Nankai Trough (Fig. 15B).
Figure 15. Simplified plate-boundary reconstructions for the Philippine Sea region at (A) 15 Ma, (B) 10 Ma, and (C) 5 Ma, adapted from Mahony et al. (2011) and Hall (2012). The proto-Nankai margin experienced sinistral slip or highly oblique subduction from 10 Ma to 6 Ma, and trench-normal subduction of the Philippine Sea plate renewed ca. 6 Ma (see also Wu et al., 2016). For simplicity, the Japanese Islands are held fixed relative to present-day geographic coordinates. Approximate position of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) transect is highlighted by the red pentagons.
The unconformity between the accretionary prism and slope sediments at Sites C0001 and C0002 (Fig. 3) reveals a long hiatus that could be a mechanical response to cessation and renewal of subduction (e.g., Tsuji et al., 2015). Alternatively, we suggest that erosion or nondeposition may be symptoms of more complicated interactions between the upper plate and the migrating triple junction or to a shift from Pacific plate convergence to renewed Shikoku Basin subduction. As summarized previously, mud composition within the Shikoku Basin changed gradually due to two major factors: (1) uplift and denudation of deeper parent rocks across the Outer Zone of Japan, which increased proportions of illite and chlorite, and (2) intensification of the northeast-directed Kuroshio Current, which brought more illitic mud from Taiwan and the East China Sea (Underwood and Pickering, 2018). As time progressed from the late Miocene into the early Pliocene (Fig. 13C), we suggest that sediment composition on the southwest side of the triple junction became increasingly depleted in detrital smectite and, thus, increasingly similar to trench and abyssal-plain deposits on the northeast side. Watersheds on Honshu to the northeast were evidently more stable over the same time period than watersheds within and southwest of the triple junction; thus Japan Trench clay-mineral assemblages remained relatively static through Miocene–Pliocene time (e.g., Mann and Muller, 1980). We contend that the combined effect of both influences was to shrink the provenance contrasts at Site C0001 (i.e., between younger inner-prism strata and coeval deposits in the Shikoku Basin) relative to similar contrasts between older accreted strata at Site C0002 versus Shikoku Basin.

Another factor to consider in the paleogeography is the topographic response to Izu-Honshu collision after 6 Ma. Sediment gravity flows eroded large submarine canyons on either side of the collision zone (Sagami Trough, Suruga Trough, and Tenryu Canyon), but those incisions required time to reach their impressive present-day dimensions (e.g., Kawamura et al., 2009). Without large, through-going submarine canyons, and with less-frequent sediment gravity flows, muddy suspended sediment probably dominated in both the Japan and Nankai trenches during the early stages of renewed Philippine Sea subduction (Figs. 13C and 15C). The sluggish response of bathymetry and coarse-sediment routing to reorganized plate interactions helps explain why the youngest strata recovered from the inner accretionary prism (3.8 Ma to 5.3 Ma) are unusually fine grained when compared to the sand and gravel deposits of the Quaternary trench-wedge facies (Screaton et al., 2009b; Underwood and Moore, 2012).

**Provenance of the Frontal Accretionary Prism**

The clay-mineral assemblages at Sites C0006 and C0007 (Fig. 8) are indicative of a mixed provenance that included roughly equal proportions of sedimentary, metasedimentary, and igneous rocks, much the same as interbeds of turbidite sand (Milliken et al., 2012). All of those rock types are widespread within the Izu-Honshu collision zone (Fig. 13A). We assert that axial (margin-parallel) turbidity currents have provided the dominant transport mechanism, with a primary source in the Izu-Honshu collision zone (i.e., funnelling through Suruga Trough and Tenryu Canyon).

Most previous workers have argued likewise that sand-rich deposits in the Quaternary trench wedge originated mostly from the Izu-Honshu collision zone (De Rosa et al., 1986; Taira and Niitsuma, 1986; Marsaglia et al., 1992; Underwood et al., 1993a; Fergusson, 2003; Underwood and Fergusson, 2005; Usman et al., 2014). Clift et al. (2013) provided a contrary and provocative interpretation in which dispersal and along-strike (axial) transport of sediment from the collision zone has been subdued throughout the margin’s history, with little or no effect on trench-floor sedimentation offshore Shikoku and the Kii Peninsula (Fig. 13); they further claimed that no sediment from the collision zone can be found offshore Kyushu, a distance of 350–500 km along the strike of the margin. The rationale behind their assertion lies mostly in an apparent mismatch between the U-Pb ages of detrital zircons from the trench-wedge deposits versus zircons from the present-day watershed of the Fuji River (Clift et al., 2013), which drains into Suruga Trough (Fig. 2). Those assertions may be correct for some of the older (Miocene to early Pleistocene) turbidites that were accreted at ODP Sites 1178 and 1176 (see also, Fergusson, 2003; Underwood and Fergusson, 2005), but we refute the interpretation for the Quaternary trench wedge for a variety of reasons. First, the mismatch in U-Pb dates versus the modern Fuji River drainage (Clift et al., 2013) can be explained by the recent construction of the active Mount Fuji (Fig. 13C), a famous stratovolcano that must have changed both topography and ground-surface geology dramatically as it grew. The modern Fuji watershed probably did not exist when the turbidites sampled at Sites C0006 and C0007 were deposited.

Beyond cogent arguments based on sand petrography (e.g., Marsaglia et al., 1992; Fergusson, 2003; Usman et al., 2014), we reiterate the following lines of evidence for a dominant source of sediment in the collision zone (Japan Alps) during the Quaternary: (1) erosion rates and sediment yield from the Japan Alps are the highest among catchments draining Japan’s eastern seaboard, higher than all of the Nankai inner forearc segments combined (Korup et al., 2014); (2) the inferred Izu-Honshu source area (e.g., Tanzawa Mountains) has experienced a 7 myr history of rapid uplift, characterized by high rates of denudation (up to 2 mm/yr) and resulting in exhumation of tonalities from midcrustal depths (Yamada and Tagami, 2008; Tani et al., 2010; Hashima et al., 2016); (3) bedrock uplift rates in the nearby Kiso Range of central Japan equal 3 mm/yr to 6 mm/yr, with denudation rates of 1 mm/yr to 4 mm/yr (Sueoka et al., 2012); (4) an exceptionally large submarine canyon (Suruga Trough) has been deeply incised from the mouth of the Fuji River into the northeastern end of Nankai Trough (Fig. 2) (Nakamura et al., 1987); (5) three subaqueous slope-type fan deltas have prograded from the head of Suruga Trough, and all are aligned with the mouths of high-gradient rivers draining the Japan Alps (Soh et al., 1995); (6) typhoon-induced sediment-transport events are frequent and flush sediment from the head of Suruga Trough, even during the Holocene highstand of sea level (Yoshikawa and Nemoto, 2010); (7) the gradient of the Nankai trench floor dips to the southwest, which favors transport in that direction after sediment gravity flows exit Suruga Trough; (8) high-resolution bathymetric records...
highlight a prominent axial channel on the Nankai trench floor; the channel begins at a point source (mouth of the Fuji River) and extends to a position offshore the Kii Peninsula (Shimamura, 1989); (9) a second large submarine canyon (Tenryu Canyon) was incised immediately seaward of the Tenryu River mouth (Fig. 2), and erosion there is deep enough to expose metamorphosed Miocene accretionary prism along the canyon walls (Kawamura et al., 2009); (10) erosion in Tenryu Canyon was rejuvenated following the collision of proto-Zenisu Ridge with the accretionary prism (Soh and Tokuyama, 2002); (11) Tenryu Fan prograded onto the trench floor at the mouth of Tenryu Canyon (Fig. 2), causing southward deflection of the axial channel (Soh et al., 1991); (12) deeper seismic-reflection character of the trench wedge (i.e., high-amplitude reflections) shows temporal continuity of axial-channel migration, extending back at least into the late Pleistocene (Shimamura, 1989); (13) paleocurrent evidence from DSDP Site 808 (Muroto transect; Fig. 2) is consistent with reflection or deflection of turbidity currents off the seaward slope (Pickering et al., 1992); (14) magnetic fabric in the distal trench turbidites of Nankai Trough at DSDP Sites 582 and 583 (Ashizuri transect; Fig. 2) is oriented parallel to the axis of the trench (Taira and Niitsuma, 1986). These observations collectively point to a long-lasting detrital source of sediment in the Izu-Honshu collision zone, combined with sustained, long-distance axial transport of sand, gravel, and suspended sediment down the Nankai trench floor by turbidity currents.

**Provenance of Forearc-Basin and Trench-Slope Sediments**

Interpretations of sediment dispersal for the Kumano Basin and coeval slope-apron sediments are more straightforward (compared to Shikoku Basin) because of the fixed position of depositional sites on the upper plate. In addition, most sediment gravity flows across a forearc maintain predictable downslope trajectories toward the trench. The clay-mineral assemblages are, consequently, more homogeneous both within and among individual sites. Although there is good evidence for sensitivity of zooplankton to climate change at the mid-Pleistocene transition (Matsuzaki et al., 2015), we see no such adjustments in the clay mineral assemblages. We attribute that behavior to the dominance of geologic and tectonic forcing relative to oceanographic forcing. Older starved-basin deposits at Site C0002 (3.8 Ma to 1.6 Ma) (Ashi et al., 2009) are modestly enriched in smectite relative to overlying forearc-basin turbidites, consistent with the long-term temporal trend in the Shikoku Basin (Fig. 7). We reiterate that the Outer Zone of Japan served as the main source for transverse routing across the forearc over the past 1.5 m.y. to 2 m.y. (Fig. 13C). That view is consistent with multiple provenance indicators (e.g., heavy-mineral assemblages and pyroxene geochemistry) from interbedded sand turbidites in the Kumano Basin (Usman et al., 2014; Buchs et al., 2015). Just as with our interpretation for Sites C0011 and C0012, the inverted trend for I/S expandability at Site C0001 (i.e., less expandable I/S moving upslope) is explained best by deeper erosion over time into higher levels of parent-rock diagenesis. In addition, the swift Kuroshio Current probably drove some along-strike movement of illitic suspended sediment in the surface waters toward the northeast from Kyushu and more distal sources (Fig. 13C); some backflow toward the southwest by comparatively sluggish bottom currents is also likely. The net effect of ocean circulation, however, was to homogenize the compositional fingerprints from multiple point sources of mud.

Results from the lower trench slope are a bit more complicated to interpret. Mass-transport deposits at Site C0018 (Fig. 3) are indistinguishable in clay composition from intact intervals of hemipelagic sediment (Fig. 12). That similarity indicates shallow remobilization of the slope apron rather than having submarine slides cut down into the underlying accretionary prism. On the other hand, younger fine-sand deposits (<1 Ma) in the slope basin are significantly more enriched in volcanioclastic materials than their older counterparts, similar to the Quaternary trench-wedge facies at Sites C0006 and C0007; that shift has been explained by tapping into longitudinal (axial) flows that emanated from the Izu-Honshu collision zone (Usman et al., 2014). The re-routing interpretation raises additional questions because of the slope basin’s elevation above the trench floor (Fig. 3). Re-routing among nearby submarine canyons and their associated watersheds (i.e., Tenryu River and Tenryu Canyon versus Fuji River and Suruga Trough), in response to seaward subduction and forearc uplift, is one viable scenario (Usman et al., 2014). Another possible contribution, however, is expansion of the frequency and dimensions of turbidity currents moving into the trench through Suruga Trough (Fig. 2) as uplift and denudation in the Izu-Honshu collision zone accelerated (Fig. 13C). We suspect that many of those axial flows were thick enough (i.e., several hundred meters) to lap significantly onto the lower slope of the trench. The chances of upslope deposition obviously increase as one moves downslope from Site C0018 toward Sites C0006 and C0007, which currently rest <350 m above the trench floor (Fig. 3). In any case, when the routing of sand to Site C0018 changed, the assemblages of clay minerals did not. We attribute that decoupling between sand and clay budgets to the homogenization of fine-grained suspended sediment in the nepheloid layer, in concert with multiple entry mechanisms and initial transport directions (i.e., turbidity currents, vertical settling from surface currents, plus resuspension by thermohaline bottom currents).

**CONCLUSIONS**

Our synthesis of XRD results from the NanTroSEIZE transect vividly demonstrates how histories of sedimentation and accretion along subduction margins can be punctuated by unexpected complications. The first-order temporal trend for the regional system is relatively straightforward: detrital clay-mineral assemblages shifted gradually from a smectite-rich assemblage during the Miocene to more illite- and chlorite-rich assemblages during the Pliocene and Quaternary. Most of the detrital smectite probably originated as weathering products of anomalous near-trench silicic volcanism that covered much of the Outer Zone of central Japan, whereas sources of detrital illite and chlorite included both low-grade metamorphic rocks and sedimentary rocks...
with moderate levels of diagenesis (e.g., Shimanto Belt). Gradual uplift and unroofing of the anomalous Miocene plutons and the surrounding country rocks resulted in gradual increases of detrital illite and chlorite. We also recognize several interesting complications to the first-order trends in clay mineralogy, listed below in order of occurrence.

1. Sandy turbidite currents evidently entered the Shikoku Basin from the East China Sea during the middle Miocene (Kyushu Fan) and carried higher concentrations of illite in their suspended loads. That mixing among sources resulted in greater scatter of clay-mineral abundances, but it is important to note that we have not sampled and analyzed the turbidite clays directly.

2. Routing of coarser sediment from the East China Sea was terminated ca. 7 Ma because of rifting in the Okinawa Trough and growth of topography along the adjacent Ryukyu arc-trench system. The sand influx to Shikoku Basin associated with the younger Zenisu Fans had a smaller effect on clay-mineral budgets because those flows tapped into volcanic and sedimentary sources (smectite-rich) near the Izu-Honshu collision zone. That provenance domain was broadly similar to parent rocks across the Outer Zone during that same time period.

3. Comparisons between early Pliocene and late Miocene strata from the inner accretionary prism (Sites C0001 and C0002) and coeval (5 Ma to 11 Ma) mudstones from the Shikoku Basin (Sites C0011 and C0012) reveal stark contrasts in clay mineralogy, particularly in their concentrations of smectite. We reiterate the suggestion (Underwood, 2018) that the older accreted sediments (more illite- and chlorite-rich) were initially deposited on the Pacific plate rather than the Philippine Sea plate, to the north of a migrating trench-trench-transform triple junction. Their mineral assemblages are similar to those in the Japan Trench.

4. Renewal of Philippine Sea plate subduction ca. 6 Ma coincided with the re-establishment of more conventional source-to-sink linkages from the Outer Zone provenance to sites of Philippine Sea deposition to the tectonic domain of frontal accretion. That frontal part of the Nankai accretionary prism (Sites C0006 and C0007) shares detrital provenance traits with coeval hemipelagic deposits in the Shikoku Basin.

5. Intensification of the northeast-directed Kuroshio surface current ca. 3.5 Ma probably brought more illite toward the trench and the Shikoku Basin from distal sources (Taiwan, Okinawa Trough). The XRD signal for that oceanographic shift is weak, however, because the current merely reinforced the compositional changes that were caused by progressive weathering of uplifted Outer Zone parent rocks. Dampered transport of smectite from the Izu-Bonin volcanic islands is also likely.

6. Accelerated collision between the Izu-Bonin Arc and the Honshu Arc ca. 1.5 Ma resulted in high rates of uplift and erosion, rapid incision of large submarine canyons (Suruga Trough, Tennyu Canyon), and frequent funneling of large, energetic turbidity currents into the Nankai Trough. Consequently, Quaternary trench-wedge deposits in the frontal accretionary prism (Sites C0006 and C0007) have been dominated by axial transport from sources in the collision zone, including the Mount Fuji stratovolcano.

7. Quaternary muds in the Kumano Basin (Site C0002) and the slope-apron/slope-basin facies above the accretionary prism (Sites C0001, C0004, C0006, C0007, C0008, C0018, and C0021) show the greatest compositional uniformity among all of the depositional domains. We attribute that homogeneity to balanced competition among multiple entry mechanisms and their associated transport directions: (1) transverse (trench-directed) re-sedimentation by unconfined gravity flows; (2) onlap of axial turbidity currents (southwest-directed) onto the lowermost trench slope; (3) steady movement of surface-water suspensions by the northeast-directed Kuroshio Current; and (4) retention or re-suspension of mud in the bottom nepheloid layer by thermohaline bottom currents.

The unusual complexity of Nankai-Shikoku tectonic history probably means that the depositional system should not be held up as the “type locality” for subduction zones, worldwide. When compared to such noteworthy examples as the Japan Trench (e.g., Kimura et al., 2012), Costa Rica (e.g., Spinelli and Underwood, 2004), and Sumatra (e.g., Hüpers et al., 2017; McNeill et al., 2017), the facies architecture of Nankai subduction inputs (including the trench wedge) is much more diverse; the lithofacies types and sediment composition have changed much more in three dimensions over time.

The significance of our exhaustive case study also extends beyond sedimentology. For example, with regard to the Nankai subduction interface (megathrust), we recognize predictable temporal changes in the composition of both hanging-wall and footwall successions that carry important ramifications for understanding deformation and fault-slip mechanisms. We expect volumetric fluid production from clay dehydration (Saffer et al., 2008) to be significantly greater in the smectite-rich footwall of the megathrust (i.e., subducting Shikoku Basin sediments of Miocene age) as compared to the illitic base of the hanging wall. Those contrasts in fluid production probably contribute to heterogeneous buildups of fluid overpressure, thereby modulating down dip transitions among stable sliding, stick-slip, and slow-slip events (Moore and Saffer, 2001; Saffer and Wallace, 2015). The same may be true for deeper levels of the megasplay.

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