Episodic seafloor mud brecciation due to great subduction zone earthquakes

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ABSTRACT

The Nankai Trough off southwest Japan has an ~1300 yr historical record of great earthquakes, including the most recent, the A.D. 1944 Tonankai (M = 8.2) earthquake. Evaluation of the activity of an individual submarine fault is difficult when only onland observations are available. Submarine core records can pinpoint individual fault activity. Here we present Integrated Ocean Drilling Program (IODP) Nankai Trough Seismogenic Zone Experiment data from the shallow portion. IODP Expedition 316 drilled and cored several holes in the shallow portion of the off shore Tonankai earthquake area, including sites in the hanging wall of a margin-dominating splay fault that has previously been interpreted to have ruptured coseismically during megathrust earthquakes. X-ray computed tomography scanning revealed that the uppermost core at one site contains repeated occurrences of mud breccia. Radiocarbon dating of the uppermost mud breccia indicates a deposition time consistent with the 1944 Tonankai earthquake, suggesting that the mud-breccia layers result from episodic brecciation caused by seismic shaking. Mud brecciation provides a potential new tool to reconstruct ancient earthquake history in subduction zones.

INTRODUCTION

Several geologic signatures have been used to reconstruct ancient earthquake and tsunami records. These include sand dikes and sills rooted in liquefiable sandy layers under low-permeability sediments (e.g., Ettenshon et al., 2002), shaking-induced grain-filled veins (Ogawa, 1980; Brothers et al., 1996; Ohsumi and Ogawa, 2008), and turbidite and debris flow deposits inferred to result from collapse of unstable submarine slopes during earthquakes (e.g., Goldfinger et al. 2003; Noda et al., 2008). For intrasediment records such as sand dikes and vein structures, it is difficult to reconstruct the exact date of the related seismic event. In cases of turbidite and debris flow deposits, triggers other than earthquakes cannot always be excluded. Marine sediment layers within coastal swamp deposits have been used to reconstruct tsunami histories (e.g., Atwater, 1987; Shi et al., 1995; Nanayama et al., 2003; Monecke et al., 2008). Tsunami deposits have contributed significantly to the reconstruction of the history of large subduction zone earthquakes, but have only been available where swamps or lakes exist along the coast.

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Some researchers have observed seafloor response to large earthquakes that consisted of suspended sediments in the water column after large earthquakes in the Cariaco Basin (offshore Venezuela; Thunell et al., 1999), the 1994 Sanriku-Oki earthquake (offshore Japan; Itou et al., 2000), and the 26 December 2004 Mw 9.2 rupture offshore Aceh (northern Sumatra; Seeber et al., 2007). Noncohesive sandy sediment easily undergoes disaggregation, and suspension will lead to gravity flows along seafloor slopes. In contrast with the behavior of noncohesive sediments, seismic shaking can fracture cohesive muddy sediment into internally cohesive mud clasts. Submersible observations 2 yr after the 1993 offshore southwestern Hokkaido earthquake (Ms 7.8) in the Sea of Japan reported brecciated ooze near the earthquake epicenter (Takeuchi et al., 1998). Cracks in horizontally layered sediments and scattered ooze clasts of various sizes were observed at the seafloor on the hanging-wall slope of the thrust. Because soft ooze clasts will not generally survive long-distance transport, this seismic sediment could preserve information regarding the location of ancient earthquakes. Sediment deformed and disrupted by seismic ground motion has been reported from deposits of Lake Lisan (paleo–Dead Sea) and was attributed to Kelvin-Helmholtz instability, which happens at the interface between different velocities and densities of two fluids (Heifetz et al., 2005; Wetzler et al., 2010).

TECTONIC SETTING

The Nankai Trough is formed by subduction of the Philippine Sea plate to the north-west beneath southwest Japan (Fig. 1A). The Nankai Trough is among the most extensively studied subduction zones in the world, and the past ~1300 yr are well documented in historical records (e.g., Ando, 1975; Yonekura, 1975). The reconstructed record shows that great earthquakes repeat every 100–150 yr in each segment, and occasionally much greater multisegment earthquakes occurred (Ando, 1975; Yonekura, 1975).

The rupture zone and area of tsunami generation for the 1944 Tonankai earthquake have been constrained by seismic and tsunami inversion analysis (Fig. 1A; Tanioka and Satake, 2001; Kikuchi et al., 2003; Ichinose et al., 2003; Baba and Cummings, 2005). High-resolution images of seismic reflection profiles clearly document two major thrusts, the plate boundary and megasplay faults (Fig. 1B; Park et al., 2002; Moore et al., 2007). The megasplay fault, which branches off from the plate boundary décollement within the co-seismic rupture zone, is divided into several fault branches at shallow depths in the prism. Because the location of the megasplay fault was concordant with the inferred rupture area, the megasplay fault has been inferred to be the earthquake fault (Baba and Cummings, 2005; Moore et al., 2007). Thus, core samples around the megasplay fault may yield direct evidence for paleo-earthquakes. The Integrated Ocean Drilling Program (IODP) Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) Expedition 316 drilled and took samples from the hanging wall (Site C0004) and footwall (Site C0008) of the megasplay fault (Fig. 1C) (Kimura et al., 2008; Kinoshita et al., 2009). Integration of nanofossil dates from the cores and seismic reflection data suggests long-term fault activity of the megasplay fault from 2.2 Ma to present (Kinoshita et al., 2009; Strasser et al., 2009).
CORE ANALYSIS
The cores were investigated using X-ray computed tomography (X-CT), which creates a three-dimensional image, depending on the density and porosity of the sediment sample in homogeneous mineral assemblages. The X-CT can visualize small structures that are difficult to observe with the naked eye (Figs. 2 and 3).

The sediments that are the focus of this paper were found in the shallowest portion of Sites C0004 and C0008 (Fig. 1C). The uppermost 80 cm of both cores are composed of soft mud and lack obvious stratification or liquefaction features (Fig. 3). The core taken at Site C0008 consists of homogeneous silt with some horizontal strata with laminae. In contrast, the X-CT indicates that at Site C0004, the core consists of interbedded stratified and brecciated mud units. The stratified units comprise thin horizontal layers with laminations less than few millimeters, and the mud-breccia units are characterized by scattered mud clasts in a mud matrix. Five mud-breccia units are distinguished (Fig. 3), and mud-breccia and stratified units alternate at 416 cm intervals. The thickness of the mud-breccia unit varies; units 1 and 4 are 3.0 cm thick, and units 2, 3, and 5 are 17.0, 7.0, and 8.0 cm thick, respectively. The mud-breccia units include muddy clasts without horizontal layering and irregular shapes with diameters varying from 1 to 5 cm. Distinct mud-breccia units are found on the hanging-wall slope (Site C0004) of the megasplay fault; these units are not found in the footwall (Site C0008) (Fig. 3).

The unconsolidated mud clasts are soft and weak, and some clasts appear to exhibit some partial incorporation into the matrix on the edges of the clasts; this may indicate that clasts underwent some transport. The mineral assemblages (predominantly clay minerals with minor other minerals) are very similar between the brecciated and stratified units under the optical microscope, but the mud clasts have a slightly lower density than the matrix. The difference between clasts and matrix decreases with depth. This change might be caused by gradual compaction. Consequently, the occurrence of mud breccia cannot be distinguished in cores deeper than 1 m below the seafloor.

Many mud-filling burrows formed by mud-filtering worm or mollusks penetrate the mud breccia and stratified units. Detailed three-dimensional observation can distinguish the burrows from mud clasts, because tubular burrows have constant cross-sectional areas along the long axis, whereas the cross-sectional areas of irregularly shaped mud clasts change along the long axis (Fig. 2).

FORMATION OF MUD-BRECCIA UNIT
We hypothesize that seismic shaking is responsible for the formation of mud-breccia units; slightly less dense but cohesive mud brecciated and scattered within a less cohesive mud matrix. They may reflect either earthquake-related in situ brecciation or slope collapse. The breccias are intact and coherent; the soft clasts could not have endured long-distance transport (e.g., in a turbidity current or long run-out landslide), and were therefore formed by on-site brecciation. An asymmetric occurrence of mud breccia between the hanging wall (Site C0004) and the footwall (Site C0008) may reflect differences in ground motion. Much stronger ground motion above the hanging walls of thrust faults is known as the “hanging-wall effect” (Abrahamson and Somerville, 1996); i.e., the upward motion of the unconfined hanging wall can impart significant motion to materials on that surface, while material on the footwall surface is not subjected to this rebound effect nearly as strongly. In the case of the dive survey at the 1993 offshore southwestern Hokkaido earthquake, the mud breccia characteristically occurred on the hanging-wall slope of the fault, and brecciation intensity decreased with distance from the epicenter (Takeuchi et al., 1998). Soft-sediment response to seismic shaking was discussed in detail for the Lake Lisan sediment, and numerical modeling suggests that a minimum ground acceleration of 1 G is needed to produce this instability during earthquakes (Heifetz et al.,...
Mud-breccia units were dated by radioisotope lead ($^{210}$Pb) and carbon ($^{14}$C) methods and results compared to the historical earthquake record (for details about methods, see the Appendix). The $^{210}$Pb method was applied to mud-breccia unit 1, and the older portion was dated by the $^{14}$C method. The fitted decay curve for $^{210}$Pb was obtained at 4 cm below the seafloor with a date of A.D. 1950 ($\pm$20) at the top of mud-breccia unit 1 (Fig 4; see details in the Appendix). Although the error bars are substantial, the data clearly reveal that mud-breccia unit 1 formed very recently and might correlate with the 1944 Tonankai earthquake via the megasplay fault.

Mud-breccia units 2 and 4 are dated as 3512 ($\pm$34) and 10626 ($\pm$45) calendar yr B.P., respectively, by $^{14}$C methods applied to tests of planktonic foraminifers found in laminated mud deposits (inferred to have deposited immediately after the formation of the mud breccia) just above the mud-breccia unit (Fig. 3). These events are much older and the intervals between them are much longer than those for known earthquakes in the historical records. We have two possible interpretations for this inconsistency. The first is a hiatus model between large events. If regular-size earthquakes rework or induce turbidity currents that are composed of both abyssal sediments and brecciated units, most records except those related to infrequent large events will be lost, and apparent fault activity will appear to be low. A second possible interpretation is that this region of the fault system has not experienced every large seismic event over the period covered by historical record. The megasplay fault is rooted in the deep plate boundary décollement and branches at shallow levels in the prism. If all branches of the entire fault system do not slip in concert with one another or with the master fault (as is commonly inferred for such systems), the earthquake history of each fault will not reflect the complete history of entire fault system.

These newly recognized mud-breccia units can be obtained using simple gravity-operated piston coring devices, and coring around fault zones on the forearc trench slope should be able to sample detailed records of seismically formed sediment deposits. The methods outlined in this paper are sufficient to detect the most recent events and those further back in the geological record, and should reveal the detailed spatial and temporal distribution of paleo–ground motion related to slip on submarine fault systems.

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APPENDIX: METHODS

The X-ray computed tomography (X-CT) image depends on the X-ray attenuation coefficient, which is a function of the chemical composition and density of the target material. The mineral assemblages (predominantly clay minerals with minor other minerals) of the sediments are homogeneous in this study, and the difference in X-ray attenuation most likely reflects a difference in density and porosity. The X-ray CT instrument on D/V Chikyu is a General Electric Yokogawa Medical Systems Light Speed Ultra 16 capable of generating 16 (0.625-mm-thick slice) images every 0.5 s, the time for one revolution of the X-ray source around the sample. The analytical standards used during Expedition 316 were air (CT number = $-1000$), water (CT number = 0), and aluminum (2477 < CT number < 2487) in an acrylic core mock-up. The three-dimensional observation was held at condition of brightness (Window level: 600) and contrast (Window wide: 800).

We took 10 samples for $^{210}$Pb and $^{137}$Cs activity analysis at 1 cm intervals in the top 10 cm of the core, including the mud-breccia unit 1 of the core at Site C0004. Radioactivity was measured by germanium gamma detection at EAWAG (Swiss Federal Institute of Aquatic Science and Technology), Switzerland. The $^{137}$Cs activity in the Site C0004 core surface sediments is lower than the detection limit. This might be explained by the fact that the hemipelagic material in this water depth is too diluted to preserve the measurable atmospheric $^{137}$Cs signal. Excess $^{210}$Pb (half-life 22.26 yr) derived from atmospheric $^{210}$Rn with rainout must approach a background-supported $^{210}$Pb with time (e.g., Noller, 2000). We assume supported $^{210}$Pb from radioactive equilibrated $^{226}$Ra in sediment and constant sedimentation rates. The decay curve of unsupported $^{210}$Pb, which was used to date the youngest event, was obtained from fitting an exponential curve through the four data points of sediment above mud-breccia unit.


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