

# Seismic slip propagation to the updip end of plate boundary subduction interface faults: Vitrinite reflectance geothermometry on Integrated Ocean Drilling Program NanTro SEIZE cores

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## ABSTRACT

**Seismic faulting along subduction-type plate boundaries plays a fundamental role in tsunami genesis. During the Integrated Ocean Drilling Program (IODP) Nankai Trough Seismogenic Zone Experiment (NanTro SEIZE) Stage 1, the updip ends of plate boundary subduction faults were drilled and cored in the Nankai Trough (offshore Japan), where repeated large earthquakes and tsunamis have occurred, including the A.D. 1944 Tonankai (Mw = 8.1) earthquake. Samples were obtained from the frontal thrust, which connects the deep plate boundary to the seafloor at the toe of the accretionary wedge, and from a megasplay fault that branches from the plate boundary décollement. The toe of the accretionary wedge has classically been considered aseismic, but vitrinite reflectance geothermometry reveals that the two examined fault zones underwent localized temperatures of more than 380 °C. This suggests that frictional heating occurred along these two fault zones, and implies that coseismic slip must have propagated at least one time to the updip end of the megasplay fault and to the toe of the accretionary wedge.**

## INTRODUCTION

The Nankai Trough (offshore Japan) is among the most extensively studied subduction zones in the world, and great tsunamigenic earthquakes, including the recent A.D. 1944 Tonankai (Mw = 8.1) and 1946 Nankaido (Mw = 8.1) earthquakes (Kanamori, 1977), are well documented in historical records of the past ~1300 yr (e.g., Ando, 1975; Yonekura, 1975). The Philippine Sea plate is subducting northwestward beneath southwestern Japan (Fig. 1A), and an accretionary wedge has developed along the entire trough as a result of the large sediment supply from mountainous central and southwestern Japan (Kimura et al., 2008). High-resolution seismic-reflection profiles in this region clearly document two major thrust faults, the plate boundary décollement and a major out-of-sequence thrust that branches from the plate boundary (Fig. 1B; Park et al., 2002; Moore et al., 2007). At the Nankai margin, this major out-of-sequence thrust, termed the “megasplay,” is an important component of the plate boundary system, extends for >100 km along strike, and has been

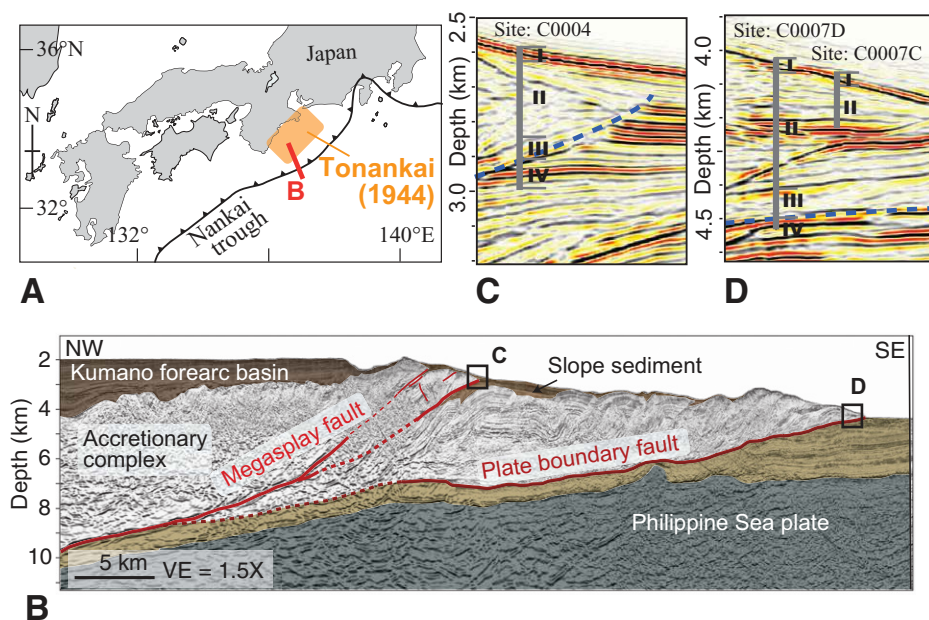
implicated in coseismic slip and tsunami genesis. The rupture area of the 1944 Tonankai earthquake has been estimated by inversion of seismic and tsunami waves (Tanioka and Satake, 2001; Kikuchi et al., 2003; Ichinose et al., 2003; Baba and Cummins, 2005). Since the location of the megasplay fault is roughly concordant with the rupture area, the megasplay fault has been inferred to be the earthquake fault (Baba and Cummins, 2005; Moore et al., 2007), despite a poor vertical resolution of the source analysis. However, seismic slip probably did not propagate until the toe of the accretionary prism.

Classically, a plate subduction seismogenic zone is considered to be bounded by a deep brittle-ductile transition zone and a shallow seismic front, and the toe of the accretionary wedge is thought to be aseismic (e.g., Byrne et al., 1988). Wang and Hu (2006) proposed that megasplay faults are the mechanical boundaries between the landward, seismogenic inner wedge and the seaward, aseismic outer wedge, and that earthquake generation along the aseismic décollement is prevented by velocity-strengthening

friction behavior of the sediments. Wang and Hu (2006) noted that velocity-strengthening behavior does not preclude trench-breaking rupture, and their simulations suggest that the updip extent of rupture can have a great impact on vertical coseismic seafloor deformation. Smectite, a common clay mineral in shallow sediments, tends to resist rapid slip due to its velocity-strengthening frictional property (Saffer and Marone, 2003). In contrast, thermal pressurization (Mase and Smith, 1987), a frictional heat-induced pore-fluid pressure rise, would decrease effective normal stress and promote rupture propagation along the shallow portion of the fault. The rupture propagation and frictional behavior along fluid-bearing shallow portions of faults are still controversial topics. Documentation of seismic slip at shallow portions of plate subduction faults is a key issue for understanding the involvement of accretionary prisms in large interplate seismic ruptures and tsunami genesis.

## TECTONIC SETTING AND METHODS

Integrated Ocean Drilling Program (IODP) Nankai Trough Seismogenic Zone Experiment (NanTro SEIZE) Expedition 316 (Kimura et al., 2008) drilled and cored several holes in the shallow portions of the megasplay and frontal plate boundary faults. At Site C0004, the megasplay fault was cored at 258.01–307.52 m (core depth below the seafloor, CSF) (Fig. 1C). The sediment has been classified into four lithostratigraphic units: Pleistocene upper slope apron (unit I, 0–78.06 m CSF), Pliocene accretionary complex (unit II, 78.06–258.01 m CSF), Pliocene fault-bounded unit (unit III, 258.01–307.52 m CSF), and Pleistocene underthrust slope basin (unit IV, 307.52–398.79 m CSF) (Kinoshita et



**Figure 1.** A: Map showing Integrated Ocean Drilling Program (IODP) NanTroSEIZE (Nankai Trough Seismogenic Zone Experiment) stage 1 and surface rupture of Tonankai earthquake (A.D. 1944;  $M_w = 8.1$ ) off southwestern Japan. Red line in A shows location of seismic profile (Moore et al., 2007). B: Seismic profile. Squares show locations of detailed seismic images shown in C and D. C: Seismic profile through Site C0004 (after Moore et al., 2007). D: Seismic profile through Site C0007 (after Moore et al., 2007). Vertical gray lines show drill sites. Broken blue lines in C and D are megasplay fault and plate boundary frontal thrust, respectively. At Site C0007, lithostratigraphic units were determined from two drill holes. Vertical exaggeration (VE) is 1.5 $\times$  (profile B) and 1.0 $\times$  (profiles C and D).

al., 2009). Two biostratigraphic age reversals were found within unit III, which represents the megasplay fault zone. Unit III is characterized by a fractured and brecciated zone (Kinoshita et al., 2009), and the fault zone within unit III was sampled at 271 m CSF, where it consists of microbreccia and a narrow dark layer ~1 cm thick that dips at ~50° to the core vertical axis (Fig. 2A).

The frontal thrust was cored at Site C0007 at 438 m CSF (Fig. 1D), in the toe region of the accretionary wedge where Nankai Trough sediments subduct beneath the accretionary wedge. Four lithostratigraphic units were distinguished in the core column: Pleistocene slope sediments (unit I, 0–33.94 m CSF), accreted Pleistocene accreted trench turbidites (unit II, 33.94–362.26 m CSF), Pliocene hemipelagic muds with ash layers (unit III, 362.26–439.44 m CSF), and subducted Pleistocene trench turbidites (unit IV, below 439.44–484.44 m CSF). There are three fault zones within units II and III, and the largest biostratigraphic age reversal, from 5.32 Ma to 3.65 Ma, is found across the lowermost part of unit III. The fault zone in the lowermost part of unit III is marked by a heterogeneous distribution of fractured and brecciated hemipelagic mudstone. The lowermost part of the unit III underwent intense brecciation into fragments, including the 2-mm-thick dark layer that was sampled at 438 m CSF

(Fig. 2B). The dark layer sharply separates intensely brecciated hemipelagic mudstone above from unbroken hemipelagic mudstone below, and an age reversal is found across this thin dark layer; the intensely brecciated interval above is older than the coherent sediments below (Kinoshita et al., 2009).

Because seismic slip generates frictional heat, localized high temperature in a fault zone is generally regarded as an evidence for rapid seismic slip. Pseudotachylite, for example, is a solidified frictional melt produced during seismic slip (e.g., Sibson, 1975). However, frictional melting is unlikely to occur in shallow, wet sediments. Hirono et al. (2009) attempted to detect significant shear heating in the same dark layer of the megasplay fault core as tested in this study, but did not detect a significant anomaly. Whereas Hirono et al. (2009) examined inorganic rock-fluid interactions, this study examines thermal decomposition of organic material, which is expected to be a sensitive geothermometer. The reflectance of vitrinite, a constituent of bituminous coal, increases when it is exposed to high temperature, and it is widely used in oil field exploration as geothermometer. Because the vitrinite reflectance increases with irreversible thermal decomposition of organic material at peak temperature, it is applied as the maximum thermometer. O'Hara et al. (2006) conducted high-velocity slip experiments and observed

an increase in vitrinite reflectance during short-duration heating and cooling on an earthquake time scale. Turbidite sediments generally contain many small coal fragments, so vitrinite reflectance may be a useful geothermometer in plate subduction zone faults. To calculate the maximum attained temperature from vitrinite reflectance, we used a kinetic model, based on activation energies of simplified parallel reactions of vitrinite (Sweeney and Burnham, 1990). The temperature can be obtained from assuming the heating duration by this program. Because the vitrinite matured much faster at higher temperatures, temperature has a stronger influence on maturation rate than duration of heating. Heating duration to reach a certain grade of vitrinite maturation is greatly different in temperature. For example, a vitrinite reflectance increases from 0.2% to 0.6% in <100 s with heating to 400 °C, whereas the same reaction requires 1 day of heating at 300 °C, and a much longer duration of 5 m.y. is needed for heating at 100 °C; the values of thermal diffusion length in these heating conditions are 7.6 mm, 220 mm, and 2900 m, respectively (Fig. 3). This paper constrains the heating duration from width of high vitrinite reflectance zone based on thermal diffusive model in the fault zone, and long heating duration of the host rock is estimated from sedimentary age (for details about methods, see the GSA Data Repository<sup>1</sup>).

The samples were analyzed by two methods. The bulk crushed analysis provided the background thermal conditions in the host rock. Coal fragments were separated by density separation of the crushed rock. The second method is carried out by scanning the surface of polished slab samples, because it preserves the fault structure. In both methods, random mean vitrinite reflectance ( $R_o$ ) is obtained under an oil immersion microscope with a microspot-lighting system developed for this study. Most coal fragments consisted of low-grade brown coal because of the shallow burial depth, and partly bituminized coal was used for the vitrinite reflectance measurement. The vitrinites we measured are from a few micrometers to several tens of micrometers in size, and were similar both inside and outside of the fault zone (for details about methods, see footnote 1).

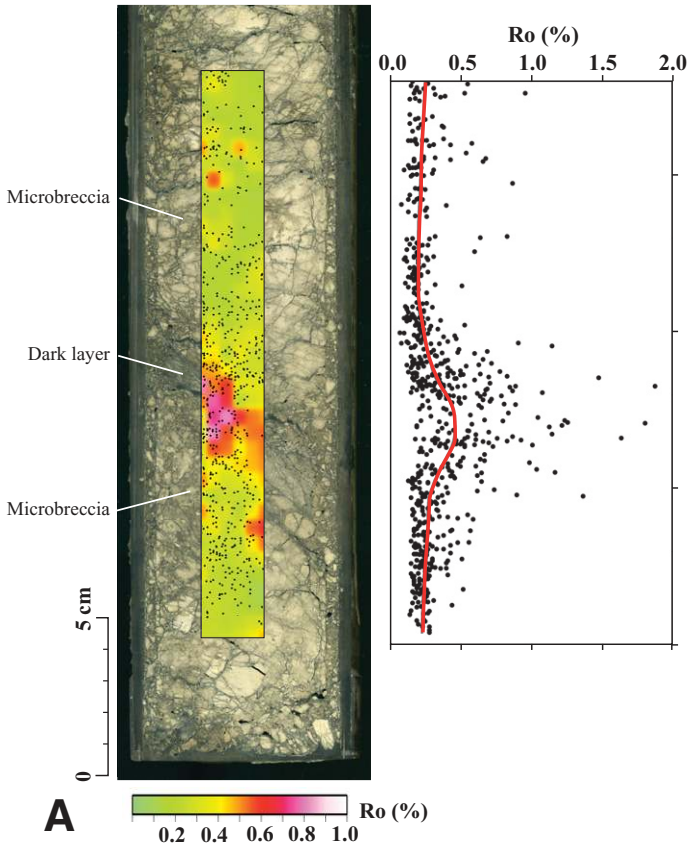
## VITRINITE REFLECTANCE

At the megasplay fault site, we collected 8 samples, each 10–50 mL in volume, at 20–90 m intervals in the core column for bulk analysis, using samples distributed over the depth range 23.8–292.8 m CSF. The upper part of unit I at

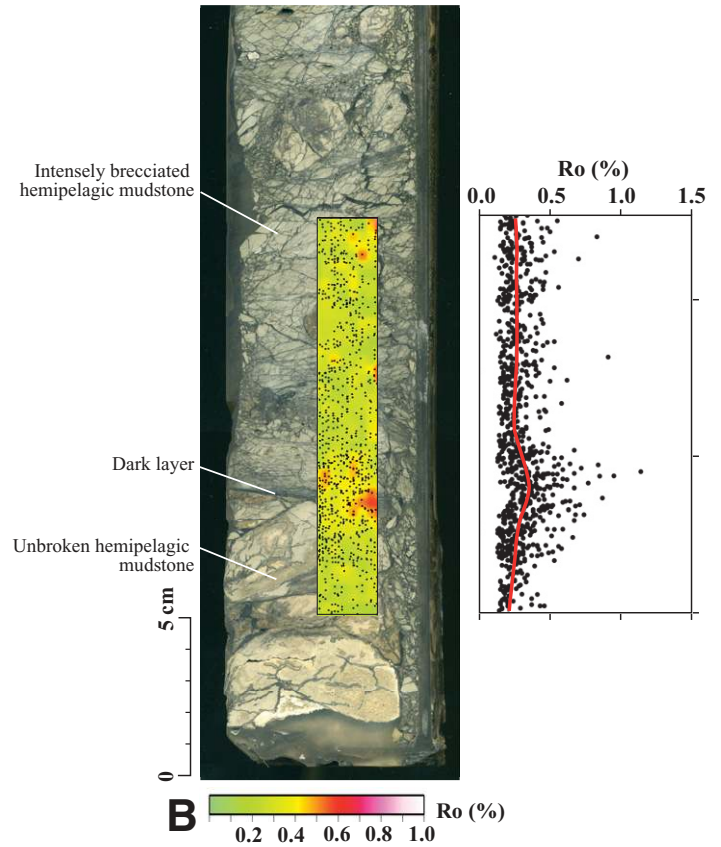
<sup>1</sup>GSA Data Repository item 2011126, methods, is available online at [www.geosociety.org/pubs/ft2011.htm](http://www.geosociety.org/pubs/ft2011.htm), or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



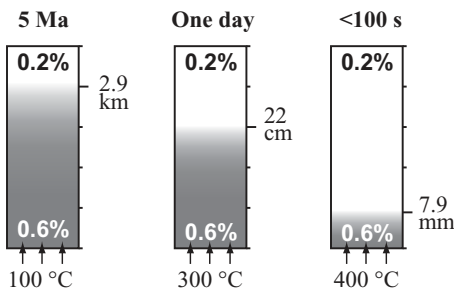
**C0004: Megasplay fault  
(271 m CSF)**



**C0007: Plate boundary frontal thrust  
(438 m CSF)**



**Figure 2. Measured vitrinite reflectance (Ro) distribution overlaid on photographs of slab core samples. CSF—core depth below seafloor. A: From megasplay fault. B: From frontal thrust. Black dots on core photographs indicate particles from which Ro was measured. Graph to right of each core shows Ro; distance is normalized to dark layer crossing core axis obliquely. Red lines show smoothed Ro curves. Near dark layers, Ro is much higher than in surrounding rock, but reflectance is uneven within high-reflectance zone.**



**Figure 3. Relationship between heating duration, temperature, and thermal diffusive length to make same vitrinite reflectance. In case of high-temperature heating, vitrinite can mature quickly and consequent thermal diffusive length is narrow. Width of high heat zone provides clue to estimate heating duration.**

this site contains only low-grade brown coal, and there is partly bituminized coal in the lower part. These non-fault-zone samples have a similar Ro of ~0.24% (standard deviation, SD, 0.18). At the frontal thrust site, we collected 15 samples of 10–50 mL in volume with 0.3–160 m spacing in the host rock for bulk analysis,

using samples distributed over the depth range 1.1–484.1 m CSF. The partly bituminized coals occur below unit II. The non-fault-zone samples have a constant mean Ro of ~0.27% (SD 0.17). The host rocks at the two sites show a similar Ro, implying a similar thermal history. In the megasplay fault zone, we measured the reflectance of more than 700 particles of vitrinite in a 20 mm × 175 mm area on the polished slab surface (Fig. 2A). The Ro was as high as 0.57% (SD 0.35) in the 20-mm-thick dark layer, and some spots with a reflectance of >0.8% are also scattered within this zone (Fig. 2A). The reflectance drops to the background level abruptly within a thickness of <10 mm away from the dark layer. In the frontal thrust, we measured the reflectance of more than 800 vitrinite particles in a 20 mm × 125 mm area on the polished slab surface (Fig. 2B). The Ro (0.37%, SD 0.16) was slightly higher in the narrow dark layer than in the host rock.

**FAULT TEMPERATURE**

The Ro values of 0.24%–0.27% in the host rocks are those of the lowest rank of bitumen

and close to the lower limit determined from the kinetic model. These values indicate that the background temperature of the host rock was <20 °C (±15), a result consistent with the temperature estimated from the geothermal gradient and from measurement in the shallow part of the borehole (Kinoshita et al., 2009).

The dark layers at megasplay fault and frontal thrusts of 20 mm and 2 mm thick have high Ro zones of 40 mm and 20 mm in thickness, respectively. High Ro outside of the dark layers occurs at 10 mm in thickness, and seems to be caused by diffusive heat in both faults. We assumed the heating duration of <100 s based on a thermal model to make the diffusion length of 10 mm in this sediment (Fig. 3) (for details about methods, see the Data Repository). The estimated peak temperature was 390 °C (±50) in the megasplay fault and 330 °C (±50) in the frontal thrust. If the fault zones have complex temperature paths, including gradual rising and residual heating, the actual heating duration will be short. In that case, the vitrinite requires a higher temperature to make the same reaction grade in a short time.

There are three models to explain the high Ro zone: (1) rock clast exhumation from greater depths due to fault activity, (2) hydrothermal fluid flows, and (3) seismic frictional heating along the fault. Because the high Ro distribution is wider than just the dark layer, the high Ro zone may be caused by heat diffusion from the fault center (models 2 or 3), but not caused by deep clast mixing (model 1). Significant hydrothermal mineral has not been observed in this zone (Kinoshita et al., 2009), and the localized high Ro of 10–20 mm may be caused by high-temperature heating with a short duration of <100 s, making model 2 unlikely.

Measurements of vitrinite reflectance within and around two discrete slip zones from IODP Sites C0004 and C0007 in the Nankai Trough along with thermal modeling indicate that seismic ruptures propagated upward to the updip ends of both the megasplay fault (Site C0004) and the frontal thrust (Site C0007). Because the vitrinite reflectance method records only the maximum temperature attained, it does not allow estimation of the number of seismic ruptures having propagated to the updip ends of the megasplay fault and of the frontal thrust. Nevertheless, our study suggests that seismic ruptures can propagate upward across entire accretionary prisms.

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