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TŌHOKU-OKI FAULT ZONE FRICTIONAL HEAT MEASURED

During IODP Expeditions 343 and 343T

By Patrick M. Fulton, Emily Brodsky, James J. Mori, and Frederick M. Chester

ABSTRACT. During the March 11, 2011, M_w 9.1 Tōhoku-oki earthquake, the plate boundary fault slipped an astonishing 50 m or more, with the slip extending all the way to the seafloor within the Japan Trench. The result was a much larger earthquake and tsunami than expected as well as considerable devastation on land. The earthquake challenged our understanding of subduction zone mechanics but also presented an opportunity to resolve long-standing questions regarding the amount of frictional resistance faults exhibit during earthquakes, resistance that influences the amount of fault slip and associated tsunami hazards. Here we report on how scientific ocean drilling successfully allowed the measurement of frictional heating within the fault zone that ruptured during the Tōhoku-oki earthquake.

THE TŌHOKU-OKI EVENT AND IODP RAPID RESPONSE

The amount of frictional heat generated per unit fault area during an earthquake is the direct product of the average shear stress during slip and displacement. By drilling through a fault and measuring the frictional heat signal within the fault zone after a great earthquake, such as the Tōhoku-oki event, frictional resistance can be evaluated. However, the measurement must be made within a year or two of the earthquake before the thermal signal dissipates.

Through the rapid-response efforts of Integrated Ocean Drilling Program (IODP) Expeditions 343 and 343T, the Japan Trench Fast Drilling Project (JFAST) was implemented aboard D/V *Chikyu* within one year after the M_w 9.1 Tōhoku-oki earthquake (Chester et al., 2013a). The objectives of JFAST were to drill across the plate boundary fault, characterize the fault with geophysical logging, collect core samples, and install a temperature observatory to monitor the frictional heat signal (Chester et al., 2013a). These two expeditions presented considerable challenges, including rapid development of an appropriate observatory system and then drilling and installing it across the plate boundary fault ~820 meters below seafloor (mbsf) in a water depth of ~7 km.

OBSERVATORY INSTALLATIONS TO MEASURE THERMAL RESPONSE

The observatory, consisting of 55 autonomous titanium-encased temperature-sensing dataloggers with an accuracy of ~0.001°C and 10-minute sampling intervals, was installed July 15, 2012 (Figure 1). The observatory was recovered successfully on April 26, 2013. The resulting data reveal a 0.31°C anomaly with a maximum centered at 819 mbsf, coincident with the primary geologic plate boundary fault inferred from core and logging data (Fulton et al., 2013; Figure 2). These results are the clearest direct measurement of frictional heat ever made after an earthquake. The anomaly is interpreted to reflect an average coseismic friction coefficient (the ratio of shear to normal stress) of 0.08 (Fulton et al., 2013). This value is much less than typical static friction values of 0.6–0.85 (Byerlee, 1978) and implies that the fault at this location had very little resistance during slip. This very low frictional resistance is consistent with high-speed laboratory friction measurements on fault core material from the same Tōhoku-oki plate boundary fault (Ujiie et al., 2013), and with stress determinations from analysis of stress-induced fracturing along the borehole walls during drilling. The borehole stress analysis reveals no residual shear stress on the fault after the earthquake, implying that the stress drop was complete at the site (Lin et al., 2011; Brodsky et al., 2017).

FAULT ZONE CORE MATERIALS

In addition to the direct temperature measurements, new advances in quantifying geologic signatures of frictional heating have been applied to the limited amount of recovered core. At 821.5–822.65 mbsf, a core section of highly sheared scaly clay was interpreted to come from the main plate boundary fault; based on core recovery, it is estimated to have a thickness of <4.86 m (Chester et al., 2013b). Given the prevalence of smectite, particularly within samples from a highly sheared slip zone about 16 cm from the top of the core, Schleicher et al. (2015) suggest that these scaly clays have not been heated above 200°C. Using combined real-time XRD and rapid heating experiments, Schleicher et al. (2015) illustrate that smectite becomes permanently altered at temperatures >200°C. Experiments have also shown that heating of smectite above 250°C can result in the authigenesis of fine-grained ferromagnetic minerals (Hirt et al., 1993; Yang et al, 2016). Although Scheicher et al. (2015) do not find evidence of thermogenic alteration in their XRD measurements, analysis of other samples within the same fault zone core by Yang et al. (2016) find magnetic susceptibility changes indicative of very fine-grained thermally generated minerals. Yang et al. (2016) interpret their results to suggest that the samples were heated to temperatures of 300°–800°C. Theoretical modeling indicates that on a fault with friction as low as 0.08, such high temperatures would be achieved at these depths only in millimeter-thick slip zones (Fulton and Harris, 2012). Whether the conflicting peak temperature estimates can be reconciled by the locations of samples relative to possible sources of frictional heat or otherwise remains unclear and motivates future theoretical and experimental investigation of fault zone materials collected via scientific ocean drilling.

Rabinowitz et al. (2015) identified several other major faults within recovered core between 817 and 833 mbsf based on chemostratigraphic evidence of large total displacements. Subsequent analysis of biomarker thermal maturity across these mudstone and pelagic clay faults reveals localized anomalies within slip zones interpreted to be the result of frictional heating above 120°C (Hannah Rabinowitz and colleagues, unpublished

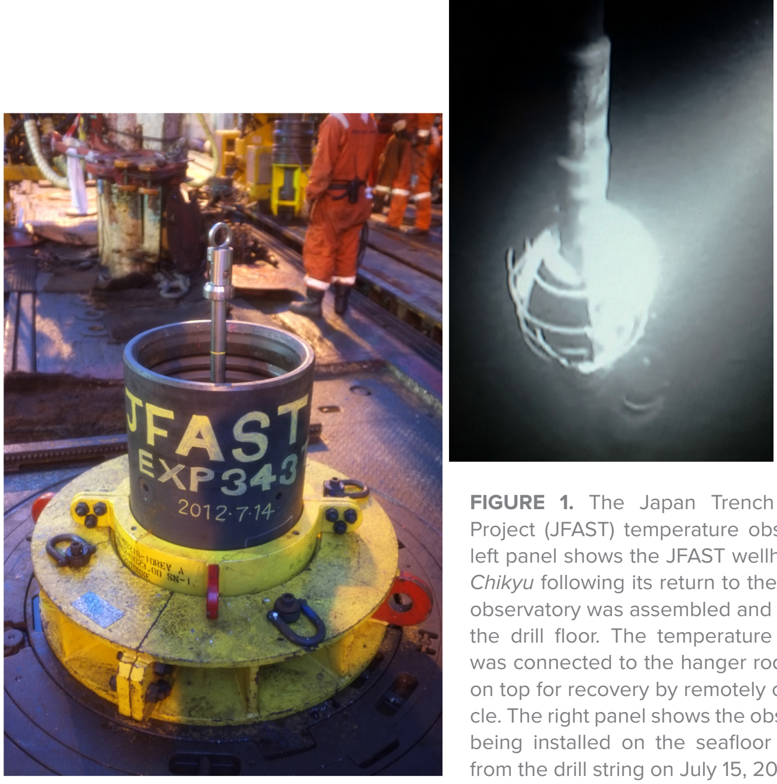

FIGURE 1. The Japan Trench Fast Drilling Project (JFAST) temperature observatory. The left panel shows the JFAST wellhead on board *Chikyu* following its return to the ship after the observatory was assembled and hung beneath the drill floor. The temperature sensor string was connected to the hanger rod with the ring on top for recovery by remotely operated vehicle. The right panel shows the observatory after being installed on the seafloor and released from the drill string on July 15, 2012.

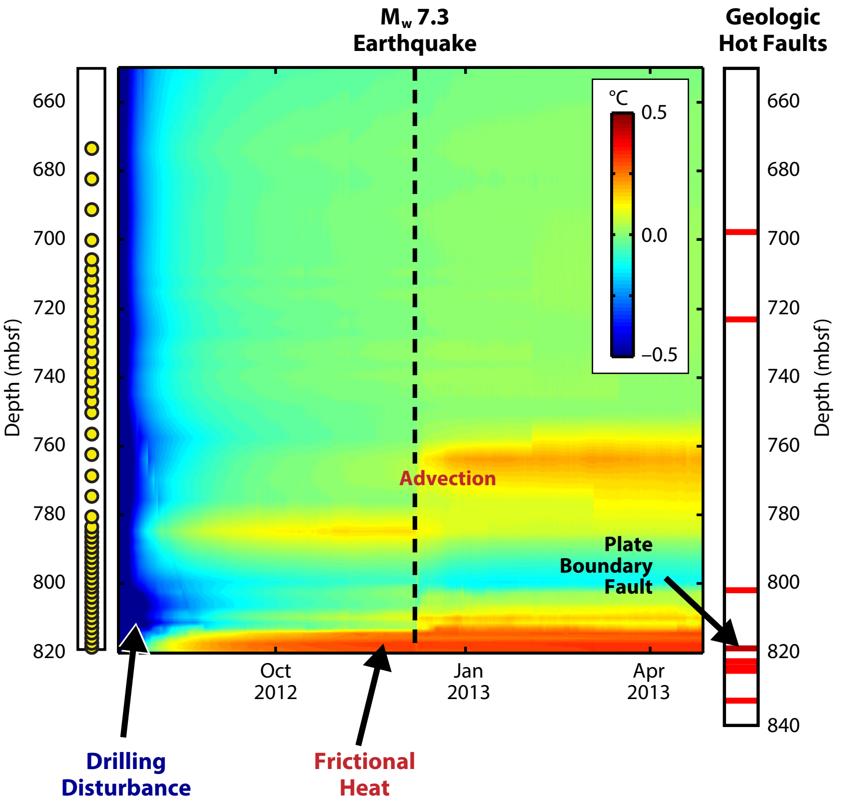

FIGURE 2. Residual borehole temperature data, after the background geotherm was removed, as a function of time from Integrated Ocean Drilling Program Hole C0019D (Expedition 343) in the Japan Trench. Yellow dots (left) mark sensor positions in the observatory and red lines (right) indicate faults identified from geologic signatures of frictional heating in core samples from Hole C0019E. Note that due to bathymetric differences between the separate coring and observatory holes, fault locations identified in the core are expected to be a few meters deeper relative to the seafloor than in the observatory (Chester et al., 2013b). Fluid advection is not seen within the plate boundary fault but is observed within the temperature data at shallower depths in response to a December 7, 2012, M_w 7.3 earthquake and other aftershocks (Fulton and Brodsky, 2016). The differences in hydrologic and thermal response to earthquakes and drilling disturbance at different depths is indicative of the dominance of conductive heat transfer within the plate boundary fault (Fulton et al., 2013; Fulton and Brodsky, 2016). *Adapted from Fulton and Brodsky (2016)*

data). The data do not constrain whether or not these particular faults slipped during the Tōhoku-oki earthquake, but they do support the possibility of multiple fault surfaces slipping during a single event. Note that the directly observed temperature signal measures the total energy over a region that includes all of these potential fault strands and thus does not resolve which (if any) were active during this particular earthquake.

Additional evidence of frictional heating in the JFAST core samples comes from other faults identified at depths around 697, 720, and 801 mbsf. Using mineral magnetic methods, electron microscopy, and X-ray spectroscopy, Yang et al. (2018) identified the presence of pyrrholite, a mildly magnetic iron sulfide mineral, exclusively within these faults zones. Ruling out other potential mechanisms for pyrrholite formation at this site, such as prolonged diagenetic reaction of magnetite or thermochemical sulfate reduction, they interpret their analyses as evidence of thermally driven pyrite-to-pyrrholite reactions at temperatures between 640°C and 800°C. There is no evidence of any frictional heat associated with these faults in the borehole temperature data, which implies that the pyrrholite occurrences in the borehole record the effects of previous earthquakes where fault slip was large.

CONCLUSION

Together, these studies made possible by IODP Expeditions 343 and 343T illustrate how both the direct and the indirect measurements of frictional heat at the Japan Trench are providing important insights into paleoseismicity and constraints on the resistive forces influencing earthquake and tsunami hazards. The JFAST project was motivated by scientific objectives that required drilling shortly after a disaster in order to obtain time-sensitive measurements. The amazing success of JFAST relied heavily on the IODP scientific infrastructure, engineering and technical expertise, and program management structures, without which such a rapid response scientific ocean drilling project would not have been possible.

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