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Investigation of the Huge Tsunami from the 2011 Tōhoku-Oki, Japan, Earthquake Using Ocean Floor Boreholes to the Fault Zone

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(left) Drilling vessel *Chikyu* used for Japan Trench Fast Drilling Project (JFAST) drilling operations. *Photo courtesy of JAMSTEC* (right) Remotely operated vehicle *Kaiko* used for temperature instrument retrieval from the borehole.

ABSTRACT. Integrated Ocean Drilling Program (IODP) Expedition 343, named the Japan Trench Fast Drilling Project (JFAST), drilled ocean floor boreholes through the fault zone of the 2011 Tōhoku-Oki earthquake (M9.0) to enhance understanding of the rupture process and tsunami generation. This project investigated the very large fault slip that caused the devastating tsunami by making borehole stress measurements, sampling the plate boundary fault zone, and taking temperature measurements across the fault zone. The results show that the earthquake rupture occurred in a narrow fault zone (< 5 m). Based on both laboratory experiments on fault zone material and temperature monitoring of the fault zone, we show that the fault had very low friction during the earthquake. The low friction properties of the fault zone might be attributed to high smectite clay content of the sediment. These physical and frictional characteristics contributed to the unusually large fault slip that occurred during the earthquake and generated the tsunami.

INTRODUCTION

When the Tōhoku-Oki earthquake (M9.0) occurred off the east coast of Japan on March 11, 2011, much of the world was watching as the devastating tsunami inundated the northeast coast of Honshu. This was the largest earthquake and largest tsunami in Japan's thousand-year recorded history of destructive events, with over 18,000 lives lost and great economic costs totaling 20 to 30 trillion Japanese yen. The tsunami heights were more than 10 m over several hundred kilometers of the coasts of Fukushima, Miyagi, and Iwate Prefectures, and a maximum over 40 m in Iwate Prefecture (Mori et al., 2011). Although the ground motions were very intense (peak accelerations exceeding 1 g over a wide region), the shaking damage was relatively small for such a large earthquake, and the tsunami caused the primary impacts. Only 4.4% of the deaths were attributed to seismic and landslides effects. In response to this earthquake, scientists quickly began planning the Japan Trench Fast Drilling Project (JFAST) to study the shallow portion of the subduction fault, which was the main source area of the tsunami (Figure 1).

One of the important features of the earthquake was the very large fault slip that occurred on the shallow portion of the subduction zone near the Japan Trench. This fault displacement of 40–60 m (e.g., Fujiwara et al., 2011) was the largest ever observed for any earthquake in the world and astounded many scientists. Because the size of a tsunami is directly related to the amount of shallow slip and resultant seafloor deformation, understanding this unprecedented large fault movement was the main scientific focus for the drilling project.

Very large tsunamis with heights of 30 to 40 m have occurred previously along the Tōhoku coast. For example, the 1896 Sanriku earthquake had peak tsunami heights comparable to those of the 2011 earthquake (Figure 2). It is likely that faulting on the shallow portion of the subduction zone also caused the large 1896 tsunami (Tanioka and Satake, 1996). The magnitude (about M8.5), and thus the source area for the 1896 earthquake, is much smaller compared to the 2011 event. This shows that it is not necessary to have an M9 earthquake to generate 30 to 40 m tsunami heights—smaller M8 earthquakes can also produce very large tsunamis. Thus, for evaluating tsunami hazards, the faulting on the shallow portion of the subduction zone is more important than the overall size of the earthquake.

In order to investigate the tsunami-generating fault slip during the 2011 earthquake, JFAST included three main scientific objectives:

1. Estimate the stress state in the region of the shallow fault from borehole breakouts.
2. Obtain core samples of the plate boundary fault zone to determine geologic structures and measure physical properties of the fault zone. Before this project, no one had directly investigated a fault zone that had recently moved tens of meters in an earthquake.
3. Determine the level of friction by measuring the temperature anomaly across the fault zone to estimate the level of frictional heat generated during the earthquake. To resolve a clear temperature signal, these observations needed to be done quickly after the earthquake, and this was the main motivation for the rapid response of JFAST.

With these goals, a proposal for JFAST was written and quickly evaluated by Integrated Ocean Drilling Program (IODP) scientific and operational panels during 2011. Final project approval was given in February 2012, and IODP Expedition 343 sailed on April 1, 2012, within 13 months of the earthquake.

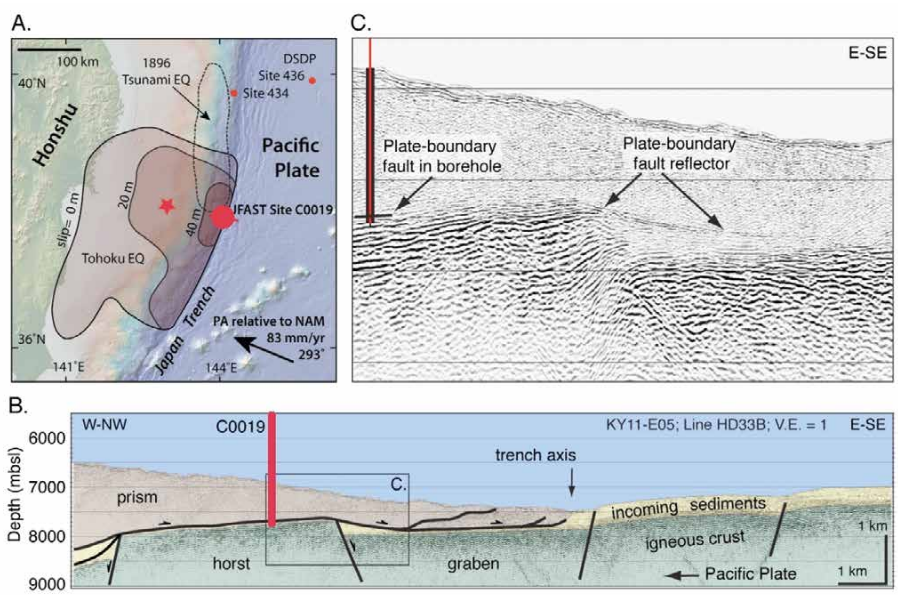

Figure 1. (A) Large red circle shows location of Japan Trench Fast Drilling Project (JFAST) site C0019 within the large slip area of the 2011 Tōhoku-Oki earthquake. (B) Seismic data showing the plate boundary fault. (C) Interpreted geological structure. Red vertical lines in B and C show the borehole location. *Figure from Chester et al. (2013)*

SHIP OPERATIONS

IODP Expedition 343 was carried out on the drilling vessel *Chikyu*, operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC; see photos on the first page of this article), whose accelerated planning and logistical preparations enabled the very fast implementation of the expedition. This is the only academic research vessel with the very deep water drilling capability needed for this project. Two months of operations, from April 1 to May 24, 2012, were scheduled for drilling several boreholes to carry out logging-while-drilling (LWD) operations, install temperature sensors in the borehole, and retrieve core samples. The drilling site was located about 220 km east of Sendai in the region of the 2011 earthquake's very large fault slip (Figure 1).

The 7,000 m water depth at the site posed various technical challenges, including the extreme weight of the long drill pipe, pipe strength, and onboard handling of the pipe sections. *Chikyu* had not previously drilled in such deep water, so these aspects required careful planning and purchase of new tools for the ship. Associated mechanical and electronic equipment that had not been used before in such deep water caused various problems during the first month at sea. Eventually, most of the difficult problems were overcome, and LWD data and cores from the plate boundary fault zone were successfully collected during the main expedition. New records were set for scientific ocean drilling, including longest drilling string (7,740 meters from the surface to the bottom of the borehole) and deepest core recovered (7,734 meters below the seafloor).

Because of delays and failure of electronic equipment, temperature sensors could not be installed during the two months of the main expedition. However, additional ship time was made available in technical Expedition 343T in July 2012 for a second attempt to install the temperature observatory. During 343T, a new borehole was drilled and temperature instruments were deployed across the fault zone in about a week with minimal problems (Figure 3). Experience gained from the previous efforts, improvements of various instrumental components, and good weather contributed to the efficient operations.

More than 50 temperature sensors recorded continuous data in the borehole for about nine months and were retrieved in April 2013. To recover the instruments, we used the remotely operated vehicle (ROV) *Kaiko*, operated by JAMSTEC (see photos on the opening page of this article). *Kaiko* is one of the few ROVs that can be used in water depths of 7,000 m.

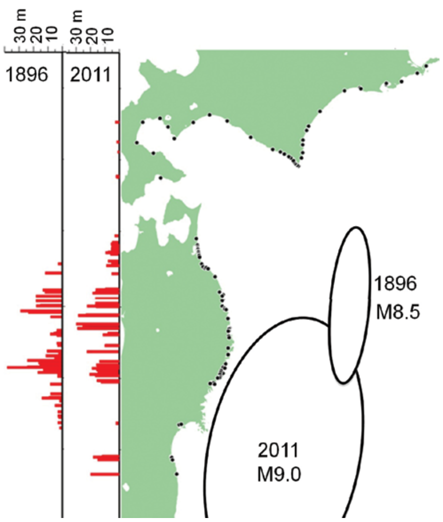

Figure 2. Comparison of tsunami runup heights for 1896 Sanriku and 2011 Tōhoku-Oki earthquakes. *Data courtesy of Hokkaido University*

Figure 3. Wellhead for the temperature observatory installed in a borehole on July 7, 2012, in the area above the slip region of the 2011 Tōhoku-Oki earthquake. The seafloor is at a depth of about 6,900 m. *Photo courtesy of JAMSTEC*

SCIENTIFIC RESULTS

Fault-Zone Structure

There was great excitement on board *Chikyu* when the core containing fault zone material was recovered with only two days left in the expedition and time nearly running out. Geology experts immediately recognized the fault zone rocks, which were very different from the material in any of the other cores. From visual examination of the core samples and measurements of physical properties of the rocks, a single

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plate-boundary fault zone was identified with a high level of confidence (Chester et al., 2013). The fault is localized in a thin layer of highly deformed pelagic clays (Figure 4), which is significantly different in structure from the sediments above and below. The entire section of the fault zone was not retrieved, but from the amount of the recovered and unrecovered sections, the total width of the fault zone is determined to be less than 5 m. This is a considerably thinner plate-boundary fault than has been observed at other locations, such as the Nankai Trough. The narrow fault zone width may contribute to the conditions that enable very large slip. The actual slip surface for the 2011 earthquake may not have been recovered, but it is assumed that the structures and physical properties of the core are representative of the entire fault zone.

Stress State from Borehole Breakouts

Fractures in the borehole wall (called breakouts) were used to estimate the local stress field. Breakouts can be observed in resistivity images of the borehole wall where local stresses cause a section of the borehole wall to fail. From the orientations and crack widths of these features, the direction and magnitude of the stress can be calculated. Consistent borehole breakouts were observed over a range of about 300 m in the hanging wall above the fault zone. The directions and sizes of the fractures suggest that this region has changed from a thrust-faulting to a non-thrust regime (Lin et al., 2013). The horizontal stress is close to zero, indicating that almost all of the stress was released during the earthquake. This confirms previous suggestions (e.g., Hasegawa et al., 2011) of a complete stress drop across the fault during the 2011 earthquake (stress drop is the difference between the stress across a fault before and after an earthquake), which is different from most other large earthquakes (Lin et al., 2013).

Friction Estimate from Laboratory Experiments

Laboratory experiments were carried out on a sample from the fault zone (Core 17) to determine the frictional strength of the material (Ujiie et al., 2013). A slip velocity of 1.3 m s^{-1} and displacements of 25 m were used, comparable to the fault slip during the earthquake. The friction of natural faults and the results from laboratory experiments depend on the water flow close to the slipping surface. Two types of conditions were used for the experiments. In the permeable case, water can move away from the sample during the run, while in the impermeable case, the water is confined in the local area of the slipping material. The measured shear strength for permeable and impermeable conditions yielded values of 1.32 and 0.22 MPa, respectively. The equivalent values for the apparent coefficient of friction are 0.19 and 0.03. These results indicate that the fault zone material can slip with a very low level of friction. Also, the frictional strengths for the material from the Japan Trench fault zone are lower than those observed at other subduction zones, such as the Nankai Trough (Figure 5).

Examination of the microstructures in the laboratory samples suggests that fluids are important in the faulting process and also contribute to low friction properties (Ujiie et al., 2013), possibly

Figure 4. Photo of Core 17 recovered from JFAST site C0019 showing the highly deformed fault zone material.

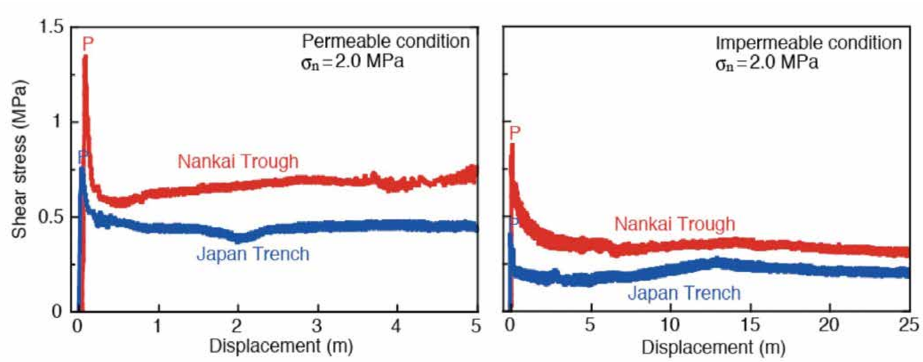

Figure 5. Results of laboratory experiments showing low strength properties of the Japan Trench fault zone material for (A) permeable and (B) impermeable conditions. Results from the Nankai Trough are also shown. *Figure after Ujiie et al. (2013)*

through the expansion of pore fluids due to frictional heating in a process known as thermal pressurization.

Friction Estimate from Temperature Measurements

One of the main JFAST objectives was to use temperature measurements to determine the frictional heat produced at the time of the earthquake. When an earthquake occurs, the fault becomes hotter because of frictional heating generated by slipping. By measuring the temperature across the fault soon after the earthquake, we can estimate the level of stress and friction during fault movement. Although the temperature increase is quite large at the time of the earthquake (hundreds of degrees), one or two years later, the peak temperature decreased to a few tenths of a degree.

The JFAST temperature observatory was installed across the fault zone under difficult conditions due to the great water depth (6,900 m). With the successful retrieval of the instruments in April 2013, a small temperature signal across the fault was observed in the data. Figure 6 shows the depth versus time temperature data with the geothermal gradient removed. Several months are needed for the observations because it takes time for the temperature in the borehole to equilibrate after being disturbed by drilling, as seen by the increasing temperatures over the first two months. The temperature signal attributed to the earthquake can be seen in the data about four months after instrument installation and 18 months after the earthquake. At that time, the temperature in the immediate vicinity of the fault zone was about 0.3°C higher than in the surrounding region, as indicated by the warm colors at depths between 814 and 820 meters below seafloor in Figure 6. This is interpreted to represent the frictional heat produced at the time of the earthquake. Analyses of these data show that this higher temperature corresponds to an average shear stress on the fault of 0.54 MPa and an apparent coefficient of friction of about 0.08 (Fulton et al., 2013). These values are consistent with estimates from the laboratory experiments described above and give an independent determination of the very low frictional properties of the fault.

INTERPRETATIONS

The devastating tsunami associated with the 2011 Tōhoku-Oki earthquake was caused by the huge amount of fault displacement on the shallow portion of the subduction zone near the Japan Trench. To better understand the mechanisms and conditions that enabled the fault to move tens of meters, we studied its frictional and geological properties. An important conclusion, obtained independently from the rock friction experiments (Ujiie, et al., 2013) and the temperature monitoring (Fulton et al., 2013), is that the dynamic friction during the earthquake was very low, much lower than typical values of static friction for most rocks (about 0.5 to 0.7; e.g., Byerlee, 1978). The difference between static and dynamic friction is important, and there can be a higher static friction that drops to a lower dynamic friction when a fault begins to move. This means that once an earthquake rupture propagates into a region, the friction drops to a low level within a few seconds or less, promoting further slip. Such slip weakening mechanisms have long been proposed for large earthquakes (e.g., Ida, 1972), but this is one of the first direct estimates of the friction level from a fault that had a recent earthquake. Slip at low friction also implies that there is little shear stress remaining on the fault after the earthquake, if the final stress is similar to the dynamic friction. This interpretation is consistent with the inference of a nearly complete stress drop from the borehole breakouts (Lin et al., 2013).

The low frictional properties of the plate-boundary fault might be attributed to its high (about 75% to 85%) smectite content (Ujiie et al., 2013). A type of clay with known low frictional properties, smectite is a major component of pelagic sediments in the plate boundary fault zone near the Japan Trench. The fault zone is especially enriched in smectite compared to other sections retrieved

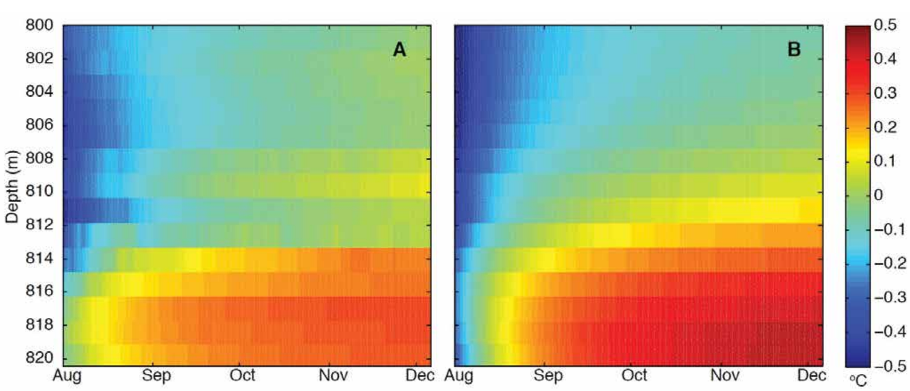

Figure 6. Borehole temperature near the fault zone with geotherm removed. (A) Observations and (B) modeled temperature using the preferred frictional model. *Figure from Fulton et al. (2013)*

from the JFAST site. Fault zones characterized by material with lower frictional properties may be more likely to slip more during earthquakes. Plate boundary fault zones in other regions, such as the Nankai Trough in southwest Japan, appear to have less smectite and a higher content of coarser-grained sediment; hence, they may slip less during an earthquake, although the number of samples analyzed is still limited. The frictional and structural properties of other subduction zone faults around the Pacific with similar geologic settings need to be further studied to test this hypothesis (Chester et al., 2013).

CONCLUSIONS

JFAST was a successful rapid scientific response to a natural hazard event that had great societal impact. Technical challenges associated with drilling in very great water depths of ~ 6,900 m were overcome, enabling borehole stress measurements to be taken, core samples of the plate-boundary fault zone to be recovered, and temperature measurements to be collected over several months. The results of the scientific investigations show that the very large slip during the 2011 Tōhoku-Oki earthquake occurred on a simple, narrow fault zone containing fine-grained sediments with high smectite clay content. Both laboratory experiments on the fault zone material and temperature measurements across the fault zone indicate that the friction level along the plate interface was very low during the earthquake. The localized fault zone, the low frictional properties of the material in the fault, and the complete stress drop during the earthquake likely contributed to the very large slip that generated the destructive tsunami.

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The success of JFAST is due to the contributions of many people and their hard work in preparations and operations: shipboard and onshore scientists, onboard drilling engineers, technical support staff, and crews of *Chikyu, Kairei,* and *Kaiko*. All those involved made valuable contributions to this project, and it could not have succeeded without the cooperative efforts of everyone involved.

REFERENCES

Byerlee, J.D. 1978. Friction of rocks. *Pure and Applied Geophysics* 116:615–626, http://dx.doi.org/10.1007/BF00876528.

Chester, F.M., C. Rowe, K. Ujiie, J. Kirkpatrick, C. Regalla, F. Remitti, J.C. Moore, V. Toy, M. Wolfson-Schwehr, S. Bose, and others. 2013. Structure and composition of the plate-boundary slip-zone for the 2011 Tohoku-Oki earthquake. *Science* 342:1,208–1,211, http://dx.doi.org/10.1126/science.1243719.

Fujiwara, T., S. Kodaira, T. No, Y. Kaiho, N. Takahashi, and Y. Kaneda, 2011. The 2011 Tohoku-Oki earthquake: Displacement reaching the trench axis. *Science* 334:1,240, http://dx.doi.org/10.1126/science.1211554.

Fulton, P.M., E.E. Brodsky, Y. Kano, J. Mori, F. Chester, T. Ishikawa, R.N. Harris, W. Lin, N. Eguchi, S. Toczko, and Exp. 343/343T and KR13-08 Scientists. 2013. Low coseismic friction on the Tohoku-Oki fault determined from temperature measurements. *Science* 342:1,215–1,217, http://dx.doi.org/10.1126/science.1243641.

Hasegawa, A., K. Yoshida, and T. Okada. 2011. Nearly complete stress drop in the 2011 M_W 9.0 off the Pacific coast of Tohoku earthquake. *Earth, Planets, and Space* 63:703–708, http://dx.doi.org/10.5047/eps.2011.06.007.

Ida, Y. 1972. Cohesive force across the tip of a longitudinal shear crack and Griffith's specific surface energy. *Journal of Geophysical Research* 77:3,796–3,805, http://dx.doi.org/10.1029/JB077i020p03796.

Lin, W., M. Conin, J.C. Moore, F.M. Chester, Y. Nakamura, J.J. Mori, L. Anderson, E.E. Brodsky, N. Eguchi, and Expedition 343 Scientists, 2013. Stress state in the largest displacement area of the 2011 Tohoku-Oki earthquake. *Science* 339:687–690, http://dx.doi.org/10.1126/science.1229379.

Mori, N., T. Takahashi, and the 2011 Tohoku Earthquake Tsunami Joint Survey Group. 2011. Nationwide post-event survey and analysis of the 2011 Tohoku earthquake tsunami. *Coastal Engineering Journal* 54:1–27, http://dx.doi.org/10.1142/S0578563412500015.

Tanioka, Y., and K. Satake. 1996. Fault parameters of the 1896 Sanriku tsunami earthquake estimated from tsunami numerical modeling. *Geophysical Research Letters* 23:1,549–1,552, http://dx.doi.org/10.1029/96GL01479.

Ujiie, K., H. Tanaka, T. Saito, A. Tsutsumi, J.J. Mori, J. Kameda, E.E. Brodsky, F.M. Chester, N. Eguchi, S. Toczko, and Expedition 343 and 343T Scientists. 2013. Low coseismic shear stress on the Tohoku 1 megathrust determined from laboratory experiments. *Science* 342:1,211–1,214, http://dx.doi.org/10.1126/science.1243485.