Report of the

Rapid Response Drilling Following the Tohoku Earthquake

Detailed Planning Group

Executive Summary

The March 2011 Tohoku earthquake generated the largest slip of any historical earthquake. It surprised both scientists and the public by surpassing all previous predictions for earthquake magnitudes on the Japan margin. The resultant tsunami devastated northeastern Honshu, Japan. In the wake of this disaster, the scientific community has an obligation to learn as much as possible from the earthquake about the mechanisms that generate such catastrophic events. Key parameters and processes, which can only be determined after the earthquake, must be known in order to evaluate the predictability of earthquakes. Questions that can be addressed by a focused effort are: (1) What stress and stability conditions allow rupture to propagate to the ocean bottom? (2) What are the fingerprints of the processes controlling stress in a large earthquake in a fault zone, and how might we recognize them in exposed or cored faults that have not produced a historical earthquake? (3) What was the stress on the fault during slip and was the stress completely released? (4) How do faults heal to regain strength and stress? (5) How are the changing stress and strength related to generating new earthquakes and aftershocks? The stress on the fault is the overriding theme behind all of these questions. Continuous or repeat borehole temperature measurements and fault core geology can constrain the stress. Optimal interpretation also requires a suite of logging, hydrology, direct stress and seismic observations.

The DPG recommends that IODP undertake rapid fault drilling for the Tohoku earthquake if the slipped fault can be sampled and multiple temperature measurements can be carried out. Initial calculations indicate that a hole would need to be completed by July 2012 in order to ensure meeting the scientific objectives. Preliminary site surveys indicate that the primary slip surface is at an accessible depth (<1 km) below the ocean floor in a region with extremely large (~50 m) local slip. The likely primary target locations are at 6-7 km water depth. Drilling and completing a cased hole for monitoring or repeat observations has never before been attempted at these water depths. The success of a rapid response drilling project will hinge on solving this technical challenge.

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I. Introduction

When the 11 March 2011 Tohoku earthquake struck northeast Japan, the world watched in real time as tsunamis up to 30 meters in height inundated the Japanese coast, causing more than 23,000 deaths and losses exceeding several tens of trillions Japanese yen. The International Ocean Drilling Program (IODP) has an obvious and important mission to investigate the huge fault slip that caused the devastating tsunamis, especially in the context of understanding the physical mechanisms of great subduction earthquakes (*Solid Earth Cycles and Geodynamics* of the Initial Science Plan), and strong emphasis on Geohazards in the new science plan for IODP (*Earth In Motion* Theme).

The 2011 event (M_w9.0) is the largest known Japanese earthquake in over 1500 years of historical records, tsunami run-up heights are the largest ever recorded in Japan, and seafloor displacements up to possibly 50 meters are the largest fault movements ever measured for any earthquake. Such unprecedented observations coupled with the societal importance of understanding the strong shaking and large tsunami potentials for future earthquakes, make this a high priority research target.

Drilling in the ocean floor to the slipped fault following an earthquake can yield geologic, geophysical, and geochemical data that help answer fundamental questions about the physical mechanisms of fault slip. The primary focus for this research is the level of stress on the fault during and after the large displacement. The stress on the fault during large earthquakes controls the behavior of the rupture, but is largely unknown by seismologists. Is the frictional stress high, as indicated by static rock properties? This would produce a large amount of heat during the earthquake. Or, do dynamic properties such as pressurization or melting significantly reduce the frictional stress during the earthquake so that slip progresses under lower stress conditions? These issues are particularly important for the shallow region of the subduction zone with the very large displacements that produced the tsunami for the Tohoku earthquake.

The stress at the time of the earthquake can be best inferred from the frictional heat generated on the fault, and measured by a temperature profile across the fault. Characterization of the local hydrologic properties and pore pressure is also needed for this calculation. Additionally, the physical fabric seen in a core sample of the fault gives valuable information on the local stress and the scale of the deformation, for the most recent and past earthquakes. Laboratory experiments on the fault material also can be carried out to directly measure frictional properties. Borehole measurements can give direct estimates of the post-seismic stress field close to the fault zone. Geochemical and mineralogical analyses provide additional constraints on the temperature and stress conditions during earthquakes.

An important consideration is that some of these observations are transitory, notably temperature distribution, the changing stress field, hydrological properties, and geochemical markers, so measurements need to be made soon after the fault slips. A borehole drilled quickly into the fault will capture the time-dependent processes and yield valuable information that is rarely available following large earthquakes.

Twenty members of the Detailed Planning Group from 6 countries met on 18-20 May 2011 in Tokyo, to discuss scientific issues related to the earthquake and assess contributions that can be made with ocean drilling (See Appendix 2 for member list). Work continued remotely and this report is the resultant scientific plan that discusses the merits of rapidly drilling into the fault region of the Tohoku earthquake.

This report begins with a summary of the major observations of the Tohoku earthquake that highlights the multiple unique features of this event both in terms of phenomena and types of data available. Section II articulates key scientific questions that could be addressed by drilling into the Tohoku fault and Section III develops the techniques that can answer the questions. Section IV reconciles the competing demands of the scientific goals and clarifies the requirements of a successful project. Significant hurdles that must be addressed by IODP are also included in the timing requirements and evaluation of capabilities subsections. Section V relates recent and ongoing fault zone projects. The final recommendation of the DPG is in Section VI.

Box 1: The 2011 Off the Pacific Coast of Tohoku Earthquake (M_w 9.0)

The March 11, 2011 Tohoku earthquake came as a disheartening surprise to the geophysical community. With a historical record of nearly 500 years including 13 M_w7 and 5 M_w8 earthquakes, this region was thought to be relatively well understood in terms of the locations and sizes of expected subduction zone earthquakes. An M_w9 event breaking through the entire region of many fault segments, with the associated huge tsunami, was not at all anticipated for this thoroughly studied area. This failure highlights the need for a more physically-based understanding of initiation and rupture.

The sequence started with an $M_w7.2$ foreshock, which occurred 2 days before and about 40 km NE of the mainshock hypocenter. In the hour after the mainshock, there were large Mw7.9 and Mw7.7 aftershocks. In addition to the countless aftershocks in the immediate region, the seismic activity of small earthquakes increased across most of Japan with several M_w5 and a few M_w6 earthquakes over the following month. Small earthquakes were also triggered at 13 volcanoes according to the Coordinating Committee for Prediction of Volcanic Eruption.

Apart from the foreshocks, there were no clear precursory signs or large pre-slip. The foreshocks themselves were only identified as precursory with hindsight. Current models of earthquake clustering suggest that the probability of having an M_w 9.1 earthquake following an M_w 7.2 earthquake within 2 days is <0.001% and thus a societally useful prediction could not be provided based on the foreshocks alone.

Modeling of seismic, crustal deformation, and tsunami data shows very large slip on the fault plane, with values up to 30-50 meters (e.g. Simons et al., 2011, Sato, et al., 2011, Ammon et al., 2011, Ohta et al., 2011, Lay et al., 2011). The area of maximum slip is on the shallow portions of the fault trenchward of the hypocenter. The large and shallow slip near the trenchward limit of the megathrust caused large deformation of the seafloor, which generated the devastating tsunami. Because of the dense network of observations in the region prior to the earthquake, the extremely large slip has been verified by direct observations of displacement on the seafloor through repeat bathymetry and GPS.

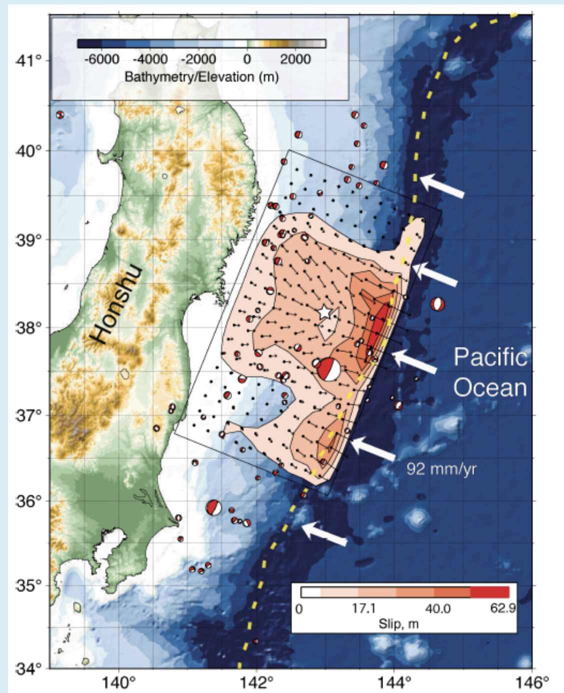

Figure 1. Teleseismic P-wave inversion for slip (Lay et al., 2011). Maximum slip ranges from 40-80 for a suite of inversion models with the majority of models placing large slip near the trench. Most models do not directly incorporate the ocean bottom observations in Figure 2 and 11 which require large slip towards the updip end of the rupture.

The earthquake produced severe strong ground motions with accelerations over 1 g and long durations of about 100 s. However, the large losses of lives and property were mainly due to the tsunami, and shaking damage was relatively limited, considering the size and intensity of the earthquake. Even the well-publicized problems at the Fukushima No. 1 nuclear power plant were caused by loss of power due to the tsunami inundation, and not by the shaking itself. The resilience of most structures throughout the region can be attributed to the high seismic standards of Japanese construction.

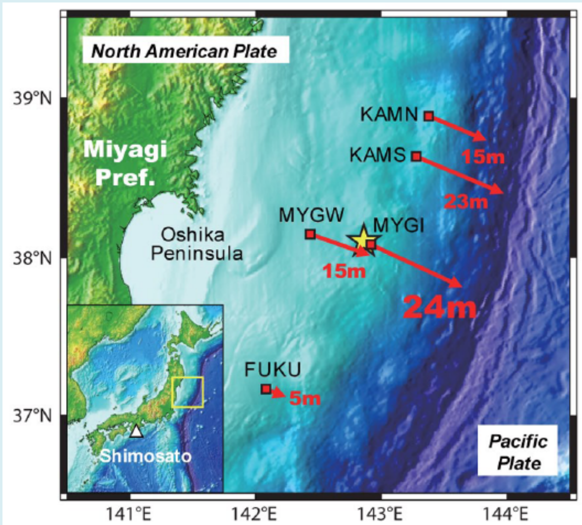

Figure 2. Horizontal coseismic displacements at seafloor benchmarks, associated with the Tohoku earthquake. Red squares are locations of GPS benchmarks and yellow star is the epicenter of the mainshock (Sato et al., 2011b).

During the Tohoku earthquake, the regions of the fault that produced the dominant high-frequency energy are different from the areas of large slip. The large slip is on the shallow updip portion of the fault, while the high-frequency radiation originated from the deeper downdip portions of the fault (e.g. Ide et al., 2011, Wang and Mori, 2011, Koper et al., 2011). The difference in frequency of the radiated energy for different portions of the fault reflects variations in rupture dynamics. The deeper portion appears to be have undergone a more brittle rupture with a higher proportion of radiated energy, while the large shallow slip probably absorbed more energy through dissipated processes. The greater dissipation may be characteristic of tsunami earthquakes and can be studied by sampling this portion of the fault with a borehole.

II. Scientific Goals of a Rapid Drilling Project

The Tohoku earthquake brought into stark focus the lack of understanding of earthquakes and tsunami genesis in subduction zones, as well as our inability to provide answers to long-standing questions in earthquake physics. Ongoing analysis of the rich observational data set for this event will continue to refine our picture of the rupture, slip, and radiated-energy characteristics of the earthquake, as well as the generation of the extremely large tsunami. However, several preliminary findings such as the incredibly large slip (up to ~50 m) and the occurrence of rupture at shallow depth near the oceanic trench were largely unexpected by the community of earthquake scientists. In addition, the disparity between the source location of the high-frequency shaking and the low-frequency energy release that directly generated the tsunami is equally noteworthy. The propagation of dynamic rupture and large slip to the toe of the thrust at the trench overturns much previous understanding of the limit of earthquake rupture and tsunamigenesis in subduction zones. An immediate implication is that such great earthquakes and tsunamis, though likely less frequent than great thrust-type earthquakes occurring at greater depths, may occur in many subduction zones around the world. This has profound significance for tsunami forecasting, hazard assessment, and mitigation of the social, political and financial impacts of possibly impending events.

A rapid response study of the Tohoku event offers a unique opportunity to address several fundamental questions about the forces and processes on a fault beneath the earth's surface during an earthquake and to further our quantitative understanding of the mechanics of dynamic faulting and release of energy. The fault with large slip at shallow depth allows access to an important seismic region that is usually located at depths beyond the capabilities of drilling.

Specifically, we can address the following questions:

1) What stress and stability conditions allowed rupture to propagate to the trench in the Tohoku earthquake?

Mechanical analyses of frictional systems analogous to the shallow faults that create great earthquakes indicate that the occurrence of slip instability depends on parameters describing both extrinsic and intrinsic conditions of faults (e.g., Scholz, 1998). Extrinsic factors include the rates of loading and magnitudes of forces (lithostatic and tectonic stress, and fluid pressure) acting on faults. Intrinsic (material) parameters include the poroelastic and fluid flow properties of sediment and rock-bounding faults, and the frictional properties of fault surfaces where slip occurs. A key frictional behavior for instability is a reduction in friction with increasing slip and slip rate, and a small critical distance for the weakening to occur.

Conventional thinking is that the marine sediments and rocks along shallow subduction zone megathrusts are too weak to support large shear stress, and that the frictional fault surface at the base of the accretionary prism is not only weak but tends to strengthen with slip, so earthquake instability should not nucleate or easily propagate throughout the shallow portion of the subduction interface (e.g., Hyndman et al., 1997; Saffer and Marone, 2003). However, recent high-velocity friction experiments on clay-rich sediments suggest that earthquake rupture can propagate through the shallow subduction zone without much resistance, once slip is sufficiently rapid (Ujiie and Tsutsumi, 2010). The kinematics and slip distribution of the Tohoku rupture provides clear exceptions to the conventional view and provide an invaluable opportunity to investigate the response of shallow subduction thrust material to megathrust rupture from deeper depths.

A viable but untested hypothesis is that the cumulative build-up of stress in the upper plate from repeated loading by great earthquakes at depth, and dynamic weakening of the basal fault surface to a vanishingly small friction coefficient during rupture propagation, together allow for the remarkable slip distribution and energy release observed in the Tohoku earthquake. The unique opportunity for rapid-response drilling into the Tohoku rupture surface at the trench would provide geophysical characterization of the extrinsic and intrinsic states of the fault zone, core samples of sediment and rock for laboratory analysis and materials-property testing, and the opportunity to conduct monitoring or repeated in situ measurements of time-varying temperature, slip, deformation and pore fluid pressure, all of which are needed to test hypotheses about the occurrence of great tsunamigenic earthquakes.

2) What are the fingerprints of a large earthquake in a fault zone, and how might we recognize such an event in exposed or cored faults for which there are no known historical earthquakes? What do the structures tell us about the processes controlling stress?

Geologic studies of fault zones have identified numerous structural characteristics that may be related to the physical and chemical processes of stressing during interseismic periods and the relatively rapid unloading during slip (e.g., Sibson, 1977; Chester et al., 1993). At the same time, experimental rock deformation studies of friction and faulting, combined with constitutive- and theoretical-modeling, have led to a number of hypotheses about dynamic processes of weakening that may operate and control stress changes during natural faulting events (e.g., Di Toro et al., 2011). Most recently, analysis of samples recovered from scientific drilling into fault zones known to have slipped during earthquakes has led to advances in the identification of structural and chemical signatures of earthquake slip and insights to the underlying microscale processes. Integrating these diverse observations and findings has led to a greater appreciation of the possibility for profound reductions of the strength of faults during rapid slip and the consequences of such weakening on earthquake energetics (e.g., Noda et al., 2009).

Core samples taken from across the toe region of frontal and out-of-sequence thrusts in the Nankai Trough have included possible structural and geochemical evidence of prehistoric earthquake slip events analogous to the Tohoku event (e.g., Sakaguchi et al., 2011; Yamaguchi et al., 2011). Rapid response drilling of the Tohoku event would help ground-truth such findings and stimulate this advancing area of earthquake science research.

3) What was the shear stress on the fault during slip and was the stress completely released? What generated the low radiated energy in the toe?

Quantifying the absolute levels of stress before, during and after earthquakes has been an elusive goal of earthquake physics. Because most of the elastic strain energy released during earthquakes is dissipated by frictional heating in the slipping zone, measurement of transient changes in temperature near a fault shortly after an earthquake provides a direct measure of absolute stress during earthquake slip (e.g., Kano et al., 2006; Tanaka et al., 2006; Fulton et al., 2010). Combined with in situ measurements of postseismic slip, aftershocks, fluid pressure and other transients, it is possible to infer through modeling the relative role of intrinsic and extrinsic weakening processes. In the case of the Tohoku earthquake, such measurements achieved by rapid-response drilling may not only address the perplexing mechanics of the recent rupture all the way to the trench, but can also address the long-standing general questions of absolute stress levels and total stress drops for large earthquakes at other plate boundaries. In addition, direct stress measurement techniques can detect the change in stress orientation across the rupture zone that may be related to the large stress release.

Seismological techniques cannot measure the absolute stress, but they do provide a window into the kinematics of earthquake slip and associated time-space record of energy release. For Tohoku, the seismology indicates an anomalously gradual release of stress in the toe resulting in low radiated energy. What is the relationship between this time history of slip and the stress state on the fault? Does measuring the material properties of the fault allow predictions about the type of seismic shaking that should be expected? We can address these questions by using the absolute stress constraints gained by the techniques above in dynamic models of rupture.

4) How do faults heal to regain strength and stress?

The inter-related hydrological, chemical, and physical properties of fault-zone rocks change dramatically during an earthquake and then evolve rapidly as the fault heals in the subsequent days and years. This healing process allows the fault-zone to regain strength lost during the rupture process and hence to eventually accumulate the stress that will be released in the next earthquake. Fracturing during the earthquake increases permeability and reduces the rigidity of the fault-zone. During the post-seismic healing period, the permeability drops and the fault-zone regains strength as fractures close, frictional contacts grow and minerals precipitate from fault-zone fluids. The recoveries of permeability and seismic velocity have been observed from surface observations, but never from within a fault zone (Kitagawa et al., 2002; Li et al., 1998; Brenguier et al., 2008). Rapid response drilling is necessary to sample the fault-zone rocks and fluids as they are changing so that we can understand the small-scale chemical processes that govern strength recovery and improve our resolution of where fault healing actually occurs. We must sample the fault-zone as quickly as possible because, as demonstrated by surface observations and laboratory studies, healing processes such as strength and seismic velocity recovery occur with the logarithm of time after slip. Therefore, a delay in sampling healing requires commitment of resources for a longer time to measure the decreasing rate of change.

A Tohoku rapid response drilling project could directly sample the rocks that have undergone the largest ever known displacement in an earthquake within about a year after rupture. These samples would provide the baseline chemical and physical property measurements for comparison with future sampling efforts undertaken as this fault heals over the coming years and decades. Moreover, a borehole observatory would provide access to continuously or repeatedly measure pore pressure, permeability, rigidity, and other key properties of the fault-zone in situ. By obtaining timeseries data through monitoring or repeat measurements, we could watch a fault change physically and chemically as it builds up the stress that will create the next great rupture and tsunami.

5) *How are the changing stress and strength related to generating new earthquakes and aftershocks?*

Aftershock sequences are generated by the changes to stress and strength of the fault-zone and surrounding rocks produced by the mainshock rupture. The rate of aftershocks decays rapidly with time, and this is the single most reliably predictable property of earthquake sequences. Despite this general predictability and thousands of sequences that have been well observed with surface seismometers, there remains a fundamental, unsolved debate about whether the spike and subsequent decay in aftershock rate with time following a mainshock result primarily from (a) the static stress changes produced by the mainshock, (b) the dynamic stress field (shaking) produced by the mainshock, (c) the static stress changes produced by afterslip, or (d) the recovery of fault strength with time. Although countless sequences that have been well-documented with seismology and geodesy, none of these provide direct constraints on the temporal evolution of the fault's stress and strength in the region where aftershocks are occurring.

A Tohoku rapid response drilling project could help provide the direct constraints on the fault's stress-state that have been missing from previous aftershock studies. First, deformation in the boreholes combined with existing seafloor instrumentation could constrain the distribution of afterslip. Secondly, a unique feature of the Tohoku earthquake among great subduction zone events is that numerous deployments of ocean bottom seismometers (OBS) before the earthquake established the updip limit of microseismicity on the thrust interface. This limit can be interpreted as demarcating the transition from velocity weakening to velocity strengthening frictional behavior on the thrust interface and its location may be time-dependent. Numerous instrument deployments that are already underway by Tohoku Univ., ERI, and JAMSTEC will provide direct constraints on whether the location of this transition changed in response to the mainshock and these deployments should be supplemented with instrumentation near the drill hole(s), VSP studies, and possibly down-hole seismometers. While recording and locating the aftershocks is relatively straight forward, only rapid drilling can provide the direct constraints on the fault's stress state that are needed to understand how earthquakes are triggered.

III. Answering the Questions

What will it take to answer these questions and advance from our current empirical model of earthquake initiation and fault slip to a more physics-based understanding of the rupture process? As outlined above, there are specific measurements that can be made following the Tohoku earthquake that constrain many of the key variables. The conditions required for an earthquake to rupture to the seafloor can be constrained by direct samples of the fault and its hydrogeology combined with constraints on the coseismic stress from temperature measurements and laboratory experiments. Recovered core from the fault zone can reveal the fingerprints of large slip and that elucidate the processes controlling the resistance to slip. The absolute value of the shear stress that existed during the earthquake can be measured by through repeat temperature measurements and the current stress can be constrained through strain recovery tests and from analysis of wellbore failures. The healing process can be captured through monitoring or repeated measurements of pore pressure, seismic velocity, strain, permeability and other properties. The origins of aftershocks can be studied through combined passive and active seismology combined with the stress constraints. In this section we begin to detail each of these techniques and measurements that directly address the questions.

Clearly all of these measurements cannot be performed simultaneously and some may not be technically possible. Any realistic project must consider the trade-offs and relative scientific advantages of each observation. In order to develop a prioritization and systematic understanding of the technical resources necessary to answer the scientific questions, the Detailed Planning Group assembled information below on each major type of observation that might occur in conjunction with rapid drilling. Competing demands and feasibility are considered in Section IV of this report along with the specific timing requirements for rapid measurements.

1. Temperature

Measuring and monitoring temperature across the fault zone quickly after a large slip event provides the most direct opportunity for quantifying the coseismic frictional resistance dissipated as heat (e.g., *Lachenbruch and Sass*, 1980). The conductive temperature anomaly, T, across a fault zone due to frictional heating can be expressed by (*Carslaw and Jaeger*, 1959),

$$T(y,z,t)=\left(\frac{\mu_f\sigma_n'(z)d}{c\rho}\right)\left(\frac{\exp(-y^2/4\alpha t)}{\sqrt{4\pi\alpha t}}\right) \qquad (1)$$

where y is the distance from the fault, z, is depth, t is time, μ_f is the coefficient of friction during slip, σ_n is the effective normal stress, d is the displacement, c is the heat capacity, ρ is density and α is thermal diffusivity. The temperature anomaly is proportional to the coseismic coefficient of friction, effective normal stress, and fault displacement and attenuates with the square root of time. The effective normal stress in turn is governed by the total overburden stress, s_v, and the pore pressure. Figure 3 graphically shows the attenuation of the temperature anomaly as a function of time and distance for a scenario similar to that expected at 1 km depth for the Tohoku earthquake rupture area. A temperature anomaly of 0.2° C is clearly resolvable with high quality thermometers and large enough to track robustly through time (*Fulton et al*., 2010).

Surface observations of heat flow (Lachenbruch and Sass, 1980) and temperature profiles across fault zones (Tanaka et al., 2006; Kano et al., 2006) have not unequivocally resolved this signal but have been used to estimate the maximum allowable coseismic coefficient of friction. In these cases, observations were made very shallow or late after the earthquake without repeat measurements and therefore were unable to robustly distinguish between models for high vs. low friction. These results indicate the difficulty in making this observation due to a number of factors including the low coseismic coefficient of friction, high pore fluid pressures, or noise.

Fulton et al. (2010) considered a number of obstacles to measuring the frictional heat. The most significant of these is likely heat advection by fluid flow. Figure 4 shows how various permeability architectures distort the frictional heating signal scaled to the Tohoku earthquake at a depth of 1 km. For perm abilities less than about 10^{-14} m^2, advective fluid flow is likely negligible. For reasonable values of permeabilities the frictional heating signal is a large percentage of the total temperature anomaly.

Figure 5 shows how the conductive and advective heat signals attenuate as a function of time for a range of permeability architectures investigated and for two end member coefficients of friction. Because advective fluid flow affects the decay of temperatures, the advective component can be recognized and modeled by monitoring the evolution of the temperature anomaly as a function of time (Fulton et al., 2010). Even in the case of advection by fluid flow, it is clear that temperature measurements can resolve the difference between a coseismically strong versus weak fault.

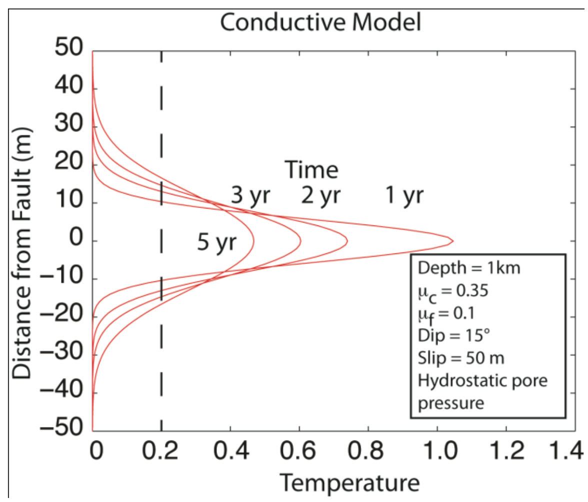

Figure 3. The diffusion of the frictional heating signal with time. Fault zone parameters used in this model are given in the inset. The maximum anomaly scales linearly with the coseismic coefficient of friction, μ_f, normal stress, σ_n, and the fault slip.

Other obstacles to resolving the frictional heating signal include the thermal disturbance of drilling, spatial variations in thermophysical rock properties and convection within the borehole. These obstacles can all be overcome with appropriate measuring strategies.

To capture and monitor the frictional heat signal of slip requires measuring in-situ temperature to high accuracy and at sufficient spatial and temporal resolution to track the evolution of the thermal field. In practice, obtaining accurate temperature measurements means establishing a borehole that recovers to as close to in situ conditions as possible. The cased borehole and annulus will need to be sealed to restrict fluid flow between the formation and the overlying ocean.

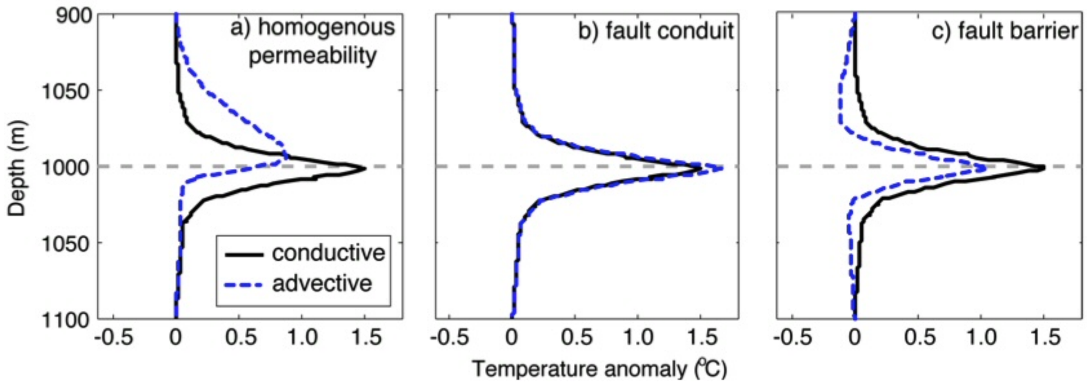

Figure 4. Frictional heating anomalies from model simulations for conductive (black line) and transient fluid flow (blue line) for three permeability architectures 2 years after the earthquake (*Fulton et al.*, 2010). Temperature values have been scaled to represent the Tohoku fault zone using the fault zone parameters given in Figure 3. The advective scenarios have permeability values of 10^{-14} m^2 for (a) the entire model domain, (b) within a 10 m wide fault zone corresponding to a fault conduit, and (c) only within the country rock surrounding a 10 m low‐permeability fault zone acting as a fault barrier.

Downhole temperature profiles have typically been measured in one of two ways: 1) repeated wireline logging; and 2) observatory mode in which thermistor strings are emplaced in cased boreholes and continuously recorded.

Wireline logging offers the opportunity to measure temperature with the greatest spatial resolution, and logs repeated annually or more frequently offer one of the best opportunities to monitor the transient evolution of the signal. Repeated high-resolution measurements are needed in the target interval of the identified fault zone. To keep fluids from circulating within the borehole at the time of logging, the conduit for temperature logging needs to be isolated from the formation. The biggest disadvantage with this technique is that the temporal resolution is limited to the period between repeat ship visits. This strategy is straightforward and requires technologically less demanding instrumentation than the observatory mode of temperature monitoring.

Observatory mode consists of continuous monitoring of the temperature using a string of thermistors with data recording at the individual sensors or central recording of all the sensors at the well head (Becker and Davis, 2005). To construct observatory type instrumentation, significant lead-time is needed for cable construction. Also, experience has shown that cables are subject to leaking causing short circuits in the wiring.

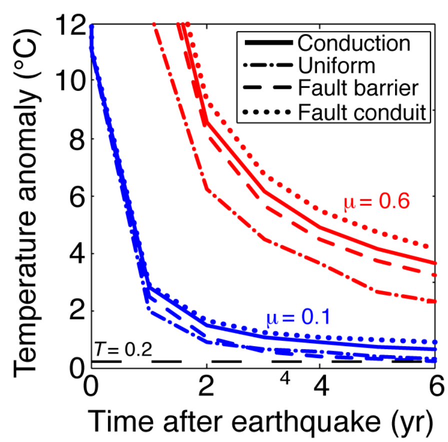

Figure 5. Thermal response to frictional heating for conductive and advective heat transfer as a function of time and for a range of coseismic friction coefficients. Temperature values have been scaled to represent the Tohoku fault zone using the fault zone parameters given in Figure 3. A coefficient of friction of 0.6 is a typical value assumed by earthquake physics studies (Byerlee, 1978) and 0.1 is a typical value from high-speed laboratory experiments (Di Toro et al., 2011). A critically tapered wedge with an internal coefficient of friction of accretionary prism material would have an intermediate value of μ=0.3-0.4. The dashed horizontal line at 0.2° C reflects a minimum target anomaly (Fulton et al., 2010).

The temperature monitoring plan will need to consider strategies to maximize spatial and temporal resolution of the temperature profiles. Operational issues, including instrument reliability, constraints on the spacing and timing of measurements, and balancing the challenges of observatory development with the expense and difficulty of repeated hole re-entry will all need to be carefully evaluated.

2. Geology of the Core

Coring across the fault zone is crucial for defining fault architecture, distribution of fault rocks, composition, mineralogy, grain size, fabric, and deformation mechanisms. All of these properties tell us about the character of the dynamic slip during the earthquake and are especially important when they can be associated with a fresh slip of tens of meters. Cores can be used for laboratory measurements of chemical kinetics, frictional, hydrologic, thermal, and physical properties. X-ray CT-scanning of whole cores has proven useful in detecting the localized slip zones and distinguishing between natural deformation and drilling-induced disturbance (Expedition 316 Scientists, 2009). Crosscutting relationship between localization of slip and surrounding damaged rocks will provide information on the recent slip zone.

The heat anomaly associated with frictional heating on faults can be detected using fluid-mobile trace elements (Li, Rb, and Cs, and Sr isotopes) sensitive to high-temperatures fluid (Ishikawa et al., 2008; Hamada et al., 2011), maturation of carbonaceous matter (Beyssac et al., 2002; O'Hara, 2004), ferrimagnetic resonance signal (Fukuchi et al., 2005; Mishima et al., 2006), mineralogical change of clay minerals such as dehydration, illitization, and chrolitization (Hirono et al., 2008; Kameda et al., 2011; Yamaguchi et al., in press). Chemical and mineralogical markers can provide a good confirmation of direct temperature measurements of heat generated on the fault.

The role of fluids during earthquake rupture is poorly understood and small-scale geologic structures provide some of the best information on possible mechanisms. Mesoscopic and microstructural analyses of slip zones will be conducted to identify co-seismic deformation mechanisms. Pseudotachylytes (solidified frictional melts) are unequivocal geological evidence of seismic slip. Very large displacement along thin slip zone with high permeability/compressibility might generate temperatures high enough for melting even at shallow depths. Characteristic geometric features such as injection structures and the detection of fragmented counterparts can be used to recognize the fluidization of fault gouge (Otsuki et al., 2003; Ujiie et al., 2007). Recent high-velocity friction experiments on the subduction zone material and the microstructural analysis of the Chi-Chi earthquake principal slip zone suggest that grain size segregation in the fault gouge is microstructural evidence for fluidization at high slip rates (Boullier et al., 2009; Ujiie and Tsutsumi, 2010).

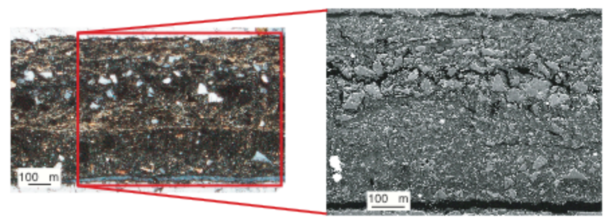

Figure 6. Microstructure of the clay-rich fault gouge after the high-velocity friction experiment, showing the grain size segregation formed by the fluidized flow at high shear rates (Ujiie and Tsutsumi, 2010). The same microstructure is observed in the principal slip zone where the earthquake rupture propagated during the 1999 Taiwan Chi-Chi earthquake (Boullier et al., 2009).

3. Laboratory Experiments on Core Material

A wide range of rock physical and mechanical properties is central to the buildup and release of stress along faults. These include rock frictional strength and constitutive behavior, elastic properties, and permeability. Rock friction controls earthquake nucleation and propagation, as well as aspects of fault healing and earthquake recurrence (e.g. Scholz, 2002). The extraordinary co-seismic displacement of the Tohoku earthquake is particularly unusual because slip may have occurred within a fault zone composed of clay-rich fault gouges, which are typically considered "velocity-strengthening" or "aseismic" materials that impede rupture propagation, at least at sub-seismic (<1mm/s) velocities (e.g. Scholz, 2002, Saffer and Marone, 2003). However, recent experiments performed at seismic slip rates suggest that clay-rich gouges may become extremely weak at slip rates greater than a few centimeters per second (Wibberley et al., 2008; Ferri et al., 2010). This weakness may result from dynamic fault lubrication that occurs by a range of physical processes (Brodsky and Kanamori, 2001; Rice and Cocco, 2007; Reches and Lockner, 2010; Di Toro et al., 2011).

Measurements of the frictional characteristics of both intact and powdered core materials over a wide range of slip velocities will be essential toward understanding the intrinsic fault properties that govern stress and stability along the fault. The use of high stress and high speed rotary-shear apparatus can reproduce the high slip rates (several meters per second), displacements (tens of meters), and normal stresses (tens of MPa) expected during rupture propagation at the accretionary wedge toe. Data on the fracture energy of fault zone materials, which can be inferred from high-speed friction studies, will help to address the question of why the Tohoku earthquake propagated through the shallow supposedly 'aseismic' zone to the seafloor. Importantly, synthetic fault rock materials produced during controlled experiments can be compared to natural microstructures observed during geological analyses of the recovered core, as described above .

Co-seismic fault strength and post-seismic strength recovery are strongly influenced by a range of other rock physical properties that can be experimentally determined using recovered core materials. For example, the porosity and permeability of fault rocks from the rupture zone mediate pore fluid pressure development both over geologic time (i.e. ambient pore pressure), and during rupture in response to frictional heating (leads to a pore pressure increase) or dilatancy (decreases pore pressure) that may lead to dynamic weakening by thermal pressurization, or to dilatancy hardening and rupture stabilization, respectively(e.g., Sibson, 1973; Rice, 2006). Fluid flow through pores and fractures following rupture is a critical aspect of fault healing (e.g. Gratier and Gueydan, 2005). To quantify permeability and storativity, a range of standard petrophysical and hydrologic tests can be conducted (Paterson and Wong, 2005). These tests include direct measurements of sample porosity, permeability, and storage properties, as well as P- and S-wave seismic wave velocities and electrical resistivity. These properties can provide important information on the topology of grain boundary and fracture networks, together with crack orientations (e.g. Carlson, 2010). Tests carried out using different sample orientations provide information on the anisotropy of permeability, an important factor that may influence the dominant directions and magnitudes of fluid flow within the rupture zone (e.g. Faulkner and Rutter, 2000). Critically, laboratory measurements on recovered core materials can be compared to measurements made by wireline logging in the boreholes, providing constraints on rock type and petrophysical properties in areas of the borehole where core recovery is poor.

4. Hydrologic Monitoring and Pore Pressure

One primary objective of rapid response drilling is to obtain direct measurements of pore fluid pressure and its variation with time within and surrounding the slip zone, in order to (a) evaluate its role as an extrinsic (state) variable in controlling stress distribution and fault slip , and (b) quantify fault zone healing. Additionally, recent observations of pore fluid pressure in sealed boreholes at several subduction zones have documented hydrologic transients related to a range of fault slip behaviors, including tremor activity and earthquake slip (e.g., Davis et al., 2011) (Figure 7). This provides a potential way to improve our understanding of the spatial and temporal distribution of strain accumulation and release.

Reliable measurements of ambient pore fluid pressure in subseafloor formations generally require long-term, continuous monitoring to provide controlled hydraulic access to the formation and allow dissipation of drilling disturbances (e.g., Becker et al., 1997; Foucher et al., 1997; Becker and Davis, 2005). Direct measurements of pore pressure within fault zones and immediate wall rock in subduction zones are scarce, though CORK installations at the Costa Rican Margin (ODP Leg 205), Barbados (ODP Leg 156), the Nankai Trough (ODP Leg 196; IODP Expedition 319), and

Cascadia (ODP Leg 146) have provided records of both ambient pore pressure and its variation over time (e.g., Wang and Davis, 1996; Foucher et al., 1997; Becker et al., 1997; Davis et al., 2011). The NanTroSEIZE study area and Cascadia have provided access to thrust splays within the accretionary prism (e.g., Screaton et al., 1995; Saffer et al., 2010).

Hydraulic access to the fault zone via screens, open hole below casing, or perforations – and to the surrounding wall rock if possible – is also essential for evaluating changes in pore fluid pressure through the seismic cycle. It is also important for identifying and quantifying any hydrologic transients that may be related to earthquakes and aftershocks, afterslip, slow slip, or secular strain accumulation in the early postseismic period during healing. All of these behaviors have been observed or inferred from pore pressure records in sealed (CORKed) boreholes at shallow depths in subduction zones. Moreover, observations of such transient processes obtained *within* fault zones themselves have been limited (Solomon et al., 2009) (Figure 8).

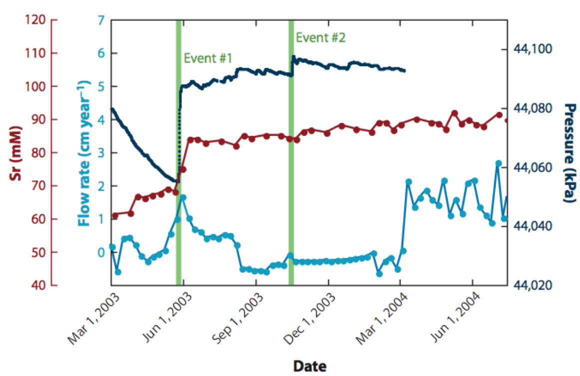

Figure 7. Records of pore fluid pressure, flow rate measured using a geochemical tracer technique, and pore fluid chemistry from the decollement zone ~600 m landward of the trench at ODP Site 1255 (after Solomon et al., 2009). Slow slip events documented by terrestrial GPS stations are temporally correlated with changes in pore fluid pressure and possibly with changes in fluid chemistry along the decollement.

Hydraulic monitoring of the formation will also allow assessment of poroelastic properties (bulk compressibility and hydraulic diffusivity) through the observed response of formation pore pressure to ocean tidal loading (Wang and Davis, 1996; Elkhoury et al., 2006). This suite of observations will allow quantification of fault zone healing, through changes in formation physical properties over time. Fault healing properties can also be studied with direct pumping measurements of fault zone transmissivity and/or permeability (e.g., Screaton et al., 1995, 1997, 2000) and repeated measurement of pore fluid chemistry (e.g., Solomon et al., 2009; Fisher et al., 2004).

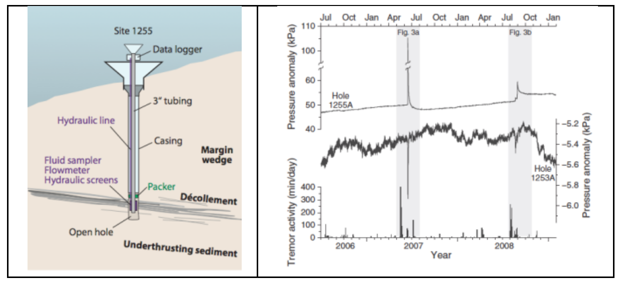

Figure 8. (**Left**) Schematic of CORK-II installation at ODP Site 1255, offshore Costa Rica (after Saffer and Tobin, 2011), and (**Right**) pressure records showing poroelastic response to tremor activity in the immediate hanging wall (Figure from Davis et al., 2011).

The scope of the hydraulic monitoring, from a few simple pressure measurements to an observatory CORK or SmartPlug deployment, needs to be evaluated in terms of its contribution to the science goals and the logistical considerations. In particular, the trade-offs of spatial versus temporal resolution will require careful study.

5. Fluid Chemistry

Observations of pore fluid chemistry, in conjunction with pore fluid pressure, is essential for the characterization of fault hydrogeology and healing, and both pore fluid and sediment chemical anomalies may be used as powerful signatures of fluid-rock reaction associated with rapid slip. Pore fluid chemistry will provide important information on fluid source and fluid flow within and surrounding the fault zones.

Diagenetic reactions such as transitions of smectite–illite and opal A–opal CT–quartz, carbonate precipitation and degradation of organic matter all affect pore fluid chemistry (Kastner *et al.*, 1991). Hydrothermal experiments using sediments and pore fluids reveal varying degrees of mobilization of major and minor elements such as Na, K, Ca, Cl, Li, Rb, Cs, B, Sr and Ba at diagenetic or higher temperatures (You *et al*., 1996; James *et al*., 2003). The diagenetic effects can be evaluated based on the observation of major and minor elements and O, C, Li, B and Sr isotopes. It is generally not easy to identify the source and the transportation path of fluids in the fault zones largely due to the lack of pore fluid data at the depth. However, temperature-sensitive geochemical indicators such as Li, B, O and Sr isotopes, methane and higher hydrocarbons can all be useful for detecting signals derived from high-temperature solid-fluid interactions as indicators of either fluid flow from depth or reaction at elevated temperatures caused by rapid slip (e.g., Saffer and Tobin, 2011). These data provide important constraints on the physical hydrogeology, and in combination with fluid flow models can be used to estimate fluid flow rates and fault zone permeability (e.g., Bekins et al., 1995; Saffer and Screaton, 2003).

The interpretation of pore fluid chemical anomalies can be especially fruitful when combined with the analytical results of solid phases because complementary mineralogical and chemical signals for the solid-fluid interactions are known to be recorded in fault-zone rocks in some cases (Ishikawa *et al.*, 2008; Yamaguchi *et al*., 2011). Ultimately, repeated sampling of pore fluids will allow evaluation of potential fluid-rock interactions related to fault healing, and identification of links between fault slip behavior and hydrologic and geochemical transients (e.g., Solomon et al., 2009).

6. Logging and Direct Stress Measurements

Logging-while-drilling (LWD) is expected to acquire important data in the first stages of drilling before coring operations begin. This will be an important step in drilling the unstable accretionary wedge and provide the first information on the location of the fault zone. LWD operations have been successful across plate boundary faults during expeditions at convergent margins such as Barbados (ODP Leg 156 and 171A), Costa Rica (ODP Legs 170), and Nankai (ODP Leg 196 and IODP Expedition 314). LWD-derived resistivity is the most effective way to identify the depth and width of a frontal mega-thrust fault zone, and will be used to design strategies for coring and wireline logging. Resistivity images with 360° coverage of borehole are also essential for identifying geometry of faults and reconstructing stress orientation by borehole breakouts. Other key LWD measurements could characterize fundamentally important fault physical properties such as density, porosity, sonic velocity, magnetic resonance, formation pressure and fluid chemistry.

Although wireline logging may be challenging at deep water sites with unstable borehole environments, wireline temperature logging may be essential for detecting heat signals from active fault zones, as discussed in Section III.1.

The temperature observations discussed above measure the absolute value of stress co-seismically, however, separate techniques are required to constrain the ambient stress magnitude and orientation. Determining the stress state during rapid response fault-zone drilling, including the orientations – and possibly the magnitudes - of in situ stresses, will provide key information about stress conditions acting on the fault zone and in the wall rock following such a large earthquake. Comparison of these data with similar measurements from other subduction zone systems that are much later in the interseismic period (e.g., McNeill et al., 2004; Chang et al., 2010) may yield insight into temporal variations in stress related to earthquake rupture. Also, repeated measurements may be able to observe time-dependent changes in the stress field that are associated with fault healing.

For example, in the vicinity of large fault slip during the Tohoku earthquake, many normal-faulting aftershocks have been observed, suggesting dynamic overshoot as a possible cause of large shallow slip near the trench (Ide et al., 2011). If this is the case, the stress state in the upper plate may have changed from trench-normal compression to extension following the earthquake. A combination of borehole logging analyses of wellbore failures (breakouts, or stress-induced borehole compressive failures; and drilling induced tensile fractures, or DITF) (e.g., Chang et al., 2010) and core-based ASR (anelastic strain recovery) stress estimation would speak directly to the dynamic overshoot hypothesis. An example of breakout analyses carried out in the Taiwan Chelungpu-fault Drilling Project (TCDP) documented a clear stress anomaly in the vicinity of the ruptured fault (Lin et al., 2007). Similar studies along the NanTroSEIZE transect have provided valuable information about both stress orientation and magnitude. More recently, application of the ASR 3D method to the NanTroSEIZE area revealed extension (normal fault stress regime) across the southwest Japan subduction zone (Byrne et al., 2009).

7. Aftershock Monitoring

The decaying aftershock sequences that follow large earthquakes are the most easily observed evidence of the rapidly changing stress and strength of the fault-zone in the early post-seismic period. The decay of the Tohoku earthquake aftershock sequence is expected to be observable for years, even decades, before the fault fades back to its typical background rate. Fortunately, in this case there were considerable efforts to deploy networks of ocean bottom seismometers (OBSs) both before (Hino et al., 2000; Shinohara et al., 2005), and immediately after the earthquake (Section V.1). Unfortunately, current OBSs are limited to water depths shallower than about 6500 m, and hence have not been deployed in the most likely drilling area. Establishing a seismological observation network in support of the rapid drilling project would improve our understanding of whether the updip portion of the fault, which was devoid of earthquakes before the mainshock (Hino et al., 2000; Shinohara et al., 2005), was nevertheless seismogenic during the early post-seismic time period. Moreover, having seismometers deployed close to the borehole will allow us to monitor the healing of the fault-zone in the surrounding area, and hence to better interpret the significance of any temporal changes detected within the boreholes. Several complementary seismological techniques including repeated active source surveys (Li et al., 1998), analysis of fault-zone guided waves from aftershocks, analysis of the properties of scatters in the fault-zone (Niu et al., 2003, 2008), and ambient noise tomography (Brenguier 2008) have detected the coseismic drop and subsequent recovery of shear-wave velocities in continental fault-zones. Moreover, the ambient noise and aftershock coda techniques have recently been shown to work well at detecting fault-zone velocity changes with OBS data (Gouedard et al, 2010).

The ideal observatory would have borehole seismometers located within the fault-zone as well as a distributed network of OBSs, Absolute Pressure Gauges, and tiltmeters to constrain the earthquake locations and the aseismic deformation field. Ideally the ocean bottom seismometers would be buried by an ROV. This is particularly important for fault-zone healing studies as coupling resonances on the horizontal components of OBSs can be time-dependent and cause temporal changes in shear-wave coda that are not related to earth structure. Borehole instruments would be ideal for detecting very small earthquakes and hence potentially for tidal triggering and earthquake interaction studies. A distributed network of ~10 OBSs within 5 km of the drill hole would allow for precise location constraints and focal mechanism estimation. Deploying a string of seismometers in the hole would allow for very detailed determinations of the seismic velocity structure that are necessary for high-precision earthquake locations. In order to observe fault-zone healing, the sensors would ideally be deployed as soon as possible and operated for a number of years.

IV. Prioritization and Implementation

1. Priorities

The potentially most exciting results from this project are estimates of dynamic friction and identification of physical characteristics for a fault that slipped 50 m. Of the many techniques described in Section III, time-dependent temperature measurements and analyses of core from the fault zone, become the top priorities. The temperature measurements following 50 m of slip provide an opportunity to constrain a fundamental feature of earthquakes that cannot be observed any other way. The core measurements are required in order to interpret the temperature measurements and contribute complementary information about the slip processes in their own right.

Other observations will greatly facilitate the interpretation of the key data sets. Logging has been used with great success to identify active fault zones in other drilling projects (See Appendix 3) and repeat logs can provide additional information about healing processes. Hydrologic monitoring is useful to differentiate advective and diffusive temperature signals. Direct stress measurements will provide a comparison between the co-seismic and interseismic behavior. Seismic velocity and aftershocks as measured with ocean bottom instruments also provide information on the evolution of the fault properties and earthquake sequence and can be collected with relatively little extra effort.

To address these priorities, it is critical that the drilling reach the fault surface which had large slip during the earthquake. The site selection Section IV.3 considers three types of target faults, megathrust, back-stop fault, and some other fault, although the best available data (large horizontal sea floor deformations, repeated seismic profiles) indicate that the large slip occurred mainly on the shallowly dipping megathrust (top of the oceanic crust). This is, therefore, the provisional target fault. Additional seismic data are being collected this summer by JAMSTEC and these should provide better information for determining where the main slip occurred. Depending on the new data, the target fault may change. If the target is one of the faults other than the shallowly dipping megathrust, the water depth will be shallower and technical challenges somewhat less.

For the temperature monitoring, a cased hole is necessary so that the changing temperature profile can be measured. Temperature measurements taken at the time of drilling will be valuable for characterizing the thermal effects of drilling. Measuring the temperature signal due to frictional heating must begin 2 months after drilling and be repeated at least 2-3 times to meet the science goals. This will be done with repeat visits to the site or continuous monitoring with a high spatial resolution string of thermistors. Wireline logging in the uncased hole may be done soon after drilling, but high priority should be placed on stabilizing the borehole with casing as soon as possible.

Experience at NantroSEIZE has shown that core recovery in weak fault zone regions is difficult. One strategy for maximizing chances of retrieving samples from the fault zone is to first collect LWD data to identify the fault. Then, a nearby second hole involving careful rotary coring in the depth range of the fault zone would maximize chances of obtaining core from the fault zone.

Another rare opportunity for this project is the ability to monitor the post-seismic deformation of the very large slip region. Deformation and seismic monitoring in the borehole and immediate surrounding area would require extensive observatory instrumentation. This may be beyond the scope of a rapid response effort, but the present borehole design should be planned to accommodate such instrumentation in the future. These observations would complement the extensive ocean bottom monitoring that is being undertaken by Japanese groups (Section V.1).

Figure 10. Photographs of slab core samples from shallow portions of the megasplay fault and the plate boundary décollement zone in the Nankai accretionary prism off Kumano. Red arrows indicate dark shear zones developed in finely brecciated clay-rich sediments, showing evidence for repeated localization of displacement to ~2-10-mm-thick shear zones within broader zones undergoing distributed fracture and brecciation. Identification of the fault zone unambiguously requires core recovery. Note that possible fingerprints related to frictional heating have been identified from these slip zones (Sakaguchi et al., 2011; Yamaguchi et al., 2011).

2. Timing Requirements

The need to drill rapidly is driven primarily by the transient temperature anomaly. As shown in Figure 3, for a coefficient of friction comparable to many of the high-speed friction experiments (μ=0.1), a resolvable temperature anomaly will persist for 6 years after the earthquake. If the coefficient of friction is at the lower limit of the extent laboratory experiments (μ~0.05) (Di Toro et al., 2011), then the temperature anomaly drops proportionally and the time to capture a resolvable anomaly drops by a factor of 4. Therefore, a working bound on the time to measurement is that a complete experiment should be measuring an anomaly within 1.5 years of the earthquake (Figure 9). Note that the verification of a coefficient of friction as low as either of these values in a natural setting would constitute a major discovery.

In order to observe a meaningful signal, the hole needs to be completed and equilibrated with the surrounding rock at the time of measurement. If the drilling fluid acts as an isothermal line source during the drilling period, the recovery time can be modeled as

$$\Delta T/ \Delta T_0 = \log(1 + t_1/t_2)/(\log(4 \kappa t /r_w^2) -0.577) \quad (2)$$

where ΔT_0 is the difference between drilling mud temperature and the original temperature at a particular depth, κ is the thermal diffusivity, t is the time since the beginning of drilling, t_1 is the duration of drilling, t_2 is the time since the end of drilling and r_w is the wellbore radius. (Bullard, 1947, Eq. I).

The anomaly at a particular depth depends on the time of drilling t_1 to that depth. Therefore, to minimize the perturbation in the region of interest, drilling should be ceased as soon as possible after crossing the fault. In other words, time 0 is the time at which drilling reached that depth. For a 3-day perturbation at 1000 m depth with typical physical properties and temperature gradient for the region (Hyndman et al., 2005) and assuming seawater bottom temperature for the drilling fluid, the drilling perturbation becomes unobservable (<0.2^o) after ~2 months.

As discussed in Section III.1, the temperature profile across the Tohoku fault is expected to reveal both advective and diffusive temperature anomalies. The time decay of a temperature anomaly is a good way to distinguish between these heat transport processes, particularly if direct hydrological information is not available. In order to capture the time decay of the temperature field, 2-3 repeat measurements are required if only logs are used (as opposed to continuous measurement techniques).

These timing constraints will require adjustment once a site is selected and the actual target depth is known.

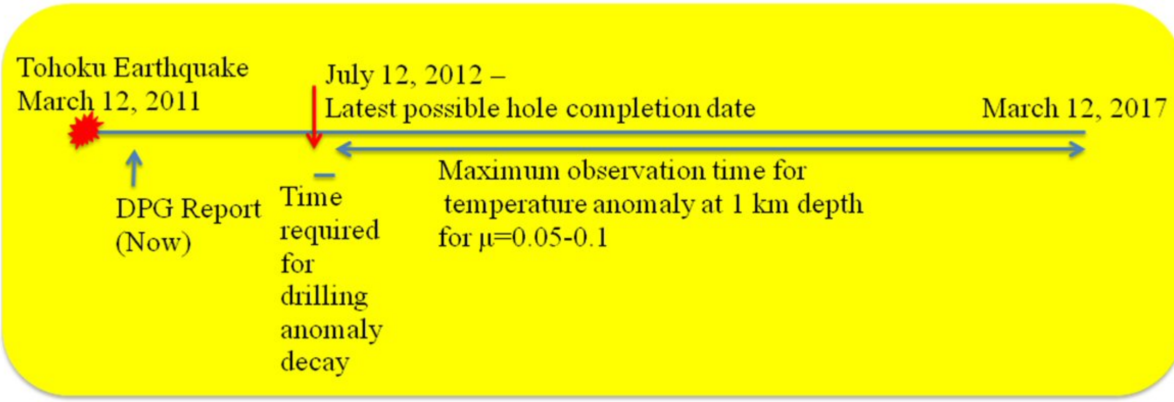

Figure 9. Timeline for measurements satisfying the highest priority scientific objectives

3. Criteria for Site Selection

This report does not have recommendations for specific borehole sites, since detailed seismic and bathymetric data are being acquired during summer 2011, that will be needed to make these decisions. However, the necessary requirements of site(s) capable of addressing the scientific questions, along with prerequisite technical capabilities can be discussed.

A primary goal of a possible Tohoku rapid response drilling project would be to penetrate the co-seismic slip zone. In order to archive this goal, appropriate sites must be selected using the following criteria.

1) Potential sites must have a target fault with large co-seismic slip. Slip can be estimated by seismic, geodetic, tsunami and aftershock data. Also, the rapid response geophysical surveys showed that differential bathymetry before and after the earthquake provides an important constraint with which to define the co-seismic slip zone (Figure 11).
2) Potential sites must have a well-imaged target fault at drillable depth. To define drillable sites, 2D Multi-Channel Seismic (MCS) data at close line spacings are necessary. In addition, a high-resolution seismic survey grid must be acquired, to image the fault targets and other details of the local geologic structure needed for evaluation of final site selection and borehole planning.
3) Potential sites must have good site characterization data. High-resolution side-scan sonar imaging, chemical analysis of fluid sample may help to identify potential fault scarps.

Seismic data which can be used for the site selection have been acquired by JAMSTEC since 1977. All seismic data are available through the JAMSTEC site (http://www.jamstec.go.jp/jamstec-e/IFREE_center/index-e.html). A characteristic structure imaged in the northern part of the Japan trench is the wedge-shaped deformed (low velocity) zone at the toe of the trench (Tsuru et al., 2002). This wedge structure is commonly observed north of 38^{o} N, where large deformation may have occur during the 2011 Tohoku earthquake and 1986 Sanriku earthquake. Two rapid response geophysical cruises were conducted soon after the earthquake, partly covering the expected large-slip zone around 38 ^{o} N. Additional geophysical cruises, including a high-resolution reflection seismic survey covering the entire area of the large-slip zone, are planned for the summer of 2011.

Based on slip distributions inferred from seismic, tsunami and geodetic data, as well as the differential bathymetry, co-seismic slip of this earthquake likely reaches the trench axis. However, existing reflection seismic and bathymetry data do not image a main co-seismic fault of this earthquake. Currently, one (or a combination) of the following interfaces is considered to be a possible co-seismic fault; 1) Top of the oceanic crust, 2) Back stop interface, including reverse faults imaged in the wedge-shaped low velocity zone, 3) Normal fault cutting an unconformity corresponding to the top of Cretaceous layer (Figure 12). Here, we evaluate each interface as a possible site.

Top of the oceanic crust: This interface is the most likely co-seismic slip interface based on the differential bathymetry data. However, a frontal thrust continuing from this interface to the trench is not observed in existing seismic data. A 1000 m borehole would be necessary to reach this interface at a water depth of 7000 m.

Back-stop interface: Deformation of the wedge-shaped low-velocity zone has been proposed as a possible cause of large tsunamis (Tanioka and Seno, 2001). A back-stop interface, as well as reverse faults in the wedge may have slipped associated with deformation of the wedge. Since the back-stop interface is traced to near the seafloor, this interface could be reached by a relatively shallow hole in water depth of around 6000 m. However, displacement along the back stop interface from this earthquake has not been recognized in the seismic and bathymetry data.

Normal fault cutting Cretaceous unconformity: A model demonstrating an extrusive structure of a crustal block between this fault and the trench has been proposed by a recent study (Tsuji et al., in press). If this model is accepted, the normal fault system may have moved co-seismically. However, additional geophysical data supporting this model have not been obtained. This normal fault structure is clear along one existing profile, but it is not recognized on existing nearby profiles. Relatively shallow drilling could reach this interface in water depth of about 4000 m.

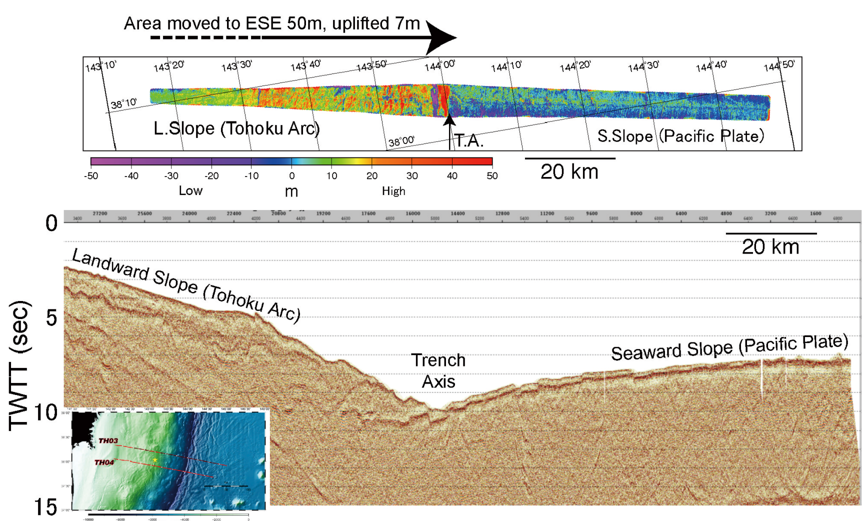

Figure 11. (bottom) Seismic reflection image obtained by a rapid response geophysical cruise by JAMSTEC. (top) differential bathymetry between seabeam data acquired in 1999 and after the earthquake. Large differences of the bathymetry are observed immediately landward of the trench. Correlation between the bathymetry between before and after the earthquake indicates that the entire overriding block extending to the trench axis moved 50 m ESE and 7 m upward.

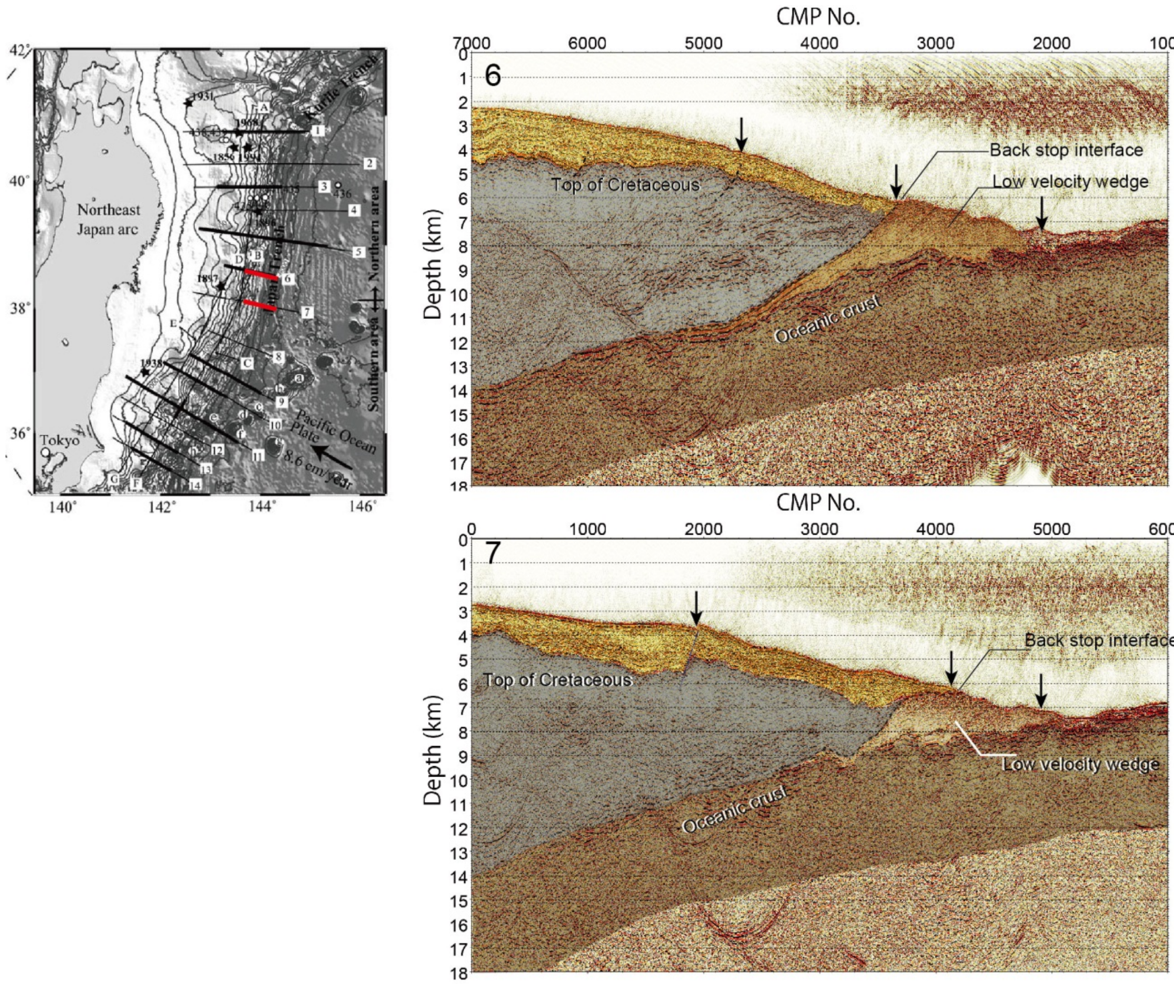

Figure 12. Prestack depth migration images. Profile 6 (Top right). Profile 7 (Bottom right). Interpretations based on Tsuru et al., (2002).

4. Evaluation of Capabilities

The objectives of drilling across the fault slip zone at 600 – 1000 m below the sea floor and establishing a borehole monitoring system present a number of technical challenges. For the current target of drilling the top of the ocean crust, we identified the following areas of potential concern: (1) water depths near or somewhat in excess of 7000 m , (2) potentially unstable formation conditions within and above the main target zone, including potential for strongly elevated pore fluid pressure, and (3) requirement for hole completion by 12 July 2011 allows only short lead time for preparation of downhole equipment and observatory elements including casing, seals, sensors, umbilical cables, and data loggers.

A drilling target in 7000 m water depth leads directly to the most serious operational and technical challenges. Based on the MCS data available at this time, the objective of crossing a large slip zone at the top of the ocean crust about 1000 meters below sea floor, appears to require a site location with about 6900 to 7200 m of water depth. This is a preliminary assessment based on two seismic lines, and more data will be available soon, but the regional bathymetry suggests that any site along strike in the large slip patch is likely to be at a similar water depth.

Ocean drilling has only been done at similar depth at one site, DSDP Hole 461A, drilled in 7034 m below sea level by *GLOMAR Challenger* in 1978 (and drilled to only 15.5 mbsf). The *JOIDES Resolution* record is 5980 m, and *Chikyu's* deepest spud-in to date was at 4080 m.

Water depth alone is not intrinsically a challenge to rotary drilling, but it creates potential complications due to drill pipe strength limits and for necessary ancillary equipment. Of particular concern is the ability to carry out borehole re-entry operations that are likely required for casing the hole(s), monitoring in situ conditions, or repeat temperature logging. Re-entry requires video camera monitoring of the well head or re-entry cone and drill string, usually carried out by ROV or cable-deployed underwater camera (UWTV or VIT camera). A non-reentry observatory system such as SCIMPI has not yet been tested in deep water.

Casing of the hole would be required because of both the reentry requirements and likely borehole instability. ODP and IODP experience suggests that simply reaching the depth objectives, apart from any monitoring effort, might require installation of at least surface casing (see, for example, strategies employed at Sites 808 and 1174 in the Nankai Trough). Therefore borehole re-entry capability might be necessary even for coring and logging. The deepest cased boreholes to date are 1201E, 810C and 765D penetrating to 527, 481 and 937 mbsf at 5710 m, 5674 m and 5712 m water depth, respectively.

We considered the capabilities of the vessels *Chikyu* and *JOIDES Resolution* for this project.

Drill Pipe: Chikyu operators have about 10,000 meters of drill pipe available. However, for a ~8000 m deployment, CDEX has indicated it will need to undertake a dynamic numerical simulation of drill pipe performance under site-specific metocean conditions (currents, wind, and waves). They state that torque limits on a long drill string might negatively impact core quality. CDEX would use their "dual elevator system" to handle drill pipe connections at the rotary table, for the first time. This system has been tested but not put into service. It is intended to handle heavy pipe loads without using slips, which impart a large hoop stress on the pipe. This system nearly doubles the pipe trip time.

Wireline: Wireline logging is done using a wireline winch and cable that has 7000 m wireline capacity. A longer cable would likely be needed; CDEX estimates that this can potentially be upgraded with 6 months of lead time.

Re-entry and casing operations: Underwater imaging is required for hole re-entry, which would have to be done for casing and observatory establishment. Imaging is normally done on *Chikyu* with the on-board ROV system (provided by contractor Oceaneering, Inc.) which has a depth limit of 3000 m. CDEX has an underwater television camera system (UWTV) that is rated to 7000 m, but it has never been used by CDEX for re-entry operations. CDEX is presently investigating whether use of this UWTV would be feasible and could be used deeper than 7000 m. Installing casing and re-entry procedures may not be possible without an ROV.

Drill Pipe: The USIO operator made an initial assessment of the suitability of their drill pipe for the 7000 m water depth plus sub-bottom depth for this project. They concluded that the *Resolution* "would need all new and high-strength drill pipe to consider attempting the DPG site," and acquiring such pipe has a typical lead time of 18-24 months (all according to email communication from M. Malone of 24 May 2011). For rapid response requirements, rental pipe might be a possibility (albeit expensive), but it is unclear if any suitable pipe would be available, again according to M. Malone.

Re-entry and casing operations: The *Resolution* normally performs all borehole re-entry with an underwater camera system (called VIT), which is rated for deployment to ~6800 meters, but could perhaps be extended a little beyond 7000 m. The VIT cable was 6860 m and has been shortened , and the winch for VIT deployment is challenged beyond 5000 m water depth. Both of these would need to be replaced with a lead time approaching one year.

In summary, for this scenario, the *Resolution* would require a large investment in new equipment with uncertain feasibility. It seems possible, but not certain, that *Chikyu* could drill, core, and run LWD operations to water depth of 7200 m plus 1000 mbsf. Successful reentry in deep water will be a difficult challenge for any ship. Staff expertise on deepwater reentries from the *Resolution* may be helpful onboard *Chikyu* and can help contribute to the integration across platforms for the program.

5. Integrated Plan

A viable rapid response drilling effort will require balancing the prioritized scientific objectives with the operational reality of challenges posed by water depth in excess of 6.5 km, hole re-entry, drilling and core recovery in brecciated and deformed rock and sediment, and the time required for design and fabrication of borehole instrumentation. The integrated strategy outlined here addresses the highest priority and most time-sensitive objectives first, while also providing flexibility for future use of the borehole(s) to address other key science objectives as the required platform time and technology become available. The integrated strategy described below provides a "road map" toward implementation of rapid response drilling.

Initial operations would consist of drilling an LWD hole to at most 1.2 km depth, across the plate boundary décollement in a zone of documented high slip, as discussed in Section IV.3. LWD measurements should include density-porosity measurement, APRS (annular pressure), resistivity and RAB imaging, gamma ray, and sonic velocity. The LWD data will be essential in providing continuous records of rock physical properties downhole, as well as imaging of the hole to identify structural features and document wellbore failures to be used as stress indicators (e.g., Lin et al., 2010; Chang et al., 2010). LWD data will also be critical toward identifying the plate boundary fault and highest-priority targets for coring, downhole measurements, and monitoring. Following LWD operations, a second hole located ~50 m away will be drilled for coring. If possible, the hole will be cored continuously to obtain samples for shipboard measurements (composition, physical properties, pore fluid chemistry, and description of sedimentology and structures) and post-expedition laboratory studies. If required to complete drilling in either the LWD or coring borehole, surface casing would be installed.

After coring, at a minimum, the cored borehole must be cased to TD with screened casing joints spanning the décollement to provide access for repeated logging (temperature and/or casing deformation) and continuous monitoring studies. If this is not possible due to hole conditions, casing through the hanging wall to the décollement would remain a top priority. After casing, temperature and caliper logs would be run. The former would provide baseline information about the immediate post-drilling thermal profile, and be used to benchmark the changes in temperature over time needed to quantify the potential signal of frictional heating and to distinguish it from the effects of fluid flow. The latter would provide a benchmark for future casing caliper surveys to document casing deformation and slip or afterslip (e.g., Zoback et al., 2011).

If possible, the hole should be instrumented with a simple suite of removable temperature and pressure monitoring instruments to achieve the highest-priority and most time-sensitive thermal and hydrologic measurements.

An alternative approach to achieve the time-sensitive temperature measurements, but which would not allow hydrologic monitoring or measurements would be to conduct repeat downhole temperature caliper logs by re-occupying the site. It is unclear whether this approach would be feasible, because it would require multiple repeated visits within a ~1-2 year time window using a drillship – or possibly other vessel if wireline deployment without drillpipe is possible - to re-enter the hole with a thermistor and/or caliper. Therefore, although this would be an acceptable strategy for achieving some of the key science objectives while also maintaining access to the borehole for future measurement or monitoring, a more realistic strategy will likely be to install simple long-term monitoring system(s). At a later date, additional sensors should be installed in the casing to monitor tilt, strain (e.g., Araki et al., 2011), and to allow continuous geochemical sampling (e.g., Solomon et al., 2009).

Additional operations of high scientific value that should be considered as contingency or primary operations if time permits include:

1) Drilling of a companion LWD hole that penetrates the décollement outside of the rupture zone, in order to provide a baseline for interpretation of structures and physical properties as consequences of earthquake slip.

2) Drilling of shallow (300-500 m) hanging wall

sites upslope of the trench to provide information about physical and rock mechanical properties of the immediate hanging wall.

3) Drilling of a third hole adjacent to the instrumented site for cross-hole hydrologic experimentation.

5. Risks for the Drilling Project

There exist a number of obvious logistical, scientific, and safety risks that could prevent the objectives of a rapid response drilling effort being met. These risks have yet to be fully reviewed, but can be broadly summarized as follows:

Logistical risks The technical challenges for this drilling are discussed in the previous section.

Scientific risks To obtain maximum scientific benefit from a rapid response drilling program, it is important to drill into the fault that slipped and to do so before the signals of interest have waned. As with all drilling operations, there are risks that borehole instability or other factors may prevent the target being reached or preclude core recovery, wireline logging, or borehole instrumentation. These risks are exacerbated in the Tohoku case by the water depth and the possibility of high overpressures (cf. Saffer and Tobin, 2011).

Safety risks Seismicity induced by drilling operations is naturally of concern whenever active faults are being investigated, and even more so when the fault of interest is demonstrably capable of producing massive earthquakes. Preliminary consideration of the risk that drilling into the Tohoku subduction thrust could trigger a moderate or large earthquake suggests that this risk is low for several reasons: (a) the M_w 9.0 earthquake appears to have involved a near-complete stress drop and substantial slip on the shallow portion of the fault (Ide et al., 2011; Simon et al., 2011), suggesting that little if any shear stress currently acts on the fault; (b) the shallow portion of the subduction thrust is considered to be velocity-strengthening, meaning that slip is unlikely to nucleate in the vicinity of a borehole; and (c) riser-less drilling necessarily involves low (hydrostatic) mud pressures that are less likely to induce fault failure compared to the overpressures used in riser drilling.

V. Related Projects

The Tohoku earthquake occurred in a region with a vast amount of baseline data and the infrastructure to quickly respond. These complementary datasets make the region a particularly interesting place to drill. The repeat seismic data shown in Figure 11, the ocean bottom seismometer deployment prior to and immediately after the earthquake, GPS seafloor observations, baseline heat flow measurements and the extensive onland seismic and geodetic instrumentation combine to make the earthquake one of the best-observed natural events anywhere. Any future drilling project should make good use of these complementary datasets as summarized below.

In addition, fault zone drilling has been a rapidly expanding field in the last 20 years as demonstrated below. The lessons learned from previous projects will be critical in ensuring the success of the Tohoku drilling.

1. Current Tohoku Ocean Floor Projects

A borehole through the fault zone would be part of a larger effort of ocean floor observations associated with this earthquake. Seismic, geodetic, and pressure monitoring are important for estimating the location and amount of slip during the mainshock and post-seismic deformation. Post-seismic observations of deformation and aftershocks are needed for the understanding the fault healing and aftershock processes.

University and JAMSTEC groups have maintained an offshore seismic network of repeated OBS deployments since 2003. The OBS observation provided detailed hypocenter distributions (Hino et al., 2006; 2007), 3D seismic velocity structure (Yamamoto et al., 2006; 2008), as well as inferring the stress field in the area (Suzuki et al., 2010). At the time of the Tohoku earthquake, 28 seismic instruments were operating. In response to the occurrence of the Tohoku earthquake, Japanese universities, Japan Meteorological Office and JAMSTEC deployed more than 80 additional OBS's to form a dense aftershock observing network covering the entire rupture area (Fig. 13; Shinohara et al., 2011).

In the immediate vicinity, seven seafloor benchmarks for geodetic survey using GPS-acoustic combination (GPS/A) measurements had been installed previous to the earthquake. The time series of the seafloor horizontal displacement obtained by the GPS/A campaigns have shown strong interplate coupling in the area (Sato et al., 2011a). The GPS/A measurements conducted soon after the occurrence of the Tohoku earthquake detected large to very large (5 to 31 m) coseismic displacements at the seven stations (Fig. 2; Sato et al., 2011b; Kido et al., 2011).

Ocean-bottom pressure observations have been made since 2008 by Tohoku University. The continuous pressure records revealed occurrence of a small slow-slip event along the plate boundary near the trench axis (Ito et al., 2010) and steady subsidence at a rate of 1 cm/a associated with the interplate coupling (Hino et al., 2011). At the time of the Tohoku earthquake, 15 pressure sensors were in place (Figure 13).

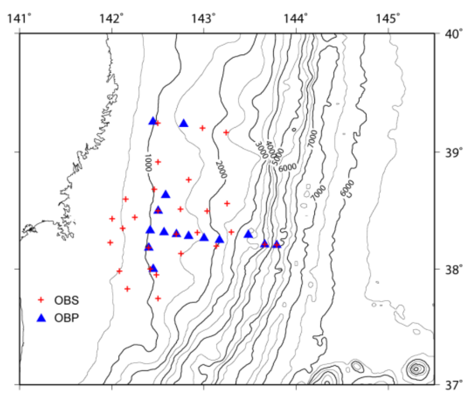

Figure 13. Seafloor seismic and geodetic stations in operation during the Tohoku earthquake on Mar. 11 2011. Crosses are ocean bottom seismographs (OBSs) and triangles are ocean bottom pressure gauges (OBPs). Three OBSs and two OBPs near 39N are stations belong to the cabled seafloor observatory.

Previous ocean drilling in this area took place during Deep Sea Drilling Project Legs 56, 57, and 87, which transected the Japan Trench at ~39.8°N-40.7°N (Scientific Party, 1980; Figure 14). These legs established the concept of tectonic erosion along a subduction zone. The Neogene subsidence history of the forearc was documented, and numerous ash records were obtained that span the past 9 m.y. During Ocean Drilling Program Leg 186, coring and logging data were obtained from Sites 1150 (39°11´N, 143°20´E) and 1151 (38°45´N, 143°20´E) located on the forearc basin (Figure 14). The drilling results provide additional observations to further our understanding of the sedimentation and tectonics of this area. Two borehole geophysical observatories (strain, tilt, and seismic sensors) were installed ~1100 meters below seafloor at Sites 1150 and 1151 (Sacks et al., 2000). Site 1150 is within an active zone in terms of interplate seismicity including M-7 class earthquakes, whereas Site 1151 is within an area with almost no seismicity. The systems started collecting data in September 1999 and have been serviced by a remotely operated vehicle (ROV) to recover continuous high sampling rate and wide dynamic range data. Unfortunately, these downhole observatories were not operating at the time of the Tohoku earthquake, it is expected that they will be revived with future ROV visits.

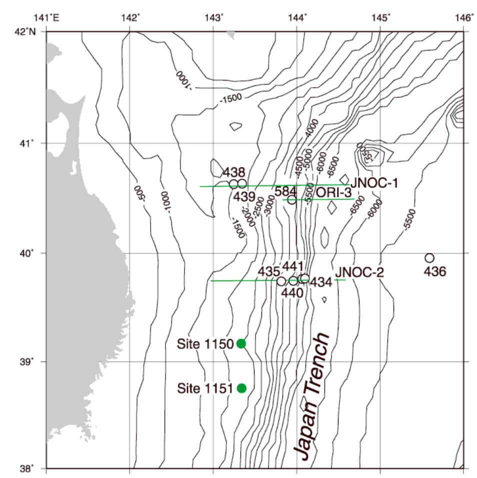

Figure 14. Map of the Japan Trench area off northeast Japan showing ODP Leg 186 Sites 1150 and 1151; previous drilling sites from DSDP Legs 56, 57, and 87; and seismic lines (Sacks et al., 2000).

Extensive heat flow measurements already exist in the region, thus providing a baseline and interpretative framework for future temperature measurements (Figure 15).

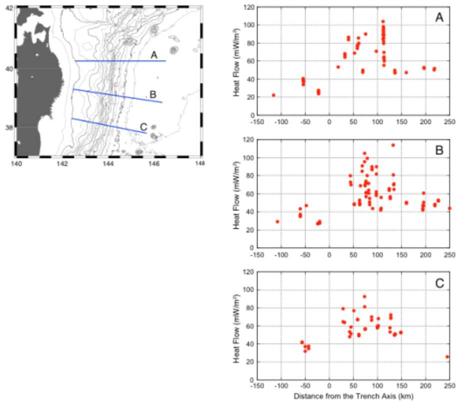

Figure 15. Heat flow profiles along three lines (A, B, and C) across the Japan Trench (Yamano et al., 2008, 2010). Data within 35 km of each line are plotted against the distance from the trench axis.

2. Recent Fault Zone Drilling Projects

Since the mid-1990s, a number of active fault drilling projects have been conducted (Brodsky et al., 2009). Some of these projects have been prompted by large earthquakes, whereas others are not linked to a specific earthquake but rather address long-term (or pre-earthquake) faulting conditions. Brief summaries of seven recent or ongoing projects are described in Appendix 3.

The first investigation to drill directly into an active fault zone was at the Nojima project 14 months following the 1995 Kobe, Japan earthquake (M_w6.9). Work on the core and pioneered the detailed geological study of fault zone fabrics and structures. Some of the first in situ measurements of fault zone properties, such as permeability were also done here. A temperature anomaly from the Kobe earthquake was not observed, but only low resolution measurements were done while logging. The first meaningful temperature measurements following an earthquake, were carried out at the Taiwan Chelungpu Drilling Project (TCDP), following the 1999 Chi-Chi earthquake (M_w7.6). Very small heat anomalies were observed 1.5 years (Tanaka et al. 2006) and 6 years (Kano et al., 2006) following the earthquake, indicating a surprisingly low coefficient of friction of about 0.1. These observations have motivated subsequent temperature measurements at other locations following large earthquakes, such as the Wenchuan Earthquake Fault Scientific Drilling program (WFSD) following the 2008 Wenchuan, China (M_w7.9) earthquake and the current effort to drill the 2011 Tohoku earthquake.

A temperature measurement to estimate the frictional level for a subduction zone earthquake has never been done. Also, all the previous temperature measurements were for fault slips of less than 10 m. The opportunity to sample and measure the heat from a 50 m slip is an exciting prospect. In addition, the seismological character of the rupture in the toe of a subduction megathrust is likely very different from the earthquakes occurring on onshore faults, so we expect to see different types of physical characteristics for the fault zone.

The expected science results from Tohoku are complementary to the current NantroSEIZE and CRISP complex drilling projects (CDPs). The Tohoku project is being drilled immediately following a great earthquake, while the drilling in Nankai and offshore Costa Rica is prior to an impending great earthquake. Time dependent differences in the two regions may reflect different stages of the earthquake cycle. Additionally, information about the large slip that caused the destructive tsunami in Tohoku, may contribute to understanding the expected large tsunami from the expected Nankai earthquake. Much of the experience gained in drilling the Nankai subduction zone during the NantroSEIZE project could be put to use in a possible Tohoku drilling project.

VI. Recommendation

This report summarizes fundamental unanswered seismological questions about the physics of large earthquakes, along with a wide range of borehole observations that could be used to address them. Based on the scientific results that are likely from a rapid borehole into the region of the Tohoku earthquake, the DPG recommended that,

1. IODP *should* carry out a Rapid Response Drilling Project for the Tohoku earthquake if,

    a. A fault with significant slip can be reached, there is a reasonable chance to obtain a core sample of the fault zone, and LWD can collect physical data (such as temperature, seismic velocity, density, resistivity, density, magnetic resonance, formation pressure) in the vicinity of the fault zone; and

    b. Time-dependent measurements (such as temperature, permeability, borehole stress, geochemical analyses) can be made soon after drilling and several months later.

2. There were mixed opinions for a Rapid Response Drilling Project if,

    a. A fault with significant slip can be reached, there is a reasonable chance to sample the fault, and LWD can collect physical data in the vicinity of the fault zone; and

    b. Time-dependent measurements cannot be made .

3. IODP *should not* carry out a Rapid Response Drilling Project for the Tohoku earthquake, if a slipped fault cannot be reached. The extreme water depth is the most obvious hurdle to drilling.

There is valuable information that can be obtained by retrieving a sample of the fault that had large slip during the earthquake, but by itself the case is not as strong that this must be done quickly after the earthquake, if the time-dependent parameters cannot also be measured. There are many other important scientific issues that should be addressed by drilling boreholes into the fault region. Measurements which are not time critical should be considered through regular IODP proposals.

Investigating the dynamics of large slip in earthquakes is a fundamental scientific issue with important consequences for generation of strong shaking and large tsunamis. For rapid response drilling, we stress the urgency required to capture the transitory temperature, hydrological, and geochemical signals from this earthquake. These observations are essential for providing the needed information for significant advances in understanding the rupture process of great earthquakes.

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Appendix 1. SPC statement and DPG Terms of Reference

The IODP community is deeply saddened by the devastating effects of the March 11, 2011 Tohoku earthquake and resulting tsunami in Japan, and expresses its deepest concerns for the well being of all affected by this natural disaster.

The SPC recognizes the scientific challenges and responsibilities that this earthquake has created regarding the understanding about the nucleation of great earthquakes, associated tsunami, and submarine slide generation, to contribute to geohazard mitigation. Spearheaded by ICDP, past workshops have addressed the scientific rationale for rapid response drilling into large slip fault zones that have recently ruptured. The existing deliberations through international workshops to determine the time frame for rapid response drilling suggests that planning for this must be initiated immediately. Based on this scientific framework, the SPC therefore recommends that IODP in conjunction with colleagues from ICDP, contribute intellectual capacity by forming a detailed planning group (DPG) to provide a scientific assessment of the viability, strategy, and time period for a potential rapid response drilling effort within the region affected by the Tohoku mega-earthquake.

The DPG will be populated and supported by IODP as per IODP policies, recognizing the especially strong knowledge base, ongoing activities, and interest held by Japanese researchers and institutions. IODP-MI in consultation with the SPC chair and the PMOs will populate the DPG based on already existing nominations provided by the community.

Terms of Reference
The rapid response drilling, Tohoku mega-earthquake detailed planning group (DPG) will:

1. Evaluate the overall scientific merits and feasibility of a rapid response drilling project addressing this unprecedented, unexpected, and truly extraordinary geohazard event

2. Assuming (1) suggests a strong scientific case can be made, outline a research and drilling plan including required pre-drilling survey data, draft locations and depths of drilling, and hole and observatory design

To accomplish this in a timely manner, the DPG needs to be formed by mid-April and submit a first, interim report to IODP-MI by June 8, 2011. If justified by the interim report, a full proposal for drilling will be requested for submission with a tentative deadline of August 1, 2011. The DPG can work in part through electronic means, but at least one planning DPG meeting is anticipated to take place as per general IODP policies.

Appendix 2. DPG members

Co-chairs

Mori	Jim	DPRI, Kyoto Univ.	Japan
Kodaira	Shuichi	JAMSTEC	Japan
Brodsky	Emily	UC Santa Cruz	USA

Chester	Fred	Texas A&M	USA
*Di Toro	Giulio	INGV	Italy
Harris	Rob	Oregon State	USA
Hino	Ryota	Tohoku Univ.	Japan
Hirono	Tetsuro	Osaka Univ.	Japan
Ide	Satoshi	Univ. Tokyo	Japan
Ishikawa	Tsuyoshi	JAMSTEC	Japan
*Kopf	Achim	Univ. Bremen	Germany
Li	Haibing	CAGS	China
Lin	Weirin	JAMSTEC	Japan
McGuire	Jeff	Woods Hole, MIT	USA
*Saffer	Demian	Penn State	USA
Saito	Saneastsu	JAMSTEC	Japan
Shinohara	Masanori	ERI, Univ. Tokyo	Japan
Singh	Satish	IPGP	France
Smith	Steve	INGV	Italy
Tanioka	Yuichiro	Hokkaido Univ.	Japan
Tobin	Harold	Univ. Wisconsin	USA
Townend	John	Victoria Univ.	New Zealand
Ujiie	Kohtaro	Tsukuba Univ.	Japan

*Unable to attend May 18-20, 2011 meeting.

Liasons and Observers

Johnson	Kevin	IODP-MI
Larsen	Hans-Christian	ODP-MI
Suyehiro	Kiyoshi	IODP-MI
Kawamura	Yoshi	IODP-MI
Divins	David	USIO
Eguchi	Nobu	CDEX

Appendix 3. Other Fault Zone Drilling and Large-Scale Response Projects

1. Nojima Fault

The Nojima project pioneered the concept of rapid response drilling following the 1995 M_w 6.9 Kobe earthquake. Several medium-depth boreholes (~550–1800 m) were drilled into strands of the Nojima Fault in the 14 months following the earthquake in order to examine the physical characteristics and postseismic recovery mechanisms of a seismogenic fault as soon as possible after a major earthquake (Ando, 2001). The combined aims of the different projects were to characterize the structure and properties of the Nojima Fault at depth; conduct geophysical examinations of the fault zone; and carry out borehole tests in order to investigate temporal changes in permeability and fault rock assemblages (see Kitagawa et al., 2002; Tanaka et al., 2007a, and references therein). The post-earthquake stress field was determined using borehole breakout observations and measurements on core samples, indicating a maximum compressive stress axis acting near-perpendicular to the Nojima Fault. The relatively moderate slip of the Kobe earthquake did not produce a recoverable temperature anomaly.

2. Taiwan Chelungpu Drilling Project (TCDP)

The TCDP was conducted in response to the 1999 M_w 7.6 Chi-Chi earthquake. Following preliminary shallow drilling in 2000 (Tanaka et al., 2002), two deep boreholes (1.3 km and 2.0 km) were drilled in 2004–2005 to address fundamental questions about earthquake nucleation and rupture, notably the character and seismogenic significance of a large-slip-magnitude (>10 m) asperity inferred from seismic waveform modeling, and the role of the Chelungpu thrust fault in regional tectonics (Ma et al., 2006).

Precise temperature observations spanning the fault plane at a depth of 1100 m were made in one of the deep boreholes, hole A, in September 2005, six years after the earthquake (Kano et al., 2006). A temperature anomaly attributed to frictional heating during the earthquake of approximately 0.06°C was detected. The magnitude of this anomaly is comparable to that expected for variations in formation thermal conductivity (Tanaka et al., 2007b). The experience of measuring temperature perturbations during TDCP reveals that temperature profile measurements are useful for constraining stress levels during faulting. At the same time, however, the data also highlight the fact that post-seismic drilling should be carried out as rapidly as possible and penetrate the fault at as great a depth as possible in order to reliably detect the thermal signatures of seismogenic slip.

3. Wenchuan Earthquake Fault Scientific Drilling program (WFSD)

Most recently, the Wenchuan Earthquake Fault Scientific Drilling (WFSD) Project has been initiated in response to the devastating 12 May 2008 Wenchuan earthquake in Sichuan, China (Xu and Li, 2010; Zhang et al., 2010). The earthquake occurred in the transition zone between the Tibetan Plateau and the Sichuan Basin, producing 270 km-long and 80 km-long coseismic surface ruptures along the Yingxiu-Beichuan and Anxian-Guanxian faults, respectively, within the Longmen Shan (Li et al., 2008). To obtain better understanding of the mechanical, physical and chemical characteristics of the faults that ruptured during the Wenchuan earthquake, the two main strands are currently being drilled under the auspices of the Wenchuan earthquake Fault Scientific Drilling program. The WFSD program is a rapid response project to study this large earthquake and its aftershocks, and drilling of the first borehole (WFSD-1) commenced 178 days after the earthquake. Five boreholes ranging in depth between 600 m and 3000 m will ultimately be drilled along the Yingxiu-Beichuan and Anxian-Guanxian faults, targeting locations of maximum coseismic slip.

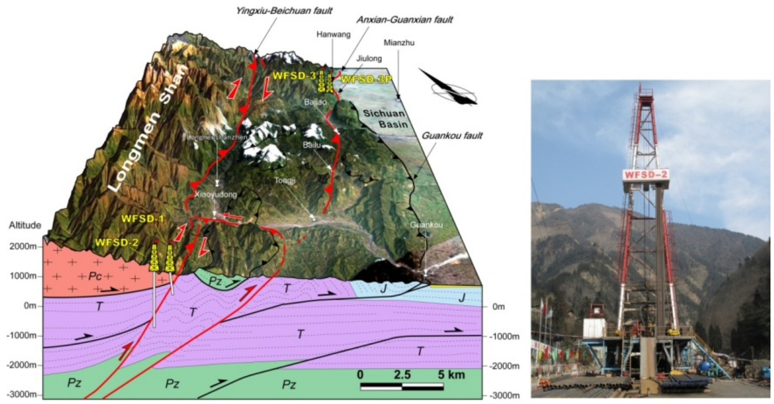

Figure S1. Left: Schematic model of the Longmen Shan fault zone and locations of WFSD boreholes. The red lines represent faults that ruptured during the Wenchuan earthquake. WFSD-1 and 2 are located in the hanging wall of the Yingxiu-Beichuan fault where coseismic displacements of ~6 m occurred. WFSD-3P and 3 are located in the hanging wall of the Anxian-Guanxian fault in the vicinity of coseismic displacements of ~4 m. Right: Photo of the WFSD-2 drilling site (target depth of 2000 m).

4. Northern Sumatran margin

To date, no rapid response drilling project has been conducted offshore following a large earthquake. However, some discussion has taken place with regard to a drilling project on the northern Sumatran margin, at the southern end of fault rupture during the M_w 9.3 earthquake of 26 December 2004. Marine surveys since the earthquake have acquired a variety of active- and passive-source seismic, bathymetric, and core data: those data suggest that the 2004 earthquake ruptured to the seabed at the frontal thrust (Singh et al., 2008), as it appears to have done in the Tohoku earthquake.

A prominent feature of the northern Sumatran margin is that the accretionary prism forms a ~150 km-wide plateau (Singh et al., 2011). This intriguing forearc structure and seismogenic behavior are not yet well-explained within the context of critical taper/mechanical models for other convergent margins, and a three-site drilling transect has been proposed in order to delineate the primary tectono-sedimentary elements of this margin and test kinematic models of forearc evolution. The longer-term goals of drilling on the northern Sumatran margin would be to examine structural controls on earthquake rupture and tsunamigenesis, by examining the state of stress across the forearc and obtaining long sediment records potentially constraining the earthquake history.

5. San Andreas Fault Observatory at Depth (SAFOD)

SAFOD was designed to directly sample fault zone materials (rock and fluids), measure a wide variety of fault zone properties, and monitor the creeping portion of the San Andreas fault zone where ongoing microseismicity is occurring (Zoback et al., 2007; Zoback et al., 2011). The experiment's location, at the northwestern end of the 1966 M6 Parkfield earthquake, corresponds to the transition between locked and creeping sections of the fault. This area has been the focus of extensive geophysical monitoring for several decades, and SAFOD represents the latest phase of a long-term natural laboratory experiment. SAFOD was designed to address both generic questions about fault zone properties and earthquake behavior, and more specific questions related to the apparent weakness of plate-boundary faults (Hickman et al., 1994).

The drilling itself was conducted in three phases between 2004 and 2007 following the successful drilling and instrumentation of a 2.2 km-deep pilot hole in 2002 (Hickman et al., 2004). The key benefit of this approach was that each phase of drilling, which reached a maximum depth during Phase of 3.0 km, could be used to inform the following phases, both technically and scientifically. A diverse range of geophysical and geochemical observations were made — and continue to be made as SAFOD enters the monitoring phase — including real-time gas chemistry measurements, cuttings analysis, spot and continuous core measurements, and extensive seismic monitoring using surface and downhole instruments. The advantage of this multi-technique, multi-phase approach was clearly seen when faults detected by casing deformation at 2.7 km depth following Phase 2 drilling could be correlated with low Vp/Vs and resistivity in geophysical logs, and then directly cored in Phase 3.

6. Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE)

NanTroSEIZE is an IODP drilling project with the objective of drilling, sampling, and instrumenting the up-dip end of a seismogenic thrust interface for the first time, to shed light on how materials and state of stress and pore pressure interact in subduction zones to govern seismogenic locking, earthquake occurrence, and tsunami generation (Tobin and Kinoshita, 2006). It targets the To-Nankai region that last ruptured in 1944 (M~8.1) in a tsunamigenic earthquake, and is considered to be in the later stages of the interseismic cycle based on its historical record. Stages 1 and 2 drilling were carried out in 2007–2010 near the up-dip limit of slip during the M_w 8.2 Tonankai earthquake of 1944 (Kinoshita et al., 2009); drilling and sampling of faults and wall rock to 1600 m below the sea floor has been completed (Tobin et al., 2009) and long-term in situ monitoring of strain, pore pressure, temperature, and seismicity commenced in December 2010. In Stage 3, drilling of a 7 km hole across the plate boundary fault zone is planned, to sample, log, and instrument the hypothesized locked zone as well as the zone generating very low frequency earthquakes and shallow tremor. The results to date show evidence that slip may propagate to the surface along splay faults during megathrust earthquakes, as well as along the basal decollement all the way to the frontal thrust region in the trench, and that stress is heterogeneous both vertically and laterally along the transect, and may vary in time. Of particular relevance to a possible rapid response drilling project off the Tohoku coast are: (1) the demonstrated benefit during NanTroSEIZE of logging-while-drilling (LWD), including resistivity-at-bit (RAB) logging measurements, which can be collected during drilling as an alternative to or in conjunction with a separate wireline logging program (e.g. Lin et al., 2010; Moore et al., 2011), (2) experience in emplacing long-term monitoring instruments in boreholes by *Chikyu*, and (3) structural and geochemical studies indicating possible past localized and rapid fault slip at shallow (100s of meters) depth (Sakaguchi et al., 2011; Yamaguchi et al., in press).

7. Deep Fault Drilling Project, Alpine Fault (DFDP)

The Alpine Fault's geometry, rapid and precisely-known slip rates, well-studied surface exposures, and >40 years of intensive research make it a site of global importance for research into the mechanics and evolution of large faults and the conditions under which earthquakes occur (Townend et al., 2009). However, unlike many other major faults — including each of those referred to above — the Alpine Fault has not produced large earthquakes in historic times, providing an opportunity to study a major fault late in the cycle of stress accumulation ahead of a future earthquake. DFDP drilling commenced in January 2011 with the successful completion of two shallow boreholes intersecting the Alpine Fault at depths of 90 m and 128 m near Gaunt Creek, South Westland. Cores and wireline logging data are currently being analyzed, and the boreholes have been instrumented with seismometers, pressure sensors, and thermistor arrays for ongoing monitoring. Planning is now underway for the second stage of drilling, provisionally scheduled for the 2012/2013 austral summer, which is intended to intersect the fault at a depth of c. 1500 m in order to determine ambient pressures, temperatures, and stresses beneath the influence of near-surface topographic effects.