Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)


SSS01-01 Room:302 Time:May 19 11:00-11:15

# Understanding trench-breaching slip in megathrust earthquakes

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Seafloor GPS measurements and repeated bathymetry and seismic surveys indicate that the fault rupture in the 2011 Tohoku-oki earthquake propagated to the axis of the Japan Trench. Earthquake and tsunami observations are consistent with this scenario. On other occasions, anomalous slip of the shallow part of subduction faults produces so-called tsunami earthquakes. For example, the 1896 Sanriku earthquake which occurred to the north of the 2011 Tohoku-oki earthquake is known to be a tsunami earthquake. In addition, recent ocean drilling in the Nankai Trough yielded evidence for frictional heating on the shallow part of a frontal thrust, suggesting rapid and probably seismic slip. The various observations showing slip to the trench point to the need to better understand the seismogenic behavior of the shallowest part of the subduction megathrust which is usually considered ro exhibit a stable-sliding behavior. However, earthquake and tsunami observations and land-based geodetic measurements usually cannot resolve the amount of coseismal slip near or at the trench axis. In order to constrain the near-trench slip and its along-strike variations, new geological and geophysical data from the trench area, laboratory experiments based on these data, and related theoretical studies are being carried out. In this presentation, as an introductory the the session, we review recent results of geophysical, geological, and theoretical studies concerning slip to the trench during the 2011 Tohoku earthquake and propose a research strategy toward understanding the slip behavior of the shallow megathrust in general.

Keywords: subduction zone, trench, earthquake

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SSS01-02 Room:302 Time:May 19 11:15-11:30

# Structure and composition of the plate boundary decollement in the area of maximum slip during the 2011 Tohoku-Oki earth

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The exceptionally large, shallow slip during the Mw=9.0 2011 Tohoku-Oki earthquake caused the strong impulsive peak of the tsunami, emphasizing the importance of understanding the controls on rupture propagation and slip on subduction megathrusts at shallow depths for hazard mitigation. The structure and composition of the decollement near the trench, which both reflect and contribute to the mechanical behavior of the fault, were investigated during Integrated Ocean Drilling Project Expedition 343. Coring results show that the frontal prism is composed primarily of moderately to steeply dipping mudstones. Two steeply dipping reverse faults containing centimeters thick gouge layers, along with numerous smaller shear fractures, attest to long-term shortening in the prism. The footwall Pacific plate sediments are distinct, consisting of shallowly dipping clay-rich mudstones, laminar pelagic clays and chert. Structural evidence of intense deformation is restricted to a layer of dark brown to orange pelagic clay $<$5 m thick, which marks the decollement. This decollement clay has a pervasive composite foliation, or scaly fabric, defined by striated, lustrous surfaces enclosing lenses of less fissile material. Extremely narrow, planar discontinuities crosscut this fabric, truncating the foliation and separating domains in the clay in which the foliation orientation and intensity change. The decollement damage zone is $<$10 m wide in both the overlying frontal prism and down-going Pacific plate. Long-term displacement on the plate boundary fault near the Japan Trench is therefore localized onto a zone $<$5 m thick. The scaly fabric is indicative of distributed shear across the recovered interval (~1 m), and may represent deformation at interseismic strain rates. However, the sharp discontinuities within the decollement clay result from localized deformation, and are similar to those observed at coseismic slip rates in friction experiments, suggesting they formed at higher strain rates. The presence of poorly lithified clay in the incoming stratigraphic section of the Pacific plate controls both the long-term and coseismic mechanical behavior of the decollement near the Japan Trench.

Keywords: Tohoku-Oki earthquake, Japan Trench, IODP Expedition 343, Megathrust earthquake, Shallow slip

SSS01-03 Room:302 Time:May 19 11:30-11:45

# Frictional behavior of shallow subduction zone thrusts: Comparison of the Japan Trench and Nankai Trough

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The unusually large coseismic slip generated by the 2011 Mw = 9.0 Tohoku earthquake, which propagated all the way to the trench, raises critical questions regarding mechanical behavior of the shallow reaches of subduction faults. These include: (1) What conditions are favorable for earthquake rupture propagation and large amounts of coseismic slip, and (2) are other areas susceptible to a Tohoku-like event? To address these questions, we compare the results of laboratory experiments conducted in a true-triaxial double-direct shear device measuring the frictional properties of natural samples from the Japan Trench and Nankai Trough. Samples from the Japan Trench were recovered from within the decollement in the region of large coseismic slip in the Tohoku earthquake during Integrated Ocean Drilling Program (IODP) Expedition 343, the Japan Trench Fast Drilling Project (J-FAST). Samples from the Nankai Trough were recovered during IODP Expedition 316 and ODP Leg 190, which respectively sampled a major, out-of-sequence thrust fault (Site C0004), and the main decollement zone near the trench (Site 1174). The samples were tested at effective normal stresses up to 25 MPa as intact wafers when possible (usually wall rock); samples from within the fault zones as brecciated fragments or remolded. Velocity-dependent friction measurements show that the Japan Trench decollement sample is slightly weaker (coefficient of friction = 0.17) compared to the Nankai decollement (0.23-0.28) and megasplay (0.36-0.44). Between 0.001 and 0.3 mm/s, the velocity-dependence of friction for both the Japan Trench and Nankai Trough is consistently velocity-strengthening, and with higher amounts of strengthening correlating with higher sliding velocity. At rates below 0.001 mm/s, however, the Japan Trench exhibits velocity-weakening behavior while the Nankai Trough samples remain velocity strengthening. X-ray diffraction analysis of the $<$ 2 micron size fraction of the Japan Trench decollement sample suggests that smectite may be important, whereas illite and chlorite play a larger role in Nankai. Lower overall strength combined with velocity-weakening behavior at low- to moderate-velocities observed for the Japan Trench indicates that it is more favorable for hosting coseismic slip propagation than either the decollement or the megasplay in the Nankai Trough.

Keywords: earthquake, tohoku, nankai, friction, fault

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# Laboratory experiments on the Japan Trench plate-boundary thrust material reveal very low co-seismic shear strength

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Widely accepted conceptual models of a seismogenic subduction zone held that shallow portions of plate-boundary thrusts slip aseismically. However, the 2011 Tohoku-oki earthquake (Mw9.0) produced unexpectedly large seismic slip of >50 m near the Japan Trench with a resultant devastating tsunami. The Integrated Ocean Drilling Program (IODP) Expedition 343, Japan Trench Fast Drilling Project (JFAST) provided an invaluable opportunity to answer why the very large slip occurred on the shallow plate-boundary thrust during the 2011 Tohoku-oki earthquake. JFAST drilled several boreholes to the plate-boundary thrust at Site C0019, located at the toe of the frontal prism near the Japan Trench. The drilling results clarified that plate-boundary faulting in this region is highly localized in pelagic clay. In order to explain the huge shallow slip, we conducted high-velocity (1.3 m/s) friction experiments on samples retrieved from the plate-boundary thrust at Site C0019 under wet conditions. The results show rapid slip weakening properties with very low peak and steady-state shear strength. The effective friction coefficient during the steady-state condition was less than 0.1, representing one of the lowest values ever measured for fault zone rocks. The low dynamic shear strength can be attributed to the abundance of smectite and thermal pressurization effects, which can enhance earthquake rupture propagation from deep depths without much resistance. This behavior may be characteristic of plate-boundary thrusts formed within smectite-rich pelagic sediments and can provide an explanation for the huge shallow slip that occurred during the 2011 earthquake.

Keywords: Japan Trench Fast Drilling Project, plate-boundary deollement, smectite, thermal pressurization

SSS01-05 Room:302 Time:May 19 12:00-12:15

# Extreme Low Friction of the Tohoku Plate Boundary as a possible factor for seismic slip propagation toward the trench

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Shallow portions of subduction plate boundaries have been generally considered to behave aseismically. However, seismic slip during the 2011 Tohoku earthquake propagated up-dip from the depth along the plate boundary, leading to unexpected large seafloor displacement of more than 50 m near the trench. To further understand mechanical explanations for this unexpected behavior, we have conducted laboratory friction experiments on core samples of the Tohoku plate-boundary fault zone, along with sediments from above and below the zone (i.e. wall rocks), collected during IODP Expedition 343 (the Japan Trench Fast Drilling Project). In the experiments, we sheared ~2 mm-thick disaggregated samples at slow (1 um/s) to coseismic slip velocities (1 m/s) under a constant normal stress of 20 MPa and fluid pressure of 10 MPa. The experimental conditions (slip velocity and effective normal stress of 10 MPa) are very close to the in-situ conditions at which seismic faulting would have occurred at the drilling site of the plate boundary.

Our preliminary results indicate that the friction coefficient (mu) for all samples tends to increase with velocity toward velocities of the order of mm/s (which we call a frictional barrier at intermediate velocity) and that above this velocity range it progressively falls to <0.1 at 1 m/s with marked slip-weakening behavior. However, the absolute frictional strength of samples from the plate boundary fault is very different from that of the wall rocks. The fault-zone material, which is rich in smectite shows (1) very low friction coefficient of <0.15 over a wide range of velocity (1 um/s to 1 m/s), and (2) a small frictional barrier at intermediate velocity (delta mu <0.02). In contrast, the friction coefficients of others samples are 0.25-0.5 at velocities of <3 mm/s and the frictional barrier is much larger than that of the fault-zone material (e.g. delta mu >0.2 in sample just below the fault zone). Smectite-rich incoming sediments (i.e. source material of the current plate boundary fault zone) to the Tohoku subduction, which were retrieved from DSDP Leg 56, display similar frictional behaviors to those of the plate boundary. Our result suggests that extremely low frictional strength, which is characteristic of smectite-rich materials within the plate boundary over slow to coseismic velocities allowed earthquake slip to easily propagate up-dip along the Tohoku plate boundary, facilitating the huge displacement near the trench.

Keywords: Tohoku earthquake, plate boundary, fault, friction, smectite

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# Frictional properties of sediments on the Cocos Plate entering the Costa Rica Subduction Zone

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Mechanical properties of the incoming sediments to subduction plate boundaries are essential to constrain subduction-related faulting processes. Recently, frictional properties of clay-rich megasplay fault material collected from the Nankai Trough have been explored (Ikari et al., 2009; Ujiie and Tsutsumi, 2010; Tsutsumi et al., 2011). However, knowledge of the frictional properties of pelagic sediments composed of abundant biogenic component, such as spicules, diatoms, and radiolarians are limited. Here we report experimental results on the frictional properties of the input sediments, which include biogenic horizons, on the Cocos Plate entering the erosive Costa Rica subduction zone.

Experimental samples are fine, soft silty clay sediments (lithostratigraphic Unit I) and silicic to calcareous ooze (Unit II), collected at a reference site off shore Osa Peninsula (Site U1381) during the IODP expedition 334 (Vannucchi et al., 2012). To be used in the experiments, the discrete samples was disaggregated, oven dried at 60 degrees centigrade for 24 hours. The experimental fault is composed of a 24.9 mm diameter cylinder of gabbro cut perpendicularly to the cylinder axis in two halves that are ground to obtain rough wall surfaces, and re-assembled with an intervening thin layer (˜1.0 mm) disaggregated sample. Frictional experiments have been performed using a rotary-shear friction testing machine, at normal stresses up to 5 MPa, over a range of slip velocities from 0.0026 mm/s to 1.3 m/s, with more than ˜150 mm of displacements for water saturated condition.

Experimental results reveal that the steady-state friction values at slow slip velocities ($v < \sim 30$ mm/s) are less than ˜0.2 for the silty clay sediments and ˜0.7 for the silicic to calcareous ooze, respectively. The silty clay always shows velocity-strengthening behavior at velocities $v < \sim 3$ mm/s. On the contrary, the silicic to calcareous ooze samples show velocity-weakening at $v < 0.3$ mm/s and neutral to velocity-strengthening at $0.3 < v < \sim 3$ mm/s. At higher velocities ($v > \sim 30$ mm/s), steady state friction decreases dramatically. At a velocity of 260 mm/s, the friction coefficient shows a gradual decrease with a large weakening displacement toward the establishment of a nearly constant level of friction at ˜0.1.

The low frictional strength of the uppermost silty clay sedimentary sequence may provide a condition for shear localization to occur within this stratigraphic horizon. The velocity-strengthening behavior observed for the silty clay suggests that faulting along the fault within silty clay horizon would be a stable sliding. On the other hand, velocity weakening behavior of the silicic to calcareous ooze, which is observed at slow velocities, could provide a condition to initiate unstable fault motion at shallow depths if a fault rupture can extend to the silicic to calcareous ooze horizon. The neutral to velocity strengthening behavior observed for intermediate velocities could stabilize the propagation process of earthquake nuclei that emerges in the velocity weakening portion along the fault. It is important to note also that a dramatic slip weakening at velocities of $v > \sim 30$ mm/s characterizes the frictional behavior of the silicic to calcareous ooze. Presented frictional properties of the incoming sediments may offer an important constraint for improving models of subduction-related faulting processes within the Costa Rica subduction channel.

Keywords: subduction zone, Costa Rica, CRISP, friction

SSS01-07 Room:302 Time:May 19 12:30-12:45

# Mechanism of 2011 Tohoku-oki Earthquake in view of Fault Mechanics

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We discuss about the mechanism of the devastating Tohoku-oki earthquake (Mw 9.0, 11 March 2011) in view of the current status of fault mechanics and to point out future tasks for better understanding of megathrust earthquakes in subduction zones. Main points of discussions are listed below.

(1) Erosional boundary and low temperature may cause diversity of seismicity. Subducting plate boundary in Tohoku is a classical erosional plate boundary which allows diverse combinations of rocks in contact at the plate boundary. Subduction zone in Tohoku is also characterized by low temperature although estimated temperature at the bottom of seismogenic plate interface varies from 210 degrees Celsius (Peacock and Wang, 1999, Science) to 400 degree Celsius (Iwamori and Zhao, 2000, GRL). Contacts between oceanic rocks (seamounts and oceanic crust) and basement rocks on the hanging-wall side can be sites of seismic behaviors in view of friction data on granite and gabbro, whereas a shift from velocity-strengthening to velocity-weakening behavior seems to occur at higher temperature for clay-bearing gouge than for granite and gabbro (den Hartog et al., 2012, EPSL). Thus combination of different rock pairs and low temperature can cause diverse behavior ranging from aseismic to seismic behaviors recognized in off-Tohoku areas. However, we definitely need data from friction experiments on representative metamorphic rocks in subduction zones at low to high temperatures.

(2) Seismogenic zones: Seismogenic plate boundary in Tohoku can be divided into three zones; (i) fore-arc accretionary prism (down to about 15 km in depth), (ii) continental crust to oceanic crust interface (about 15-25 km), and (iii) wedge mantle to oceanic crust interface (about 25 to 50-60 km). We will discuss characteristics of those zones in the presentation. Several friction experiments revealed that friction coefficient increases with increasing temperature, and hence frictional strength will be higher in (ii) than in (i). Moreover, high-permeability of fractured rocks in (ii) will low pore pressure there than in (i). Thus high friction and less pore pressure could have been the cause of asperity during the Tohoku-oki earthquake. Sealing of fractures at depths will cause build-up of pore pressure in (iii), but not as high as in Nankai trough, is probably a cause more frequent earthquakes in (iii).

(3) Megathrust earthquake: An important issue raised by this earthquake is how a megathrust earthquake occurs along a plate interface that is not coupled 100%. Earthquake rupture can propagate into velocity strengthening regime if fault weakens dramatically at high slip rates (Noda and Lapusta, 2013, Nature) and this provides a mechanism for megathrust earthquake. However, majority of moderate to large earthquakes do not develop into a megathrust earthquake, so that earthquake modeling including intermediate to high-velocity friction is needed. In particular, the effects of marked velocity-strengthening at the intermediate velocities (Sawai et al., 2012, AGU) on earthquake rupture propagation should be addressed.

(4) Tsunami earthquake and large displacement at shallow plate interface: Dramatic gouge weakening and thermal pressurization probably made it possible for shallow parts to undergo very large displacement and even overshooting. Recent high-velocity experiments (e.g., Faulkner et al., 2010, GRL) demonstrated that wet gouge exhibits almost no peak friction allowing rupture propagation and fault motion very easy. However, the tsunami earthquakes appear to be rather rare events compared with moderate to large earthquakes in Tohoku. We suggest that the bottom part of (i) and the upper part of (ii) above undergo dilatancy upon initiation of fault motion which prohibits easy rupture propagation into shallow plate interface to cause tsunami earthquake.

Keywords: 2011 Tohoku-oki earthquake, fault mechanics, earthquake mechanism

SSS01-08 Room:302 Time:May 19 14:15-14:30

# Using Temperature to Measure Fault Stress

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Knowledge of the shear stress on a fault during slip is necessary for any first principle understanding of earthquake mechanics, yet measuring the shear stress on the fault during an earthquake has been an elusive goal of earthquake mechanics for decades. The slip of the recent Tohoku earthquake to through the nominally rate-strengthening regime highlights the need for better observational constraints on this key quantity. Temperature measurements immediately after an earthquake record the energy dissipated by this stress. A major goal of the JFAST expedition is to measure the temperature on the fault. There are only two extant similar measurement projects: the Taiwan Continental Drilling Project (TCDP) and the Wenchuan Fault Scientific Drilling (WFSD). Both TCDP and WFSD have apparent temperature anomalies consistent with extraordinarily small effective coefficient of friction. In particular, in WFSD a 0.02oC temperature anomaly was observed from 1.5 years to ˜3 years after the earthquake. It appears to be advecting vertically ˜5 m/year and is consistent with a shear stress of ˜0.2 MPa at a vertical depth of 578 m. Assuming Andersonian mechanics for the long-term normal stress on the fault, the stress is equivalent to a coefficient of friction of 0.02, which is a factor of 50 below the canonical static value and less than the current generation of high-speed laboratory results. In particular, here we synthesize those results with what is known from preliminary data of JFAST.

Keywords: Earthquake, Fault, Friction, Wenchuan, JFAST, Trench

SSS01-09 Room:302 Time:May 19 14:30-14:45

# The JFAST Fault Zone Observatory: Monitoring the frictional heat from the 2011 Tohoku Earthquake

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The 2011 Tohoku Earthquake presented unique circumstances that permitted access to a fault that recently slipped tens of meters and installation of a subseafloor observatory for time-sensitive temperature measurements of the frictional heat signal. These data provide insight into the stress level on the megathrust fault during slip and are crucial for building a full physical model of the earthquake cycle and characterizing tsunami hazard. The observatory consists of 55 autonomous titanium-encased temperature sensors/dataloggers (10 also measure pressure) attached to a rope and hung within 830 m of steel tubing below a seafloor wellhead. The observatory was successfully installed as part of the IODP Japan Trench Fast Drilling Project (JFAST) on 16 July, 2012 in the extreme water depth of 6910 meters, making it the deepest ocean observatory of any kind. It is estimated to intersect that plate boundary fault zone at ~809 mbsf. Sensor spacing varies from 1.5 m near the fault zone to larger intervals to characterize the background geothermal gradient. Data from the observatory is only accessible by retrieving the sensor rope. At the time of this writing, in mid-February 2013, recovery of the sensors and data is currently being attempted with the Kaiko7000II ROV. Preliminary temperature data acquired during drilling reveal very low heat flow at the site. The JFAST expedition and observatory highlights important advances in rapid response drilling capabilities and subseafloor monitoring in extreme water depths and fault zones. It is expected to help provide insight into the cause of the extreme slip of the Tohoku Earthquake that contributed to such a large tsunami.

Keywords: JFAST, Tohoku, Heat Flow, Earthquake

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SSS01-10 Room:302 Time:May 19 14:45-15:00

# Boron and strontium isotope constraint on the origin of interstitial water from IODP Expedition 343, JFAST

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The Integrated Ocean Drilling Program (IODP) Expedition 343, Japan Trench Fast Drilling Project (JFAST), drilled three holes through the plate boundary near the Japan Trench to investigate the cause of very large fault slip during the 2011 Tohoku-Oki earthquake. Twelve interstitial water samples were recovered from the Hole C0019E at the depths predominantly between 689 mbsf and 831 mbsf. Here we report the results of onshore boron and strontium isotope analyses as well as onboard inorganic chemical analyses for the interstitial water samples.

The 87Sr/86Sr ratios of the interstitial water samples show relatively constant, seawater-like values at the depths above 730 mbsf, but clearly decrease with increasing depth below 780 mbsf. The relationship between strontium concentrations and the 87Sr/86Sr ratios indicates that the interstitial water compositions are essentially controlled by three-component mixing, and the waters around two major fault zones require distinct end-component fluids. This conclusion is also supported by significantly different characteristics of some minor and trace element concentrations in the interstitial waters around these two fault zones.

The boron isotope ratios (d11B values) of the interstitial waters are all higher than that of seawater, and show a small minimum around 700 mbsf and a clear maximum around 820 mbsf. The increase of d11B value around 820 mbsf, where the presence of a plate boundary fault is inferred, is associated with decrease in boron content. This indicates effective removal of light boron from the water around this depth possibly through adsorption of boron onto solid surface, and requires much larger effective solid surface area per unit fluid mass compared to the surrounding area. Such an increase of solid surface area may have been derived from extensive fracturing around the plate boundary fault.

Keywords: IODP, Tohoku, earthquake, geochemistiry, fluids, isotope

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# Bending-related normal faulting influence on near trench decollement propagation along the Japan Trench

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Geophysical analysis of the great 2011 Mw 9.0 Tohoku earthquake revealed co-seismic rupture to the trench with a combination of uplift and landslides contributing to tsunamigensis. After ˜150 seconds of rupture along the main decollement, normal faulting focal mechanisms started to dominate, especially along the outer rise. These bending-related normal faults appear to affect the updip geometry of the decollement, where seismic reflection data show downcutting of the decollement into a local trench graben. We investigate bending-related normal faulting to a maximum of ˜70 km seaward of the trench using depth migrated regional 2D seismic lines and trench focused 2D high-resolution seismic lines to understand the incoming plate geometry near the Tohoku earthquake epicenter. We studied two different classes of normal faults: faults that cut the basement, which dominate the outer-rise topography, and faults that cut the sediment section near the trench but do not penetrate the oceanic basalt, which are seen only in the high-resolution images. Basement-cutting, bending-related faults in the Japan Trench are well documented from multiple bathymetric surveys. We use structural reconstructions to constrain dip and basement offsets along those faults. This process revealed dips varying between 50-80 degrees with a general trend of increased displacement towards the trench. Faults within the sediment column exhibit offsets of ˜20m or less but with densely spaced populations of ˜30 faults within ˜2km. From this understanding of bending-related normal faulting, we propose a simple mechanism for the decollement's propagation into the graben using local stress changes. Before the decollement propagates into the trench graben, co-seismic rupture to the fault tip creates large tensional stresses down into the trench graben, promoting secondary crack formation in the damage zone or activation of the near surface sedimentary faults. Furthermore, tensional stresses from the potentially active basement-cutting, graben bounding normal fault also rotate the local stress within the graben. Later in the earthquake cycle, thrust faulting would experience the stress rotation or exploit these weak surfaces to propagate into the graben. These results demonstrate the significance of the incoming bending-related normal faults to the geometry of the updip extent of the megathrust at the Japan Trench.

Keywords: Outer-rise normal faults, Tohoku earthquake

SSS01-12 Room:302 Time:May 19 15:15-15:30

# Turbidite paleoseismology in the Japan Trench floor: Results from Sonne SO219A and Mirai MR12-E01 cruises

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The large sea-floor displacement in the Japan Trench slope by the 2011 off the Pacific Coast of Tohoku earthquake was inferred from the repeated bathymetric surveys. Because the Japan Trench is a remarkable depression near the epicenter, the gravity flows generated by the earthquake and its related phenomena might be focused in the depression (more than 7500 m in water depth) and might form the gravity flow deposits like turbidites. Therefore, the Japan Trench is a target area to detect the past earthquake event deposits. To obtain the past earthquake records, we conducted two survey cruises; Sonne SO219A and Mirai MR12-E01 cruises. All of the cores obtained from the Japan Trench floor by two cruises (3 cores by Sonne and 4 cores by Mirai) showed the same lithostratigraphy. The 2011 event deposits, which were composed of thin sand at base and diatomaceous mud/ooze with multistoried upward fining grading structure, occurred at the uppermost part of the cores. Below the 2011 event deposit, at least three thick (several tens cm to a few meter thick) turbidite units were recognized. Third turbidite unit was very unique and was characterized by the calcareous nanno fossil bearing turbidite muds suggesting the transportation from upper-mid slope. A volcanic ash from the Towada volcano intercalated in hemipelagic mud between second and third turbidite units. Results on our tephra correlation using geochemical and petrographic properties suggest that the ash might be correlative to Towada-a ash, which occurred just above the Jogan tsunami deposits on the Sendai Plain. Radiocarbon dating using bulk organic carbon and radiolarian faunal assemblages suggested that the ash horizons are the Holocene deposits. Exact correlation of the ash layer is very important to connect the deep-sea event deposits in the Japan Trench and on-shore tsunami deposits on the Sendai Plain. The result indicates that turbidite along the Japan Trench might give us important information on the spatio-temporal occurrence of the past earthquakes.

Keywords: turbidite, paleoseismology, Japan Trench

SSS01-13 Room:302 Time:May 19 15:30-15:45

# A Slump in the Trench: Tracking the impact of the 2011 Tohoku-Oki earthquake

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Subduction earthquakes can rupture the seafloor and trigger submarine slumps, which are potentially tsunamigenic and may affect the structural evolution of convergent plate boundaries. Bathymetric and seismic data in the Japan Trench, obtained before and after the 2011, Magnitude 9 Tohoku-oki earthquake off Japan, document significant seafloor- and subseafloor changes as tectonic and geomorphic expressions of this mega-earthquake. One challenge groundtruthing geophysical data and models, however, is to access sea- and subseafloor samples, which can be dated to assign the hypothesized process to a given earthquake. Here we present multibeam bathymetry, reflection seismic, sediment core and pore-water geochemistry data from the Japan Trench, collected after the 2011 Tohoku-Oki earthquake. Analyzing the diffusive re-equilibration of disturbed SO42- profiles over time allows us to constrain that the observed sediment disturbance and mass movements, which link to bathymetric and structural changes observed in geophysical datasets, were indeed triggered by the 2011 earthquake. We conclude that a slump in the trench significantly impacted the geometry and evolution of the shallow plate boundary system by emerging a submarine fold-and-thrust belt and abruptly narrowing the trench up to 3 km in width.

Keywords: Japan Trench, Submarine Mass Movements, Sediment core, Sulphate, R/V Sonne Cruise SO219A, RV Mirai Cruise MR12-E01

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# Earthquakes recovering the strain energy lost at interseismic stage

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Earthquakes are generally believed to be a process of releasing elastic stress accumulated before the earthquake. Recurrence of great earthquakes along a plate boundary has been successfully explained with this concept. Here, we show that this is not always the case. There is another class of plate-boundary earthquakes whose slip recovers original stress that has been lost through the interseismic stage. Such earthquakes do not occur in the seismically active inner (landward) segment of a megathrust wedge. Their occurrence is limited to the seismically less active outer (oceanward) segment, characterized in topography by steep seafloor and gently dipping plate interface. We develop a two-dimensional, analytical elastic model of the wedge, subject to gravitational body force, with a sloping seafloor at the top and frictionally dragged at the base by a rigid plate. The intensity of drag force is measured by basal frictional coefficient mu_e. It can be shown that as mu_e is increased from 0, shear strain energy in the wedge initially decreases, reaches a minimum and then begins to increase. If mu_e reaches a threshold before it brings the wedge into the minimum shear energy state, the resultant slippage takes place towards increasing shear strain energy as well as horizontally tensile stresses. Such a seemingly strange process can be understood by considering the role of gravitational potential energy associated with the seafloor slope. Earthquakes in this category include most of tsunami earthquakes and the 2011 great Tohoku-Oki earthquake involving both the outer and inner segments with much larger slip in the outer segment.

Keywords: great earthquake, tsunami earthquake, megathrust wedge, fault frictional slip, absolute stress

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# Investigating the Relation Between Trench-breaching Rupture and Shallow Afterslip

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Afterslip commonly occurs in fault areas of coseismic stress increase (i.e., negative stress drop), peripheral to the areas of stress drop. It is thus logical to expect afterslip to avoid the area of largest coseismic slip. Seafloor geodetic measurements made after the 2011 M 9 Tohoku-oki earthquake are thus intriguing. They appear to indicate rapid afterslip of the shallowest, near-trench part of the megathrust which, according to many models, is also the area of very large or largest coseismic slip. If we assume some coseismic stress increase near the trench is needed to drive the shallow afterslip, then we must infer that the same stress increase must have acted to resist coseismic rupture. If true, the coseismic slip should peak at some distance landward of the trench but decrease to a smaller value when it breaches the trench. Such an inference or any counter argument has important implications to fault mechanics. To investigate this problem, we are currently making the follow efforts. (1) To constrain the pattern of ongoing shallow afterslip, we need to make corrections to seafloor geodetic measurements to account for the effect of mantle viscoelastic stress relaxation. To model the short-term mantle relaxation, we have developed a 3D finite element model with transient mantle rheology. The results necessitate a correction for a systematic landward motion of the entire frontal forearc, arguing more strongly for the presence of shallow afterslip. (2) To understand how well the near-trench or trench-breaching rupture is resolved by observations, we have compiled near-trench slip distributions of coseismic rupture models based on the inversion of various geodetic, seismological, and tsunami observations. The compilation indicates that the near-trench slip is poorly resolved. (3) We are developing a rupture scenario that features large slip to explain main coseismic observations yet acquires some stress increase in the shallowest part of the megathrust to drive afterslip.

Keywords: subduction earthquake, fault mechanics, earthquake deformation, seafloor geodesy, post-seismic deformation, Tohoku-oki earthquake

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# Shallow episodic tremor and slip near the Japan Trench before the 2011 Tohoku-Oki earthquake

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Instances of episodic tremor and slip (ETS) have been discovered in several subduction zones in the past decade. Most ETSs have been found in the deep regions of subduction zones, such as those of the Nankai, Cascadia, and Mexico subduction zones. We report on a shallow ETS (<20 km depth) event that occurred prior to the 2011 Tohoku-Oki earthquake. Two transient slow slip events accompanied by long duration seismic signals, or tremors exceeding 1 h, were observed by ocean-bottom seismic and pressure sensors near the Japan Trench. The first ETS, which occurred over the period of a week in November 2008, was recorded simultaneously by ocean-bottom pressure gauges, and an on-shore volumetric strainmeter. Tremor signals were also observed at ocean bottom seismometers near the trench. This observed deformation was interpreted as being an M6.8 episodic slow slip event. The second ETS was observed from the end of January 2011 until just before the 2011 Tohoku-Oki earthquake; the moment magnitude of this event was 7.0. The ETS in 2011 preceded the interplate earthquake of M7.3 (March 9, 2011), which was the largest foreshock of the 2011 Tohoku-Oki earthquake. An anomalous tremor exceeding 24 hours duration was observed only at a seismometer located 20 km away from the trench, in the updip extension from the hypocenter of the largest foreshock. No obvious tremors were observed at the seismic stations just above the epicenter and coseismic slip area of the largest foreshock. The observed bottom pressure data also indicated a slight shift of the updip tip of the slow slip fault to the trenchward direction just before the largest foreshock. Our findings reveal that the slow slip events mainly occurred at the updip extension of the coseismic slip area of the largest foreshock. There was no obvious slow slip, or pre-slip near the hypocenter.

Keywords: slow slip, tectonic tremor, The 2011 Tohoku-Oki earthquake, subduction zone

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# Enhanced dewatering and non-deforming upper plates: Facilitating high slip near the trench at non-accretionary margins?

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In subduction zones, both earthquake nucleation and large coseismic slip are typically restricted to depths >~10-15 km. However, for some earthquakes, regions of high slip extend to shallow depths, and in some cases to the trench. A subset of such events also excite tsunamis that are anomalously large with respect to their seismic magnitude; these are termed "tsunami earthquakes" and are characterized by longer source durations than typical earthquakes. Although the sample size is small, events exhibiting high slip at shallow depths commonly occur at non-accretionary or sediment-starved margins, including both tsunami and "normal" earthquakes (for example, the 1896 Sanriku, 1992 Nicaragua, 1960 and 1996 Peru, 1994 Java, 1995 Jalisco, and 1963 and 1975 Kurile events). Here, I explore the hypothesis that non-accretionary subduction zones facilitate large shallow slip through a combination of two processes: (1) enhanced drainage, resulting from complete subduction of a typically thin sediment section; and (2) lack of permanent anelastic deformation in the upper plate. In contrast, at accretionary margins, the sediment section is thicker, and as a result, the subducted sediments have lower porosity and permeability - leading to a greater propensity for fluid overpressure. Sediment accretion also leads to large lateral compactive strains in the upper plate, such that the net long-term displacement rate across the plate boundary decollement near the trench is a small fraction of the plate convergence velocity. Numerical modeling studies, as well as estimates of in situ pore fluid pressure, are consistent with the idea that the thin sediment section at non-accretionary margins globally (mean of 600 m) should allow more efficient drainage than at accretionary margins where the sediment is typically thicker (mean 2200 m). Ultimately, this enhanced drainage should lead to higher effective normal stress along the subduction megathrust in the outer forearc, and thus increase the potential for locking and unstable slip. In conjunction with the lack of permanent anelastic deformation in the upper plate, this may provide a mechanism to explain why the majority of events that exhibit large shallow slip occur at non-accretionary subduction zones. This idea is also consistent with observations of small (M 3.8-4.9) very low frequency earthquakes that release modest stored elastic strain in the seaward-most reaches of accretionary margins, but which apparently do not occur at their non-accretionary counterparts.

Keywords: pore pressure, tsunami earthquakes, subduction zones

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# Pore pressure distribution in the Nankai Trough off Kumano: Potential rupture propagation from mega-splay to decollement

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The Nankai subduction zone has repeatedly generated great earthquakes in excess of Mw 8. Because great earthquakes at convergent plate margins are believed to occur both at the plate interface and on mega-splay faults, seismic reflection data were acquired to reveal the structure of these seismogenic faults. However, we cannot clearly interpret the evolution of such a mega-splay fault system from the reflectivity images alone because of the low signal-to-noise ratio at the landward side of the active mega-splay fault, which may be due to rock consolidation as well as multiple reflections. Furthermore, the transition zone between the landward mega-splay fault and the seaward decollement is unclearly imaged because of the topographic relief at the outer ridge. The structures and pressure conditions of the transition zone are critical to evaluate coseismic rupture propagation close to the trough axis that may lead to tsunami generation. The 1605 Keicho earthquake (Mw7.9) is well known as a tsunami earthquake in the Nankai Trough, and was characterized by coseismic rupture close to the trough axis. The tsunami of the 2011 Tohoku-oki earthquake was also generated because of rupture propagation close to the trench.

Kamei et al. [2012, EPSL] applied frequency-domain Waveform Tomography (WT) to controlled source Ocean Bottom Seismometer (OBS) data, and retrieved high-resolution P-wave velocity images of the mega-splay fault system. By exploiting recorded seismic waveforms beyond their first arrivals, the WT method achieves a much higher resolution than that of conventional traveltime tomography methods, and resolves the transition zone between mega-splay fault and seaward decollement. In this study, we explore the evolution of the mega-splay fault and its relationship to the decollement based on pore pressure distribution. We applied the methodology in Tsuji et al. [2008, JGR] in order to estimate the pore pressure around the Nankai mega-splay fault from the WT-derived seismic velocity model by integrating logging data and laboratory-derived data. Our results suggest that a high pore pressure zone at the footwall side of the deep mega-splay fault continues to the seaward region close to the trough axis. The normalized pore pressure ratio of the footwall of the basal mega-splay fault (abnormal pressure zone between the fault and crustal surface) have almost constant values. This high pore pressure distribution indicates the possibility of coseismic rupture propagation from the deep mega-splay fault to the seaward trough region.

Keywords: Nankai Torugh, Pore pressure, Mega-splay fault, Decollement

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# A Shallow Interplate Coupling Model in The Java Trench, Off The Western Coast of Java, Indonesia, Revealed from GPS Data

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Shallow thrust earthquakes producing tsunami earthquakes have been occurring along the Java subduction zone, for example the 1994 M7.8 Banyuwangi Earthquake and the 2006 M7.7 Pangandaran Earthquake. We investigate weather interplate coupling is apparent in the shallow part of the Java Subduction off the western coast of Java, Indonesia, where no large interplate earthquake (M>7) are recorded. We use 3 years data of 13 stations of the Indonesian Permanent GPS Station Network (IPGSN) in 2008-2010. We processed GPS phase data using Bernese GPS Software 5.0 and derive the site velocities by linear fitting of the coordinate time series. The majority of the calculated horizontal and vertical velocities show 2.4 to 14.7 mm/yr and -7.0 to 14.5 mm/yr, respectively, with an average white noise error of 0.3 and 0.9 mm/yr, respectively, at 95% confidence level. We interpret the main source of the observed velocity in West Java resulting from contribution of interplate coupling on the main thrust zone and the contributions postseismic effects from the 2006 Pangandaran Earthquake. With current results, we estimate (1) an interplate coupling in the shallow part of the subduction plate, adjacent to the western boundary of the 2006 Pangandaran Earthquake, with a slip deficit rate of ~5.8 cm/yr, length ~300 km, in depth with a range of 6~20 km, which is equivalent to 87% coupling; and (2) an afterslip with a rate of 7.8 cm/yr, length ~300 km, in depth with a range of 20~35 km, adjacent to the deeper boundary of the ruptured area of the 2006 Pangandaran Earthquake. The shallow coupling might indicate a plausible occurrence of a tsunami earthquake such as demonstrated by the 2006 Pangandaran Earthquake. It is also not impossible to occur a megathrust earthquake such as the 2004 M9 Aceh-Andaman and the 2011 M9 Northeast Japan Earthquake.

Keywords: Shallow subduction earthquake, Interplate coupling, Afterslip, Slip deficit, Java Trench, GPS measurement

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# Imaging megathrust zone and Yakutat/Pacific plate interface in Alaska subduction zone

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We image the subducted slab underneath a 450 km long transect of the Alaska subduction zone. Dense stations in southern Alaska are set up to investigate (1) the geometry and velocity structure of the downgoing plate and their relation to slab seismicity, and (2) the interplate coupled zone where the great 1964 (magnitude 9.3) had greatest rupture. The joint teleseismic migration of two array datasets (MOOS, Multidisciplinary Observations of Onshore Subduction, and BEAAR, Broadband Experiment Across the Alaska Range) based on teleseismic receiver functions (RFs) using the MOOS data reveal a shallow-dipping prominent low-velocity layer at ~25-30 km depth in southern Alaska. Modeling of these RF amplitudes shows a thin (<6.5 km) low-velocity layer (shear wave velocity of ~3 km/s), which is ~20-30% slower than normal oceanic crustal velocities, between the subducted slab and the overriding North American plate. The observed low-velocity megathrust layer (with P-to-S velocity ratio (Vp/Vs) exceeding 2.0) may be due to a thick sediment input from the trench in combination of elevated pore fluid pressure in the channel. The subducted crust below the low-velocity channel has gabbroic velocities with a thickness of 11-12 km. Both velocities and thickness of the low-velocity channel abruptly increase as the slab bends in central Alaska, which agrees with previously published RF results. Our image also includes an unusually thick low-velocity crust subducting with a ~20 degree dip down to 130 km depth at approximately 200 km inland beneath central Alaska. The unusual nature of this subducted segment has been suggested to be due to the subduction of the Yakutat terrane. We also show a clear image of the Yakutat and Pacific plate subduction beneath the Kenai Peninsula, and the along-strike boundary between them at megathrust depths. Our imaged western edge of the Yakutat terrane, at 25-30 km depth in the central Kenai along the megathrust, aligns with the western end of the geodetically locked patch with high slip deficit, and coincides with the boundary of aftershock events from the 1964 earthquake. It seems plausible that this sharp change in the nature of the downgoing plate controls the slip distribution of great earthquakes on this plate interface.

Keywords: Megathrust, Fault zone property, Yakutat terrane subduction

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# Fluid transport property of sediments near the plate boundary fault at Japan Trench

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The 2011 Tohoku earthquake (Mw 9.0) produced huge fault slip (~50m) on the shallow portion of plate boundary fault. On the basis of previous studies of the rheology of subduction faults and historical observations of seismicity, neither large Mw 9.0 earthquakes near the Japan Trench, nor rupture of the shallow portion of the subduction thrust were anticipated. Thus, questions remain about the dynamic processes during the earthquake, which can be addressed though evaluation of physical properties of the fault zone. Fluid transport properties of fault zones influence pore fluid pressures and how fluids migrate at depth. Permeability of fault rocks and surrounding sediments directly influences (1) the efficiency of the thermal pressurization process during coseismic faulting and (2) the evolution process of pore fluid pressure generated by the chemical dehydration reactions of the subducting sediments along a plate boundary. These processes consequently affect fault dynamics. Thus, we have measured hydraulic property of core samples around the plate boundary materials recovered from the Japan Trench during IODP expedition 343 (JFAST), performing laboratory tests on mudstones from the hanging wall near the plate boundary fault zone (Lithological Unit 4, 714 mbsf and 785 mbsf). Permeability and porosity were measured at confining pressures of 0 to 30 MPa and pore pressures of 0.2 to 0.8 MPa at room temperatures (about 20 degree Celsius). Permeability was determined by a steady-state flow method with NaCl solution (35 per-mil) and distilled water as a pore fluid.

Permeability and porosity for mudstone from 713 mbsf are $3*10^{-17}$ $m^2$ and 43%, respectively, at 1 MPa effective pressure. These parameters decrease to $2*10^{-18}$ $m^2$ and 30% with increasing effective pressure to 10 MPa. Specific storage shows from $5*10^{-8}$ to $1*10^{-8}$ $Pa^{-1}$. A sample from 785 mbsf has measured permeability of $7*10^{-17}$ $m^2$ and porosity of 40% at 1 MPa effective pressure and $5*10^{-18}$ $m^2$ and 31% at 10 MPa effective pressure. For both samples, permeability decreased exponentially with a decrease of porosity. Permeabilities at conditions comparable to the in-situ depth (ranging from $10^{-17}$ $m^2$ to $10^{-18}$ $m^2$) are therefore low enough that processes (1) and (2) are expected to occur. We will model these processes more specifically considering the friction properties of the plate boundary fault, temperature structure at depth and shear-induced permeability change.

Keywords: permeability, JFAST, Tohoku Earthquake, IODP Expedition 343

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# Structural heterogeneities around the shallow megathrust zone of the 2011 Tohoku earthquake

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The coseismic rupture area of the 2011 Tohoku Earthquake has estimated over the wide region from the coastline to near the Japan Trench. Several kinds of studies, such as tsunami source inversion [e.g., Fujii et al., 2011], coseismic slip inversion [e.g., Ide et al., 2011], submarine topography change [Fujiwara et al., 2011] and seafloor displacement observation [Sato et al., 2011; Ito et al., 2011; Kido et al., 2011], share the common feature that the largest coseismic slip occurred at the shallow plate boundary in close vicinity to the Japan Trench. However, the structural image just beneath the largest coseismic slip area was unclear since the observation areas of previous ocean bottom seismographs (OBSs) in this region were limited and there were few OBSs near the Japan Trench [e.g., Yamamoto et al., 2011]. To understand the relationship between coseismic rupture behavior and structural heterogeneities, it is necessary to know the seismic velocity structure of the subducted slab crust and mantle near the trench axis.

After the occurrence of 2011 earthquake, some National Universities (Hokkaido, Tohoku, Chiba, Tokyo, Kyushu, and Kagoshima), JAMSTEC, and Meteorological Research Institute together have conducted the aftershock observations along the landward slope of Japan Trench to obtain detail hypocenter distribution [Shinohara et al., 2012]. Tohoku University has performed the other OBS observation off Miyagi prefecture from 2010 to 2011. During this observation, a sequence of foreshocks, the mainshock, and aftershocks of the 2011 Tohoku earthquake were recorded [Suzuki et al., 2012]. In addition, JAMSTEC has conducted the aftershock observation at outer slope of Japan Trench, around the epicenter of a Mw 7.6 earthquake that occurred about 40 minutes after the 2011 mainshock, from May to June [Obana et al., 2012].

In this study, we performed the three-dimensional seismic tomography by combining these OBS dataset and land seismic data to obtain the fine hypocenter distribution and velocity structure around the largest coseismic slip zone of 2011 Tohoku earthquake. From the relocation results, we found that some deep intraslab earthquakes occur near the trench and their focal mechanism are normal fault type. Since these earthquakes occurred before the 2011 mainshock showed thrust type [e.g., Gamage et al., 2009], our results suggest the change of stress regime in this region. In the outer-rise area, the hypocenter distribution of the relocated shallow earthquakes has a linear trend along the horst-graben structure. Subducted oceanic crust has some heterogeneous structure around the hypocenter of the 2011 mainshock as follows: (1) relatively low Vs and high Vp/Vs zone at landward side of the mainshock location, (2) high Vs and low-Vp/Vs in the south of mainshock. These structural heterogeneities might represent the heterogeneous distribution of fluid in the oceanic crust and/or existence of subducted seamount. In addition, the velocity of uppermost slab mantle from 143 degree E to the trench axis showed low Vp, Vp/Vs (~1.70) and high Vs ($>$ 5.0 km/s). This feature might reflect the existence of strongly anisotropy in the slab mantle or indicate the locally orthopyroxene enrichment.

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Keywords: Tohoku megathrust earthquake, seismic tomography, ocean bottom seismic observation, oceanic crust

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# Rock-magnetic properties of the plate-boundary thrust material drilled during IODP Expedition 343 (JFAST)

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During IODP Expedition 343, Japan Trench Fast Drilling Project (JFAST), boreholes were drilled through the prism and across the fault that is thought to have slipped during the 11 March 2011 Tohoku-Oki Earthquake. 74 subsamples of the core recovered from hole C0019E were subjected to rock magnetic analyses to identify magnetic minerals, determine the magnetic-grain size distribution and investigate rock magnetic changes related to fault zone processes.

Magnetic hysteresis curves and backfield DC demagnetization curves of isothermal remanent magnetization were measured using a MicroMag 2900 alternating gradient field magnetometer. Hysteresis parameters (Ms, Mr, Hc, Hcr) were calculated and coercivity spectra were obtained as the derivative of DC demagnetization curves. Thermal demagnetization of low-temperature IRM acquired at 10 K and 5 T after zero-field cooling was performed with an MPMS-XL. Thermomagnetic analyses in 0.4 T and ambient pressure were carried out with a Natsuhara NMB-89 thermobalance.

Samples from the sheared scaly clay zone (Lithologic Unit 4: 820-824 m CSF, inferred to be the plate boundary decollement) clearly have low Hc and Hcr (10-13 and 22-24 mT) compared with the lower part of the frontal prism sediment (Lithologic Unit 3: 688-820 m CSF; Hc = 15-52 mT; Hcr = 45-85 mT) and the brown underthrust sediment (Lithologic Unit 5: 824-832 m CSF; Hc = 13-26 mT; Hcr = 45-85 mT), suggesting a difference in magnetic mineralogy and/or grain size. However, there is no obvious variation in magnetic properties within between the decollement zone.

As for the thermal demagnetization curves of low-temperature IRM, the samples from llithologic Unit 3 show loss of magnetization at ˜120 K, reflecting the Verwey transition of stoichiometric magnetite. In contrast, the samples from the lithologic Units 4-5 do not show significant loss of magnetization at the Verwey transition temperature. For the thermomagnetic curves, the heating branches of some samples from lithologic Unit 3 have humps above ˜400 deg C possibly caused by thermal decomposition of some iron-bearing minerals and formation of magnetic minerals during heating, while the samples from lithologic Units 4-5 do not show any humps on the heating branches. These results imply a difference in magnetic mineralogy between lithologic Units 3 and 4-5 (ie. a difference between hangingwall and fault zone / footwall).

Within Lithologic Unit 4, the lower four samples (822.07-822.48 m CSF) show large magnetization increases in the cooling branches below ˜100 deg C which might reflect the formation of magnetic minerals with low Curie temperatures during heating, compared with the upper four samples (821.54-821.78 m CSF). These samples may correspond to material that generated a peak in the on-board magnetic susceptibility log.

In summary, we found minor magnetic signals at the lower part of the sheared clay zone core sample of fault zone processes resulting from localized variation of magnetic mineralogy within the sheared clay zone samples recovered from the hole C0019E, but the origin and process of the minor magnetic variation should be further examined.

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# Sediment fabric record in the trench axis formed during the 2011 Tohoku-oki earthquake

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The rupture of the 2011 Tohoku-oki earthquake propagated to the trench. Kodaira et al., (2012) revealed that the several ten meters scale displacement of the lower landward slope of Japan Trench occurred during the earthquake. Meantime an uplifted seafloor appeared in the trench axis, and the seismic reflection image beneath the trench floor reveals a thrust up structure. These observations are important keys to understand the slip of the 2011 Tohoku-oki earthquake. In order to detail the dynamics of the slip, surface sediments around the trench deposited before and after the earthquake were studied. Surface sediment cores were collected in the upheaval and un-upheaval areas from the trench axis, and the foot of the lower landward slope using piston and gravity cores. Cores from the trench axis consist mainly of coherent hemiplegic layers. On the other side, the sediment cores in the foot of the lower landward slope is characterized by mass-transport deposits and inclined layers of hemipelagite interbeded with silt/sand layers. Anisotropy of magnetic susceptibility (AMS), which is sensitive to soft sediment deformation, was studied to detect the sediment deformation. AMS from the trench axis shows fairly foliated magnetic fabric parallel to bedding planes, and parameters of AMS suggest that no lateral compression is recorded in the surface sediment. Instead, their sediment magnetic fabric in the trench sediment involve information of paleo-current of turbidites. On the other hand, AMS from the foot of lower landward slope is characterized by randomly orientated magnetic fabric indicating chaotic depositions, and inclined magnetic fabric indicating layer tilting downslope. Those fabric patterns in the slope suggest that the surface sequence were slid toward the trench. Preliminary interpretation on those data is that AMS reveal no compressional environment in the seafloor surface but sediment transporting information. If the upheaval structure in the trench axis formed during the earthquake, it should controlled the sedimentation pattern in the trench axis. It is expected that analysis of the sedimentary fabric in the area document such pattern. It will provide an unique information to understand the deformation during the slip in the trench axis. In this presentation, we will present detail properties of sedimentation on the basis of magnetic fabric.

Keywords: the 2011 Tohoku-oki earthquake, Japan Trench, turbidite, mass-transport deposits, Magnetic fabric

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# Seismic imaging in the Japan Trench axis area off Miyagi, northeastern Japan

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On March 11, 2011, the M9 great Tohoku megathrust earthquake ruptured the plate boundary at the Japan Trench off eastern Honshu, Japan. Several seismological, geodetic and tsunami wave inversion studies indicate a large magnitude of slip (30-60m) occurred on the shallow portions of the plate boundary. Differential bathymetric and seafloor geodetic studies also document large coseismic displacement near the trench. Thus, it is important to understand the detailed structure of the shallow portion of the subduction zone and the trench axis area of the Japan Trench to evaluate mechanisms of deformation and the geometry of the structures that accommodated shallow slip.

We conducted a high resolution reflection seismic survey in the vicinity of the Japan Trench axis off Tohoku in October-November, 2011. The high-resolution seismic profiles we obtained successfully image the detailed structure around the Japan Trench axis, and were used for site selection of the rapid response drilling program for IODP Expedition 343 (JFAST). We identify four seismic units in the study area: an acoustically transparent frontal wedge (Unit I), a sequence of parallel continuous reflections interpreted as sediments on the incoming plate (Unit II), a sequence of relatively strong reflections correlated to chert recovered in DSDP Site 436 (Unit III), and acoustic basement of the Pacific plate (Unit IV). The incoming Pacific plate sediments, including the basal chert layer (Units II and III), have been offset by normal faulting during plate bending seaward of the trench. Mapping of the relief on the igneous oceanic basement (Unit IV) shows that the trench axis in the survey area is located in a graben. The relief observed on the basement landward of the trench is related to the subduction of horsts and graben formed seaward of the trench. The hemipelagic/pelagic sediments (Unit II) overlying the basal chert layer (Unit III) are imbricated at the trench axis. The detachment surface is located slightly above the top of the chert-rich layer (Unit III) in the trench axis graben. We observe a seaward-dipping reflection branching off the top of the chert-rich layer (Unit III) at the edge of a horst block at the base of the landward trench slope. This reflection short-cuts the horst-graben normal fault, and soles into a horizon slightly above the top of chert-rich layer (Unit III) in the trench graben. This reflection is interpreted as a part of the decollement in the lowermost Japan Trench inner slope, and was likely generated by an increase of the loading and failure of the underthrust hemipelagic/pelagic sediments. The imbricate structure of the graben-fill sediments could have been developed by a combination of aseismic deformation as well as repeated megathrust earthquakes which caused failure and slip along the seaward dipping decollement. These data clearly image structures resulting from deformation and sediment subduction at the Japan Trench in the region that ruptured during the March 11, 2011 great Tohoku earthquake.

In January 2013, we carried out another seismic survey around the JFAST drill site using larger volume of sounding sources, longer streamer cable, and ocean bottom seismographs. Preliminary processed data provide seismic profiles with enhanced quality in the deeper portion. We will also present the velocity model deduced from the analysis of these seismic data.

Keywords: seismic image, Japan Trench, Tohoku earthquake

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# New approaches to advanced GPS/A geodetic observation on the seafloor

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(1) A plan for better positioning in shorter time

The 2011 Tohoku-oki earthquake was accompanied with exceptionally large coseismic slips near the trench axis, where land-based GPS has little resolution on the seismic coupling on the plate boundary. Then we have added 20 GPS/A observation sites along the Japan Trench for the Japanese geodetic group with a fund from the MEXT Japan. The Japan Coast Guard has also added 9 observation sites along the Nankai Trough. Although there still remains a big difference from the GPS networks on land, the extension of the GPS/A observation was a big progress. On the other hand, it requires more ship time. We have to solve this problem to fill the gaps such as the area near the Nankai Trough axis. Since we have spent half a day or a full day at a site for GPS/A observation, the first thing we should do is to reduce the time at a site.

We have estimated from our observation results that a breakthrough for the problem would be measurement of horizontal gradients of sound speed in the surface layer of the ocean. The group of Nagoya University had proposed to carry out acoustic positioning by using a few moored buoys. We have found that an important point in such positioning lies in nearly simultaneous acoustic ranging from two surface units apart at certain distance to four precision acoustic transponders (PXPs). Then we can roughly measure a sound speed gradient in the direction connecting the two surface units. The value in any direction can be obtained by changing the positions of the surface units. After some trials to get know-hows, we can reduce the observation time to get a repeatability of a few centimeters. If three surface units are available, a precise position can theoretically be obtained at each acoustic positioning. The Japan Trench area is one of the major fishery fields in the world, and many fishery nets longer than 10 km are extended there. We hope to carry out experiments at an appropriate site to validate this method consulting with fishermen.

(2) An approach to semireal-time continuous observation

Real-time continuous observation is the final goal of seafloor geodetic observation. A realistic target for the moment will be to get daily or weekly positions of the seafloor. There are two major problems in the way to semireal-time continuous GPS/A observation. Firstly GPS/A observation needs sea surface vehicles for the GPS positioning. A self-navigating buoy called Wave Glider can sail at about 1.5 knot with the power of surface waves of the ocean. It can survive in the rough seas associated with typhoons. We estimate that two sets of Wave Gliders or a pair of moored buoy and a Wave Glider can solve the first problem.

The second problem is precise GPS positioning. The kinematic GPS method we have used needs sending the GPS data from the sea surface unit to a land station. This requires satellite data transmission at least 4800 baud, for which we are studying a solution with a group of the JAXA. Recently we have found a tentative solution. Yamamoto et al. (this meeting) evaluated the stability of the kinematic solution of a station on land with the corrected signal by the StarFire system in October 2012. They confirmed that the standard deviation of the horizontal solutions is less than 1.5 cm. And also, the obtained time series is within 2 cm from the daily position by the GIPSY-OASIS II software version 6.1.2, which we use for the kinematic GPS positioning.

The battery capacity of the PXPs newly deployed in 2012 can respond about 20 times every day in a long-term observation. We expect that three surface units can get several centimeters of repeatability. Although the daily cost for the StarFire and the Iridium is much less than that for ship time, one week will be the minimum interval, if the observation continues for a year or longer. We need less expensive satellite data telemetry to get daily GPS/A positions for long time.

Keywords: seafloor geodetic observation, GPS/A, Tohoku-oki earthquake, seismic coupling, horizontal gradient of sound speed, daily position

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# Precursory Seismic Activity Surrounding the High-Slip Patches of the 2011 Mw9.0 Tohoku-Oki Earthquake

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The 2011 Tohoku-Oki earthquake (Mw9.0) was preceded by foreshock activity that occurred north of the main-shock epicenter two days earlier. The epicentral area of the foreshock activity is almost the same as that of the prominent seismic activity in 1981 [Ando and Imanishi, 2011; Shao et al., 2011a]. The question arises, why did the 1981 event not trigger an event like the 2011 Tohoku-Oki earthquake? The time difference of 30 years is negligible in comparison with the long time required for the slip deficit of more than 40 m. In order to address this problem, we investigated the long-term seismicity pattern with reference to the slip distribution of the Tohoku-Oki earthquake. We used the earthquake catalogue compiled by the Japan Meteorological Agency (JMA) for the past 90 years since 1923. We assume that the variation of frictional strength on the megathrust, as suggested by the slip distribution of the Tohoku-Oki earthquake, would manifest itself in the spatio-temporal distribution of seismic activity.

The slip distribution of the Tohoku-Oki earthquake we obtained from the coseismic displacements of the GEONET and sea-bottom stations is characterized by a low-slip zone sandwiched between the two patches of high slip ( 20m) along the Japan Trench. The epicenters of the foreshock activity are distributed over the boundary between the low-slip zone and the two high-slip patches (LHSB seismic zone), where other prominent activity had been accommodated during the past 90 years. The main-shock initiated near the junction of the northern edge of the southern high-slip patch and the mid-asperity seismic zone that divides the southern high-slip patch into two parts. The main-shock was able to rupture the western half of the southern high-slip patch, which is located down-dip of the main-shock epicenter, because the stress increased by the foreshock activity surpassed its strength. However, we infer that it is not only because the foreshock activity was the largest to have ever occurred in the LHSB seismic zone, but also because the western half of the southern high-slip patch had been sufficiently weakened by surrounding events since 2003. A substantial reduction of its strength might have been caused by the 2003 M6.8 event in the mid-asperity seismic zone and the 2005 events in the area of characteristic events such as the 1936 and 1978 Off-Miyagi earthquakes. The afterslip of the 2008 and 2010 events off the coast of Fukushima prefecture might also have contributed to weakening the western half of the southern high-slip patch. The last significant stress change was caused by the foreshocks that occurred along the northern edge of the southern high-slip patch one day before the main-shock.

The following rupture of the eastern half of the southern high-slip patch, which is located up-dip of the main-shock epicenter and includes an area of slip greater than 60 m, was probably made possible because that portion had also been sufficiently weakened by the surrounding events since 2003. The contribution of the 2003 activity extending along the southern edge of the center of the southern high-slip patch may be important because no prominent activity had occurred there before. A couple of moderate-sized events on the eastern edge of the southern high-slip patch might also have made important contributions. We infer that the foreshocks occurring along the northern edge of the southern high-slip patch also played an important role for weakening of the center of the southern high-slip patch. Lastly, the main-shock was able to expand to its large size by rupturing the center of the southern high-slip patch. The magnitude of the slip caused the subsequent ruptures of adjacent areas including the northern high-slip patch. The doughnut-shaped seismicity pattern that formed around the center of the southern high-slip patch is considered to be due to the presence of an extremely strong area on the megathrust.

Keywords: Off the Pacific coast of Tohoku Earthquake, Tohoku-Oki earthquake, Pacific plate, subduction zone, precursory seismic activity, foreshock activity

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# Aftershock seismicities of three great earthquakes and their implications for lithospheric deformation

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Assessment of influence of great earthquakes on reginal seismicity is high priority for seismic hazard mitigation. However, the properties of aftershock seismicity have not been fully understood. Since 2004, there were three great earthquakes with magnitudes greater than 8.8, which are the 26 December 2004 M9.1 Sumatra-Andaman earthquake, the 27 February 2010 M8.8 Maule earthquake, and the 11 March 2011 M9.0 Tohoku-Oki earthquake. In this study, we investigate the seismicities and focal mechanism solutions of earthquakes in the three regions that belong to active convergent plate boundaries. The seismicities and focal mechanism solutions of the earthquakes before and after the great earthquakes during 2000-2012 are investigated by time period, focal depth, and faulting type. It is observed that the numbers of events increase abruptly right after the great earthquakes, and decrease gradually with time. Thrustal earthquakes occur dominantly in the regions. It is observed that a large number of strike-slip events occur in the Sumatra-Andaman region after the great earthquake. On the other hand, thrustal earthquakes are still most dominant in the Maule region after the great earthquake. Also, we find large numbers of shallow-focus normal-faulting events in the Tohoku-Oki region after the great earthquake. It is intriguing to note that all three regions present shallow-focus normal-faulting earthquakes that are clustered around the slab boundaries with large slips. Thrustal earthquakes are found to be clustered around the slip edges. The observation suggests that the ambient stress field changes by the slip amount. The occurrence of normal-faulting earthquakes in large slip regions can be explained as a result of lithospheric elastic rebounds of plates after the great earthquakes.

Keywords: aftershock, seismicity, focal mechanism, b value, lithospheric deformation