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

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

Japan Geoscience Union Meeting 2013
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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

Japan Geoscience Union Meeting 2013
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SSS01-04 Room:302 Time:May 19 11:45-12:00

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

Japan Geoscience Union Meeting 2013
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SSS01-06 Room:302 Time:May 19 12:15-12:30

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

Japan Geoscience Union Meeting 2013
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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

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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

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

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

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

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

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

SSS01-14 Room:302 Time:May 19 15:45-16:00

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

SSS01-15 Room:302 Time:May 19 16:15-16:30

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

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

SSS01-16 Room:302 Time:May 19 16:30-16:45

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

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

SSS01-17 Room:302 Time:May 19 16:45-17:00

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

SSS01-18 Room:302 Time:May 19 17:00-17:15

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

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

SSS01-19 Room:302 Time:May 19 17:15-17:30

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

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

SSS01-20 Room:302 Time:May 19 17:30-17:45

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