microscopy as well as X-ray techniques, that the mineral assemblages in the ultracataclasite formed after the cessation of motion along the fault, and that fault-related mineral assemblages have been overprinted by post-faulting alteration. This illustrates how detailed characterizations of the phyllosilicate mineral assemblages in the SAFOD Pilot Hole can be used to constrain interpretations of exhumed fault zones by establishing a baseline characterization of phyllosilicate mineral assemblages at depth. This allows for the recognition of fault-related and non-fault-related phyllosilicates in exhumed fault zones, aiding interpretations of fault strength and permeability structure, both of which can be strongly influenced by phyllosilicates.

T41D-0264 0830h POSTER

Predicting Macroscale Physical Properties Using Microscale Image Data

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Geologic materials, including tight crystalline rocks, shales, and weakly consolidated sandstones and limestones, exhibit geometrically complex microscale structures that control physical and mechanical properties at the macroscale. The past decade has seen remarkable development of several new techniques that enable high-resolution three-dimensional imaging of the pore structure of complex geomaterials. This, coupled with advances in numerical simulation methods, computer hardware, and development of fast computer architectures, provides unprecedented opportunities for the prediction of bulk physical and/or mechanical properties directly from microscale image data. We present data obtained using the two highest fidelity methods for 3D imaging, synchrotron computed microtomography and laser scanning microscopy, and discuss the advantages and disadvantages that each method presents in the specific context of microscale imaging and subsequent use of 3D image data in numerical simulations. We also contrast the application of these modern techniques with conventional serial sectioning techniques. We directly apply the image data in massively parallel numerical simulations of single phase fluid flow. Using data obtained for several natural and synthetic sandstones at a range of resolutions and encompassing different solid volumes, we explore fundamental issues related to representative volumes and length scales necessary to characterize geometrically complex porous media and enable accurate prediction of physical properties at the macroscale. This work was performed at Sandia National Laboratories funded by the US DOE under Contract DE-AC04-94AL85000. Sandia is a multiprogam laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

T41E MCC: 2002-2004 Thursday 1020h

At the Seismogenic Front: Dynamic Processes at Convergent Margins II *(joint with G, S)*

Presiding: **S Bilek,** New Mexico Institute of Technology**; Y Liu,** Harvard University

T41E-01 1020h INVITED

Friction Mechanics at the Updip Limit of Seismogenic Faulting Along Subduction Megathrusts.

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The mechanical behavior of plate boundary fault zones can be divided into three main zones: a deep aseismic zone, the seismogenic zone, and an updip aseismic zone. Identifying and understanding the stability transitions from seismic to aseismic faulting are key goals in understanding subduction zone megathrusts. We focus on the mechanics and frictional properties of the upper stability transition from stable to unstable faulting. Two hypotheses for the updip limit of subduction seismicity have been proposed. The clay mineral hypothesis posits that a thermally- driven transition from dominantly smectite to dominantly illite clay produces a transition from aseismic to seismic behavior. The consolidation/lithification hypothesis posits that the stability transition is the result of a change from distributed granular shear, in which aseismic behavior is related to grain crushing, consolidation, and strain- rate dependent dilatancy, to localized shear within highly consolidated material, for which unstable friction behavior results from properties of adhesive contact junctions. We summarize laboratory friction data and constitutive laws in the context of requirements for unstable faulting. We report on laboratory experiments designed to investigate the frictional behavior of smectite-illite clays and clay-quartz mixtures, with emphasis on processes that control frictional stability. Double-direct shear friction experiments were carried out on powders (2-500 5 μm) at normal stresses from 5-150 MPa, sliding velocities from 0.1-200 μm/s, and shear strains up to 20 at room temperature. We find that the coefficient of friction (μ) is 0.42-0.68 for illite shale, consistent with previous work. Over the full range of conditions studied, illite shale exhibits only velocity-strengthening behavior, opposite to the widely expected, potentially unstable velocity- weakening behavior assumed in the clay mineral hypothesis. Smectite sheared under identical conditions exhibits low friction (μ = 0.15-0.32) and a transition from velocity weakening at low normal stress to velocity strengthening at higher normal stress (>35 MPa). Our data suggest that the transformation of smectite to illite results in an increase in friction, but do not support the hypothesis that the smectite-illite transition is responsible for the seismic-aseismic transition in subduction zones. We show that mixtures of smectite and quartz undergo a transition from adhesive frictional behavior, in which contact junctions exhibit time-dependent behavior and friction exhibits rate and state properties, to viscous behavior in which shear strength is purely rate dependent. We suggest that processes, such as cementation, consolidation, and slip localization, play an important role in determining the updip limit of the seismogenic zone in subduction zones, and that these processes, in addition to clay mineralogy, should be the focus of future investigations.

T41E-02 1035h

The Upper Aseismic to Seismic Transition: A Silica Mobility Threshold

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The up-dip portions of accretionary subduction zone decollements slide stably and are therefore aseismic, but become seismogenetic at a depth of 5-15 km. Thermal models of modern subduction zones and accretionary wedges predict that the aseismic-seismic transition occurs at 100-150°C. This correlation between temperature and the onset of seismogenesis suggests that fault behavioral properties are modified by a diagenetic-metamorphic reaction affecting the fault zone mineralogy. The Kodiak Accretionary Complex, Alaska, is a well-exposed sediment wedge associated with Mesozoic through recent Aleutian subduction. We compare two tectonic units that were subducted, one to just above the seismogenic transition, and one to within the seismogenic zone. The Eocene rocks were subducted to approximately 2.4-3.9 km and experienced temperatures of 100-125°C before accreting into the wedge. The Paleocene rocks subducted to 10-14 km (280-320 MPa) and reached 215-290°C. Both formations host disrupted zones interpreted as paleo thrust faults by previous authors, which were probably associated with paleodecollement systems. Quartz cementation is rare in the paleo-thrust faults of the Eocene rocks but ubiquitous and extensive in the paleo-thrust faults of the Paleocene rocks, in fault-parallel and fault-crossing geometries. We suggest that the formation of a quartz network along and across fault zones may cause the onset of seismogenesis. The frictional behavior of sheet silicates is generally velocity strengthening, resulting in stable sliding behavior, while quartz exhibits velocity weakening, or stick-slip frictional behavior. Thus, the aseismic-seismic transition may be controlled by quartz mobility and the appearance of volumetrically significant quartz ± calcite precipitates filling, coating, and cementing fault surfaces, creating "deadbolts" across slip surfaces, establishing frictional control over surfaces whose properties were previously controlled by sheet silicates.

T41E-03 1050h

Seismic activity in the Japan Trench forearc from network observation in the seafloor

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In the forearc region of off-Sanriku area in the Northeast Japan Arc, subduction of the Pacific plate beneath the arc gives rise to seismogenesis of smallest to M7-class earthquakes. Seismicity in the area shows non-uniform distribution of earthquakes and its relation to the structural heterogeneity at the plate boundary has been suggested. Such a structural heterogeneity may relate to horst and graven structure of the subducting plate that is prominent in the oceanic crust of the Pacific plate before subduction in the area. The subducting plate motion is accommodated by deformations and displacements near the plate boundary. Condition of the plate boundary is subject to change under subduction. This, in turn, control the manner of seismogenesis and are observed as non-uniform seismicity, transition of earthquake mechanisms, or possible aseismic slip in the plate boundary. In order to understand such processes, observation of seismic activity to define precise location and mechanisms of earthquakes in relation to the subducting plate geometry is important. As the occurrence of large earthquakes account for only about 30 % of the plate motion of about 10 cm/y across the Japan Trench, we also need to search for possible slow slip in the area. Existing land observatories, which are apart from the area by more than 100km, are inappropriate for these targets. Therefore, we deployed network of seafloor instruments consisted of borehole seismo-geodetic observatories, seafloor pressure gauges, and arrays of ocean bottom seismometers (OBS) in the forearc region of off-Sanriku area. Two borehole observatories (JT1 and JT2) were installed in 1999. We installed 2 broadband seismographs (CMG1T and PMD2123), tiltmeter (AG510), and a strainmeter. Sensors are buried near the hole bottom approx. 1.1km below seafloor. With these state-of-art borehole sensors situated only 10km above the plate boundary, we expect earthquakes and slow crust deformation observed at the highest precision. We have conducted maintenance cruises to the borehole observatories, and recovered total of a half-year data from JT1 and two sets of 3-month data from JT2. The long period performances of the borehole observatories are good enough for tidal tilting of the boreholes to be observed. The seafloor pressure gauges (Paroscientific 8B7000) deployed adjacent to the JT1 and JT2 sites are useful to detect vertical crustal movement as small as a few millimeters. In June 2003, we recovered the first 8-month data from near JT1 site. We started 1-year pressure observation at the two sites from June 2003. Series of OBS array deployments in 2001, 2002 and 2003 of each several months enabled us to get detailed image of earthquakes with plate subduction in this area. In 2002, we deployed 17 OBS at 7-15km spacing around the JT2 site. During the deployment, we also shot airgun along 5 seismic lines on the OBS network. In 2003, we focused on the JT1 site deploying 5 OBS in 5 n.m. separations from the JT1 borehole, and we made simultaneous observation with the JT1 and JT2 borehole. From the year 2002 OBS dataset, clusters of microearthquakes are clearly imaged near the depth of plate boundary, and a small number of earthquakes are identified below the oceanic crust of the subducting plate. The airgun shot data along with the seismic structure obtained from previous airgun-OBS surveys enables us to correlate the seismicity with the crustal structure under the network.

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T41E-04 1105h

Seismicity along the Nankai trough seismogenic zone: results from micro-seismicity observations using ocean bottom seismographs

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Along the Nankai Trough, southwestern Japan, the Philippine Sea plate is subducting beneath the Eurasian plate with a convergence rate of about 4 cm/year. Large interplate thrust earthquakes that are caused by the subduction of the Philippine Sea plate have occurred repeatedly. Records of the great earthquakes can be seen in historical documents since the seventh century and the recurrence interval between them is about 100-200 years. Most recent events are the 1944 Tonankai and 1946 Nankai earthquakes occurred in the eastern and the western part of the Nankai trough, respectively. On the other hand, current seismicity is very low and hypocenters are not determined accurately by the land seismic network. Many seismic surveys using controlled sources have been conducted to obtain crustal structure at the Nankai trough seismogenic zone. We performed micro-seismicity observations using ocean bottom seismographs at the coseismic slip area of the 1944 Tonankai and 1946 Nankai earthquakes. Hypocenters were determined using 2- or 3-D realistic velocity structure based on the results of the seismic surveys. Off cape Muroto, fault area of the 1946 Nankai earthquake, several micro earthquake clusters locate around the plate interface. The seaward limit of the seismicity is characterized by clusters of earthquakes with very similar waveforms. These clusters locate about 30-45 km landward from the deformation front and coincide with the stepping down of the decollement. These earthquakes are considered to occur at small asperities in the aseismic-seismogenic transition zone of the plate interface. Off Kii peninsula, the rupture area of the 1944 Tonankai earthquake, seismicity is locally active near the axis of the Nankai trough. Although the depths of these earthquakes are not constrained well, they are considered to be shallower than the Moho of the subducting oceanic crust. On the other hand, micro-seismicity in the rupture area of the 1944 Tonankai earthquake is very low. The recent GPS survey shows a fully coupled plate interface along the Nankai trough seismogenic zone. Analyses of the seismic and tsunami waves show a uniform distribution of the coseismic slip during the 1944 Tonankai Earthquake. These facts imply an existence of a large asperity with a uniform interplate coupling off Kii Peninsula.

T41E-05 1120h

Geometry and velocity structure of the northern Costa Rica seismogenic zone from 3D local earthquake tomography

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We present results of a 3D local earthquake tomography study of the Middle America Trench seismogenic zone in northern Costa Rica. Local earthquake tomography can provide constraints on the updip, downdip, and lateral variability of seismicity and P- and S-wave velocities; these constraints may in turn provide information on compositional and/or mechanical variability along the seismogenic zone. We use arrival time data recorded by the Nicoya Peninsula seismic array, part of the Costa Rica seismogenic zone experiment (CRSEIZE), a collaborative effort undertaken to better understand seismogenic behavior at the Costa Rica subduction zone using data from land and ocean bottom seismic arrays, oceanic fluid flux meters, and GPS receivers. We invert $\sim$10,000 P-wave and S-wave arrival times from 475 well-recorded local earthquakes (GAP $< 180^\circ$, $>$8 P-wave arrivals) to solve for the best-fitting 1D P- and S-wave velocity models, station corrections, and hypocenters using the algorithm VELEST. These 1D velocity models are used as a starting models for 3D simultaneous inversion using the algorithm SIMULPS14. Preliminary P-wave inversions contain a positive velocity anomaly dipping beneath the Nicoya Peninsula, interpreted as the subducting Cocos Plate. Earthquakes occur in a narrow band along the slab-continent interface and are consistent with the results of *Newman et al.* (2002). The updip limit of seismicity occurs $\sim$5 km deeper and 5-10 km landward in the northern vs. the southern Nicoya Peninsula, and this shift spatially correlates to the change from Cocos-Nazca to East Pacific Rise derived oceanic plate. P-wave velocities in the upper 5-10 km of the model are consistent with the geology of the Nicoya Peninsula. We will correlate relocated microseismicity to previously noted variability in oceanic plate morphology, heat flow, fluid flow, and thermal structure and compare the resulting P- and S-wave velocity models to wide-angle refraction models and hypothesized mantle wedge compositions.

T41E-06 1135h

Transient Fluid Pulsing and Noise in the Costa Rican Subduction Zone: Nearly Silent Slip Events?

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Long-term measurements of fluid flow were made across the Costa Rica (Pacific) convergent margin utilizing a recently developed osmotically driven Chemical and Aqueous Transport (CAT) meter designed to quantify both inflow and outflow rates on the order of 0.01 to 1500cm/yr. As part of the study 14 ocean bottom seismometer (OBS)/CAT meter combinations and another 7 autonomous CAT meters were deployed across the Costa Rica margin northwest of the Nicoya and Osa Peninsulas for respective periods of about 180 and 75 days. Significant transience in flow was observed both on the incoming plate and through the surface of the forearc. A series of pulsed flow events on the incoming plate suggest significant repeated transient episodes of volumetric dilation that could relate to dilational hardening and the onset of instability prior to a Mw 6.4 normal faulting event in the outer rise region of the trench. Three periods of correlated flow signals are also seen on the trench slope of the subduction zone. These elevated flow events are seen between several instruments located in the out-of-sequence thrust (OOST) zone over along-margin strike distances of aprox. 30 km. The causes of the transience are still being investigated but seismic "noise" on the local OBS instruments also picks up during three correlated flow events at one site (i.e. there are three associated periods of elevate seismic noise). The noise was originally a broad band signal and appears to be transmitted as S-waves who's frequency content is locally modified by a soft substrate under the instrument location. The grouping of three flow events, and three elevated seismic "noise" events argues against coincedence. The flow signals do not correlated with instruments further up the trench slope or on the incoming plate. The toe or OOST structure therefore seems to be highly sensitive to what we postulated are episodic tectonic volumetric strains and associated hydrologic pulsing. We suspect the strain events are associated with the propagation of slow lateral rupture along the subduction thrust to the toe of the wedge. Our current working hypothesis is that a component of the plate boundary slip at shallower depths is occurring via slow nearly silent rupture processes that occur discontinuously on a critically stressed Nicoya segment.

T41E-07 1150h

Fluidization of Fault During Slip: A Possible Mechanism of low Dynamic Friction During the 1999 Chi-Chi, Taiwan Earthquake and Implication for Seismic Slip Along the Splay Fault in the Nankai Accretionary Prism

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The 1999 Chi-Chi, Taiwan earthquake (Mw7.6) caused a spectacular surface rupture along the Chelungpu thrust fault in the uplifted accretionary prism. The near-field strong-motion data obtained during this earthquake provided an invaluable opportunity to examine what dynamic process in the fault controls the large slip with low level of high-frequency seismic radiation. The Chelungpu fault drilling project involved drilling through the possible rupture zone within the upper 350 meters of the ground surface. Structural and physical property analyses of the possible rupture zone and high-velocity, undrained ring shear experiments using simulated material suggest that the fault was fluidized during the seismic slip. When the decay time of pore pressure in the fault due to diffusion in wall rocks is longer than duration of seismic slip, the fault composed of granular material in a loose state could lose frictional resistance due to fluidization. In general, unconsolidated material within the shallow portion of fault has a stable frictional slip property. However, if the shallow portion of fault is fluidized during earthquake, the seismic slip may propagate upward from seismogenic depths into the frictionless fault in a stable slip regime. This dynamic process appears to induce the seismic slip with low level of high-frequency seismic radiation during the Chi-Chi earthquake and may be applicable to fluid-saturated faults in accretionary prisms. We suggest that faulting under drained/undrained condition and consolidation state of fault before earthquake will control upward propagation of seismic slip from seismogenic zone into a stable slip regime.

T41E-08 1205h INVITED

Source Process of the 1999 Chi-Chi, Taiwan Earthquake: Comparisons to Shallow Faulting in Subduction Zones

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The 1999 Chi-Chi, Taiwan earthquake (Mw 7.6) occurred along a zone of rapid convergence in central Taiwan. Since there were large amounts of slip at shallow depths on the Chelungpu fault (8 to 10 meters of thrust faulting at depths of a few kilometers to the surface), the earthquake provides a first-hand opportunity to study many of the physical properties associated with large slip on a fault. There has been a large variety of geological and geophysical observations of this event, including, a dense network of strong-motion instruments that recorded the earthquake, GPS observations of the pre-, co- and post-seismic deformation rates, borehole sampling into the fault, and surface geology studies. The combination of these studies produces one of the most complete pictures of the source process of a large thrust earthquake. Especially, the detailed imaging of the area of large slip in the northern part of the fault provides information about the fault dynamics that may control the large amounts of slip on a fault. The faulting process appears very different between the large slip areas in the north and the more moderate slip regions in the south. The large slip regions in the north appeared to be associated with 'smooth' rupture, that generated relatively low levels of high-frequency radiation and caused relatively low levels of damage. This is in contrast to the more typical high-frequency radiation produced by the fault in the south, which caused considerably more damage, even though the amounts of fault slip were less. The rather unusual characteristic of the large slip in the north may be associated with low levels of dynamic friction on the fault. The thrust faulting of the Chi-Chi earthquake may be similar to the shallow faulting in subduction zones, such as the Nankai Trough. The geometry of the Chelungpu fault, which is connected to more shallowly dipping fault structures at depth, is similar to the splay faults that are mapped in the Nankai subduction zone. For the Nankai trough, it is unclear if slip on the splay faults occurs during the great subduction earthquakes or in separate earthquakes. Part of the answer to this question may come from the results of current projects, such as the borehole sampling of the Nankai splay faults and comparisons with similar borehole samplings of the Chelungpu fault.