els. The approach consists of two steps. First the large-scale mantle flow field is calculated in a global model, in the whole mantle. This global and robust flow field serves as a background flow in the regional model, in which the interaction of the mid-Atlantic ridge and the Iceland plume is calculated. A time-dependent model of the large-scale mantle flow field was obtained by using paleogeometries of the Atlantic and Eurasian plates reconstructed from magnetic anomalies and by advecting density anomalies backward in time. The motion of the plume source on the bottom of the model box is calculated according to the distortion of an initally vertical plume conduit in the large-scale mantle flow field. In the regional model the changing large-scale flow field and the moving plume source are introduced as time dependent boundary conditions. In this way, the interaction of the Iceland plume and the mid-Atlantic ridge is investigated in a 3D model containing detailed ridge geomtery. Results with time independent boundary conditions show that the large-scale mantle flow field controls the development of the plume. In the regional model the plume is tilted to the north in the upper mantle, which is also shown by seismology. However, the northward channeling of the plume material in the model does not explain the geochemical anomalies, which show an increased plume influence south of Iceland. Simulations with time dependent boundary conditions (time dependent ridge geometry and plume source position) modify this channelling of plume material and give a more precise view of plume-ridge interaction.

T41C-0243 0830h POSTER

The Dynamics of Slab detachment: Process Initiated by Melting of Subducted Crust

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It is well recognized that slab detachment or breakoff is a realistic geological process, as shown by recent tomographic imaging [1]. Using 2-D upper-mantle model with an area of 660 km deep and 2000 km wide we have investigated with a finite-difference and marker numerical technique the multi-resolutional character of thermomechanical phenomena related to this complex geological process. We have used up to 50 million markers on a shared-memory computer for delineating the complex multiscale structures in the composition, viscosity, accumulated strain, shear heating, and other field variables. Our experiments show that this process can be initiated by slab weakening due to the thermal relaxation of the slab and related melting of the subducted oceanic crust. The melting propagates within the subducted oceanic crust at the top of the slab occurring at the restricted depth interval of 100 to 200 km defined by the non-linear dependence of wet solidus temperature of the oceanic crust with pressure. The detachment process is self-accelerating due to the strain and thermal erosion focussing and strong thermal feedback from the shear heating. Slab detachment develops around 10% faster with viscous dissipation included, thus showing the importance of shear heating in this process. Detached slab rapidly fall down having a tendency of coherent rotation. This may produce near horizontal relatively cold slab fragments laying on denser mantle at 660 km discontinuity. Influence of a temperature- and pressure-dependent thermal conductivity for the process of thermal relaxation of the slab is significant. Overall 20% increase in thermal conductivity of mantle produce 20% decrease in timescale of detachment. This support the idea that breakoff process is mainly driven by focussed thermal erosion with timescale linearly dependent on heat conductivity. Rapid changes in topography and significant volcanic activity due to the massive melting of subducted oceanic crust during the slab detachment process are plausible consequences of this vigorous geodynamic scenario. [1] Levin, V., Shapiro, N., Park, J. and M. Ritzwoller, Seismic evidence for catastrophic slab loss beneath Kamchatka, Nature, 418, 763-767, 2002.

T41C-0244 0830h POSTER

Slab Dynamics and Non-Newtonian Rheology in the Upper Mantle

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One of the fundamental aspects of plate tectonics and mantle convection in the Earth is one-sided subduction of plates at trenches with apparent slab dips ranging from 30° to 90°. While this aspect of plate tectonics is not often reproduced in large scale mantle convection simulations, the importance of slab dip to the thermal structure of the slab-wedge system has lead to numerical models of slab thermal structure, which fix the slab dip at a specified value and impose one-sided subduction.Understanding the balance of forces that lead to the range of observed slab dips can provide constraints on the viscosity structure of the shallow mantle and the importance of phase changes in modifying the buoyancy forces driving subduction. We present 2-D, time-dependent, finite element models of thermal convection exploring the dependence of slab dynamics on the viscosity structure and phase changes in the upper mantle. The viscosity structure evolves in time and is defined by a composite rheology which is temperature, pressure and strain-rate dependent, including both diffusion (Newtonian) and dislocation (non-Newtonian) flow laws and a yield criterion at low temperatures. The plate boundary within the lithosphere is included as a narrow shear zone with low viscosity. We find that slab dynamics are strongly dependent on the assumed boundary conditions and proximity of the subduction zone to the side boundaries.Flat slab subduction and/or two-sided subduction often occurs for models in which the viscosity is not strain-rate dependent. The strain-rate dependence of viscosity can lead to weak regions that cut through the full thickness of the subducting lithosphere within the subduction zone, producing steeply dipping slabs.

T41C-0245 0830h POSTER

On the Curvature of Oceanic Arcs

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The key feature of plate tectonics is the subduction of cold oceanic plates into a hot convective mantle. These subducting plates, as seen from the surface, mostly portray a distinct concave arc shape at the trench with respect to the leading edge of subduction. The origin of arc curvature is not yet understood. A common belief is that it is probably an effect of the Earth's sphericity. However, the spherical effect of the Earth creates convex, long-wavelength arc shapes. We thus investigate whether concave arc curvature can be explained by: (1) Exogenic feedback between the migrating lithosphere and the secondary induced mantle flow, (2) Endogenic heterogeneities within the lithosphere itself, e.g. owing to differences in cooling ages of the plate at the trench. Although both mechanisms create concave arcs, for isolate subduction systems, only the endogenic effects are sufficient to explain the magnitude of observed arc curvature. We compare our results to the Aleutian and Sandwich arcs. Our method is based on a novel 3-D numerical tool. We model the subduction process as a solid (lithosphere) - fluid (mantle) interaction. Two different numerical methods are used to solve for the constituents: Implicit Finite Element (FEM) for the lithosphere and Implicit Boundary Elements (BEM) for the mantle. The methods are chosen on the basis of a critical isotherm allowing a fluid mechanical approximation of the full continuum-mechanical problem above 1200 K. Thus the calculus of an approximate average drag effect is feasible through semi-analytical methods. This approach extends the 2-D setup of Funiciello et al., (JGR, 2003) into 3-D by adding the BEM solution. The BEM method builds on the stokeslet theory as a semi-analytical solution for the mantle drag. It shows that the drag mainly depends by the integration of the singularities at the lateral extremities of the slab.

URL: http://www.sg.geophys.ethz.ch/geodynamics/gabriele/

T41C-0246 0830h POSTER

Blob Tracing Models for the Central Mexican Volcanic Belt

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The numerical model of steady state temperature and velocity fields in the mantle wedge of the Central Mexican Volcanic Belt (CMVB) is used to compute a dynamic model of buoyant blob tracing in the non-newtonian mantle wedge velocity field. Considering that the main component of the volcanic material is generated by the melting processes on the subducting plate surface, a dynamic model simulating the motion of detached blobs in a viscous mantle wedge flow was developed. The blob's motion is determined by the action of drag, mass, and buoyancy forces in the mantle wedge velocity field. The blobs of the realistic diameter of 0.2 - 2.0 km show very different trajectories only at very low wrapping viscosity (1015 Pas). The blob rise time which is necessary to reach the bottom of the continental crust is from 0.04 up to 12.5 million years depending on the plume diameter and surrounding viscosity.

T41D MCC: Level 1 Thursday 0830h

Deformation Mechanisms: From the Lab to the Lithosphere I Posters *(joint with V, MR)*

Presiding: **I Katayama,** Yale University**; D L Goldsby,** Brown University

T41D-0247 0830h POSTER

Dislocation Creep in Magnesium Calcite

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To investigate the effect of dissolved Mg on plastic deformation of calcite, we performed triaxial deformation experiments on synthetic calcite with varying amount of Mg content. Mixtures of powders of calcite and dolomite were isostatically hot pressed (HIP) at 850°C and 300 MPa confining pressure for different intervals (2 to 20hrs) resulting in homogeneous aggregates of high-magnesium calcite; Mg content varied from 0.07 to 0.17 mol%. Creep tests were performed at differential stresses from 20 to 160 MPa at 700 to 800°C. Grain sizes before and after deformation were determined from the images obtained from scanning electron microscope (SEM) and optical microscope. Grain sizes are in the range of 5 to 20 microns depending on the HIP time, and decrease with increasing magnesium content. Both BSE images and chemical analysis suggest that all dolomite are dissolved and the Mg distribution is homogeneous through the sample, after 2 hrs HIP.

At stresses below 40 MPa, the samples deformed in diffusion region (Coble creep), as described previously by Herwegh. The strength decreases with increasing magnesium content, owing to the difference of grain size. At stresses above 80 MPa, the stress exponent is greater than 3, indicating an increased contribution of dislocation creep. The transition between diffusion to dislocation creep occurs at higher stresses for the samples with higher magnesium content and smaller grain size. Preliminary data suggests a slight increase in strength with increasing magnesium content, but more tests are needed to verify this effect. In a few samples, some strain weakening may have been evident. The activation energy in the transition region (at 80 MPa) is $\sim$ 200 KJ/mol with no dependence on magnesium content, agreeing with previous measurements of diffusion creep in natural and synthetic marbles.

URL: http://www.agu.org̃lilixu

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T41D-0248 0830h POSTER

The Effect of Humidity and Particle Characteristics on Friction and Stick-slip Instability in Granular Fault Gouge

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Previous studies have shown that particle characteristics such as shape, dimension, and roughness affect friction in granular shear zones. Other work shows that humidity plays a key role in frictional healing and rate/state dependence within granular gouge. In order to improve our understanding of grain-scale deformation mechanisms within fault gouge, we performed laboratory experiments using a double-direct-shear testing apparatus. This assembly includes three rigid forcing blocks with two gouge layers sandwiched between rough or smooth surfaces. Roughened surfaces were triangular grooves 0.8 mm deep and 1 mm wavelength. These promote distributed shear throughout the layer undergoing cataclastic deformation. Smooth surfaces were mirror-finished hardened steel and were used to promote and isolate grain boundary sliding. The center block is forced at controlled displacement rate between the two side blocks to create frictional shear. We studied gouge layers 3-7 mm thick, consisting of either quartz rods sheared in 1-D and 2-D configurations and smooth glass beads mixed with varying amounts of rough sand particles. We report on particle diameters that range from 0.050-0.210 mm, and quartz rods 1 mm in diameter and 100 mm long. The experiments are run at room temperature, controlled relative humidity ranging from 5 to 100%, and shear displacement rates from 0.1 to 300 microns per second. Experiments are carried out under a normal stress of 5 MPa, a non-fracture loading regime where sliding friction for smooth spherical particles is measurably lower than for rough angular particles. We compare results from shear between smooth boundaries, where we hypothesize that grain boundary sliding is the mechanism influencing granular friction, to rough sample experiments where shear undergoes a transition from distributed, pervasive shear to progressively localized as a function of increasing strain. For shear within rough surfaces, stick-slip instability occurs in gouge that consists of less than 30We expand on previous work done by Frye and Marone 2002 (JGR) to study the effect of humidity on 1-D, 2-D, and 3-D gouge layer configurations. Our data show that humidity has a significant effect on frictional strength and stability and that this effect is observed for both smooth surfaces, where grain boundary sliding is the dominant deformation mechanisms, and for shear within rough surfaces where gouge deformation occurs by rolling, dilation, compaction, and grain boundary sliding.

T41D-0249 0830h POSTER

Influence of Intermediate Stress on Yielding of Berea Sandstone

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The onset of brittle failure of Berea sandstone has been investigated under varying stress states by subjecting solid and hollow cylindrical samples to confining pressure P_c (to 120 MPa) and axial stress σ_z (to 260 MPa) in a conventional triaxial deformation apparatus. Inelastic yielding of solid and hollow samples is marked by cascading acoustic emissions and axial displacements that depart from the initial linear elastic response. For hollow samples, uniaxial ($\sigma_z > \sigma_\Theta = \sigma_r = 0$) and biaxial ($\sigma_z > \sigma_\Theta > \sigma_r = 0$ or $\sigma_\Theta > \sigma_z > \sigma_r = 0$) stress states are obtained with deviators that (1) are maximum at the inner wall, (2) decay in a predictable manner with increasing radius prior to yielding, and (3) are insensitive to frictional boundary conditions at piston-sample contacts throughout much of the sample. X-ray CT scans of deformed samples reveal different modes of failure associated with the stress states imposed. Zones of anomalous X-ray density within hollow samples that mark deformed sandstone are localized near the inner wall, nearly midway between sample ends, and inner walls have lost their cylindrical geometry. Axial cavities of hollow samples become elliptical when axial stress is the intermediate principal stress ($\sigma_z = \sigma_2$), with geometries resembling wellbore break-outs used to infer in-situ horizontal stresses in scientific drilling studies, while toroidal spalls are developed when the tangential stress is the intermediate stress ($\sigma_\Theta = \sigma_2$). Our results for solid specimens under conventional triaxial conditions ($\sigma_z > \sigma_r = \sigma_\Theta > 0$) are in agreement with results reported for Berea sandstone. However, the results for hollow specimens require a yield criterion that includes intermediate stress σ_2. Yield criteria that fit our combined data may be expressed in terms of first and second invariants of stress I_1 and J_2; for example, using the modified Wiebols and Cook (1968) criterion, $J_2^{1/2} = A + B\, I_1 + C\, I_1^2$, data for Berea sandstone are well matched by parameters A = 16.5 MPa, B = 1.05, and C = -0.0013 MPa^{-1}.

T41D-0250 0830h POSTER

Experimental Study of Hybrid Fractures and the Transition From Joints to Faults

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Joints and faults are end members of a continuous spectrum of brittle fractures including the hybrid fractures, hypothesized to form under mixed compressive and tensile stress. However, unequivocal evidence for the existence of hybrid fractures has not been presented. To investigate this transition, we have conducted triaxial extension experiments on dog-bone shaped cylindrical samples of Carrara marble at room temperature, an axial extension rate of $2x10^{-2}$ mm s^{-1}, and confining pressures between 7.5 and 170 MPa. Two parallel suites of experiments were completed, one using very weak, latex jacketing to obtain accurate failure strength, and another using copper foil jacketing to preserve fracture surfaces. The combined data set provides strong evidence for the existence of hybrid fractures on the basis of the progressive change in failure strength, fracture orientation, and fracture surface morphology from joints to faults. At the lowest confining pressures (7.5 to 60 MPa), fractures are oriented approximately parallel to the maximum principal compressive stress, form at a tensile axial stress of approximately -7.75 MPa (i.e. the uniaxial tensile strength), and display fracture surfaces characterized by many reflective grain-scale cleavage faces, consistent with jointing. At the highest confining pressures (130 to 170 MPa), fractures are oriented from 13.4 to 21.6 degrees to the maximum principal compressive stress, form under completely compressive stress states where the axial stress is between 0 and 4.3 MPa, and are characterized by short slip lineations and powdery, finely comminuted grains consistent with faulting. At intermediate confining pressures (70 to 120 MPa), fractures are oriented from 3.7 to 12.4 degrees to the maximum principal compressive stress, form under mixed stress conditions with the axial stress ranging from -10.6 to -3.0 MPa, and display both reflective cleavage faces and short slip lineations with comminuted grains, consistent with hybrid fracturing.

T41D-0251 0830h POSTER

Acoustic Emission Analysis of Stick Slip Behavior on Rough and Smooth Fractures in Westerly Granite

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We present results from stick slip experiments on a rough and a smooth fault, and use Acoustic Emission (AE) data to make a comparison between the nature of slip on these two surfaces. Two Westerly Granite cores were pre-fractured to represent rough and smooth end member models of fracture surface geometry. One core featured a rough, natural fracture which was propagated quasi-statically by triaxial loading (under AE-feedback control). The second core contained a saw-cut fracture, the surfaces of which were hand lapped to produce a smooth finish. The pre-fractured cores were triaxially loaded to induce stick slip, at a confining stress of 150 MPa. In the rough fractured sample, one stick slip event was recorded at an axial stress of 625 MPa. During a five minute period about this slip, over 4000 AE events were triggered. A marked contrast is seen for slip on the smooth fractured sample, where a total of three discrete slip events occurred, at axial stresses of 380, 400 and 460 MPa. These slip events are characterized by a seismic quiescence; only 90 AE events were triggered during the five minute period about the final slip event. This extremely large difference in the amount of AE activity observed between slip on a rough and smooth fracture can be explained, as expected, by the presence of interlocking asperities on the rough fracture surface. In order to further analyze the characteristics of stick slip, we locate AE hypocenters to identify nucleation sites, calculate b-values, and resolve AE focal mechanisms to investigate the fundamental micromechanical processes operating on smooth and rough fracture surfaces.

T41D-0252 0830h POSTER

Photogrammetrical fracture analysis of rock bodies

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We tried to introduce a new way to determine the 3-D distribution of a fracture system. The fractured rock bodies are stereo-photographed by a calibrated analog camera, and the photos were processed using a stereo-comparator to get raw data and the computer software to get the digital terrain model of the rock bodies and the 3-D distribution of the fracture systems. A target for this trial was chosen from the Cretaceous sandstone layers exposed in the Pacific Coast near Nakaminato, Ibaraki, which have been suffered different fracturing successively since its deposition. THe 3-D distribution of the fractures suggests the following facts. (1) Four sets of small scale faults are distinguished, making homogeneous domains; (2) Joints are not displaced by faults; (3) Joints are not continuous across the boundaries of the fault domains; (4) Each joint system developed within a fault-bounded is different in orientation,from that of neighboring. From these observations we can safely conclude that, in this particular case, faults are formed at first, making fault bounded blocks in the Cretaceous sandstone. Then joint systems were formed under subsequent stress condition, but according to the preexisting fault systems, resulted stress field were in different orientation according to the block. This suggests that the boundaries of the blocks gave new boundary condition when joints were formed. Joint systems were accordingly oriented to slightly different directions in neighboring blocks. This is only an example, but shows that this new method is useful enough for 3-D analysis of the fractures.

T41D-0253 0830h POSTER

Development of Discrete Compaction Bands in Two Porous Sandstones

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Compaction band formation has been documented by recent field and laboratory studies as a localized failure mode occurring in porous sandstones. The coupling of compaction and localization may significantly alter the stress field and strain partitioning, and act as barriers within reservoirs. Two end-members of this failure mode that develop subperpendicular to the maximum principal stress have been identified: numerous discrete compaction bands with a thickness of only several grains, or a few diffuse bands that are significantly thicker. Much of what is known about discrete compaction bands derives from laboratory experiments performed on the relatively homogeneous Bentheim sandstone with 23% porosity. In this study we observe similar compaction localization behavior in the Diemelstadt sandstone, that has an initial porosity of 24.4% and a modal composition of 68% quartz, 26% feldspar, 4% oxides, and 2% micas. CT scans of the Diemelstadt sandstone indicate bedding corresponding to low porosity laminae. Saturated samples cored perpendicular to bedding were deformed at room temperature under drained conditions at a constant pore pressure of 10 MPa and a confining pressure range of 20-175 MPa. Acoustic emission activity and pore volume change were recorded continuously. Samples were deformed to axial strains of 1-4% and recovered from the triaxial cell for microstructural analysis. The mechanical data map the transition in failure mode from brittle faulting to compactive cataclastic flow. The brittle regime occurred at effective pressures up to 40 MPa, associated with failure by conjugate shear bands. At an effective pressure range of 60-175 MPa strain hardening and shear-enhanced compaction were accompanied by the development of discrete compaction bands, that was manifested by episodic surges of acoustic emission. Preliminary microstructural observations of the failed samples suggest that bedding influenced the band orientations which varies between 75-90° relative to the maximum principle stress. Our study demonstrates that despite their different mineralogy, failure modes and development of the compaction localization are similar in the Diemelstadt and Benthiem sandstones.

T41D-0254 0830h POSTER

Formation of Compaction Bands in Sandstone as a Phase Decomposition Associated With a Non-convex Stress Potential

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Permanent compaction of pore volume into localized regions, compaction bands, in sandstone has been observed in the outcrop and the laboratory. The current theoretical framework treats the onset of compaction banding as a bifurcation of the deformation field at a particular set of values of constitutive properties. A shortcoming of the theory as it exists is that it says nothing about the evolution of the specimen after the onset of banding. Stress-shortening curves for specimens undergoing compaction band formation and spread are characterized by a plateau of nearly constant stress during shortening. During this plateau the compaction bands form and spread throughout the specimen, in effect, changing the specimen from the original porosity (density) to a new, lower porosity (higher density). This type of curve is characteristic of many materials that show band formation and spread (interface propagation). Such a stress-deformation relation arises from the global minimization of an associated non-convex, multi-well stress potential curve that is characterized by three numbers λ_1, λ_2 and p_M (note: three numbers only if there are just two wells in the energy curve) that may be construed as constitutive parameters of the original porous rock. The deformation state at the onset of banding is characterized by λ_1, deformation at the completion of banding by λ_2 and the plateau stress is the Maxwell stress p_M. During a triaxial test on a specimen of porous sandstone, the stress difference first increases from zero to peak stress where the deformation is λ_1. At this point a new phase of deformation characterized by λ_2 appears. Throughout the plateau, there is a continuous rearrangement of phases, λ_1 being replaced by λ_2. The volume fractions of the two λ's are related to the overall shortening $\bar{\lambda}$ by the standard mixture rule. Nothing is predicted about the distribution of phases, only the relative amounts. Thus deformation could proceed as one thickening band or a series of intercalated bands of compacted and uncompacted material. Furthermore, the bands could be few in number and thick, or multitudinous and thin. All that is required is that the mixture rule be obeyed. Currently, we are examining a Hertzian fracture mechanism as the possible origin of the energy non-convexity. Identification of the appropriate micro-mechanism may lead to better understanding of the effects of such variables as grain size and distribution of sizes on the type of compaction observed—thick bands, thin bands, or homogeneous deformation.

T41D-0255 0830h POSTER

Frictional Properties of Mylonite Under High Pressure and High Temperature

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In order to understand the earthquake generation process, we need to understand the frictional and rheological properties of fault zone materials under high-pressure and high-temperature conditions. Laboratory data on frictional properties of fault surfaces of fault zone rocks are useful for that purpose. We carried out a series of conventional triaxial compression tests of mylonite at constant displacement rate. The strain rate of deformation was 5.5 x $10^{-6}s^{-1}$, the temperature was raised at a rate of 10C/min for all experiments. We analyzed the stress-strain relation and the frictional behavior of the fault surface formed in the tests. Mylonite samples taken from an exposed brittle-ductile transition zone, the Hatagawa fault zone, northeast Japan, are tested under the confining pressure up to 200 MPa and temperatures up to 800C both in the dry and wet conditions. In the wet conditions, pore water pressure was applied up to 70 MPa. The sample shape was a cylinder of 16.0 mm diameter and 40.0 mm length. The sample axis of the mylonite samples was 30 degrees from the orientation of the foliation structure of the mylonite block. Under the dry condition of 200 MPa confining pressure at 800C, samples show the ductile behavior. The yield stress of mylonite sample is much smaller than that of granite sample under the same condition. The internal structure of fault rocks such as foliation structure may significantly affect the deformation process under the high-pressure and high-temperature regime. Even under the same effective confining pressure, presence of pore water dramatically reduces the peak shear stress at the temperature regime higher than 600C. Frictional properties of fault surface formed during the deformation tests are investigated. In the dry conditions, stick-slip behaviors were observed at the room temperature and 200C. For the temperature range up to 600C, frictional forces are almost same level. In the wet condition, we didn't observe stick-slip behavior for all temperature ranges. The frictional force decreased as the temperature increased. Fluid such as water in the deep crust may play an important role in deformation process.

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T41D-0256 0830h POSTER

Conditions for Localized Deformation in Porous Granular Materials Under Axisymmetric Loading Using a Two Yield Surface Model

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Strain localization in porous granular rock occurs in field and laboratory settings. Compaction bands and dilation bands are of particular interest since localized deformation may increase (or decrease) porosity/permeability, possibly affecting fluid flow within geological formations and impacting drilling and extraction applications. Mollema and Antonellini (1996) first identified compaction bands as "thin planar zones of pure compressional deformation," oriented perpendicular to maximum compression. Bésuelle (2001), and Du Bernard, Eichhubl and Aydin (2002) recently reported dilation bands (oriented perpendicular to minimum compression) in laboratory and field settings, respectively. Rudnicki and Rice (1975) modeled strain localization as a bifurcation from homogeneous deformation using a single yield surface model to describe shear localization in low porosity rock. However, recent reexaminations of this model reveal that predicted band orientations do not agree with experimental observations of compaction bands in high porosity sandstone. Microstructural observations by Menéndez, Zhu and Wong suggest multiple active damage processes, prompting development of a two yield surface model by Issen to describe strain localization in high porosity sandstone. The first yield surface corresponds to a dilatant, frictional mechanism, while the cap corresponds to a compactant mechanism. This model successfully predicts the experimentally observed compaction bands under axisymmetric compression (ASC) when the slope of effective mean stress-inelastic volume strain curve is zero or slightly positive, corresponding to the stress plateau characteristic of compaction band formation. Determining conditions for dilation band formation under axisymmetric extension (ASE) using the two yield surface model is facilitated by certain mathematical symmetries with compaction band conditions for ASC. The conditions for dilation band formation though complex, depend largely on the dilation coefficient and slope of the shear yield surface with dilation bands being predicted for a wide range of probable material parameter values. These conditions are less restrictive than the analogous conditions for compaction band formation under ASC, suggesting that dilation band formation could be a common deformation mode for high porosity sandstone. Furthermore, since multiple stress paths are possible for a single stress state (e.g., ASC or ASE), the chosen stress path defines the region of the yield surface activated (and therefore the appropriate constitutive model), thus influencing whether the localization condition can be satisfied. This may have important implications for band formation in geological settings.

T41D-0257 0830h POSTER

Effect of Confining Pressure on Compaction Localization in Notched Samples of Bentheim Sandstone: Experimental Observations and Finite Element Modeling

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In tectonic settings the coupled development of compaction and strain localization may significantly impact the stress field, strain partitioning and fluid flow, and therefore it is desirable to have a better understanding of how such localization develops at various burial depths. Field studies indicate that compaction localization may develop due to structural and stress heterogeneity. In a previous laboratory study to investigate these phenomena a stress concentration was introduced by a V-shaped circumferential notch in a cylindrical sample of Bentheim sandstone and conventional triaxial experiments were conducted at the confining pressure of 300 MPa. Our acoustic emission and microstructure data indicated that discrete compaction bands initiated from the notch tips and propagated by sequential increments as "anti-cracks". The transverse propagation of a compaction band was inferred to be faster than the axial displacement rate by 2 orders of magnitude. Energy dissipated for compaction band formation was estimated to be comparable to the shear fracture energy for shear band propagation. Guided by experimental observations, a finite element analysis was conducted to simulate the initiation and evolution of compaction localization. The ABAQUS model was developed using a Drucker-Prager with cap constitutive model, and the numerical simulations confirm that a stress concentration exists at the notch causing a stress state favoring an axially compacted zone to extend perpendicular to the maximum compressive stress. To clarify the pressure effect we conducted additional experiments at confining pressures of 250 and 350 MPa. Our mechanical data show that the critical stress for the initiation of a compaction band from a notch tip decreased with increasing confining pressure, similar to the yield stress for an unnotched sample that maps out a cap with negative slope in the stress space. Differential stress vs. axial strain plots from numerical simulations support the experimental observation that the yield stress shows negative pressure dependence. Preliminary microstructural observations indicate a similar failure mode for notched samples at the three different confining pressures. Synthesis of the experimental and numerical results can provide useful constraints on the stress singularity at the notch tip and how it influences development of compaction localization.

T41D-0258 0830h POSTER

Anisotropic schist foliation orientation determined using time domain electromagnetics

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Remote detection of metamorphic rock formations beneath sedimentary cover using geophysical methods would greatly assist efforts of geologists to study regional tectonics. Metamorphic rocks are often characterized by foliations oriented in a preferred direction. The foliations may generate anisotropic physical properties. Electromagnetic methods can be used to detect anisotropy in electrical conductivity at depth within the earth. Around 1.1 billion years ago the Llano uplift exposed Precambrian igneous and metamorphic rocks in central Texas. In centrally located Mason, Texas the uncovered Packsaddle Schist maintains the characteristic preferred foliation orientation of metamorphic rocks, providing an ideal survey region. Time domain electromagnetic surveys with a 20 - 40 meter offset loop configuration were conducted azimuthally in the Packsaddle Schist. A transmitter loop with a five meter radius was centrally located. Voltage induced within a receiver loop was recorded over time and plotted on 360 degree polar azimuthal graphs. The graphs consistently show elliptical voltage responses over time with larger voltage readings trending northwest-southeast at early time. Larger voltage readings within the elliptical response correspond to slower decay of the induced volt-

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age and lower apparent conductivity. Further interpretation of electromagnetic responses in anisotropic media involves consideration of the paradox of anisotropy. A paradox of anisotropy occurs when apparent conductivity is larger across strike than along strike due to local induced electric current flow control of the response. Accordingly, lower apparent conductivity values correlate with the along strike direction. Therefore, the graphs generated by electromagnetics show the orientation of the Packsaddle Schist foliation trends northwest-southeast. Additional DC resistivity surveys of the same region show higher apparent resistivity oriented more subtly northwest-southeast. Under the paradox of anisotropy, higher apparent resistivity, or lower apparent conductivity, correlates with the along strike direction of the foliation. DC resistivity supports the same preferred foliation orientation found based on time domain electromagnetics. Utilizing time domain electromagnetics with an understanding of the paradox of anisotropy provides an effective and noninvasive means to detect the foliations characteristic of metamorphic rocks and determine the preferred orientation of the foliations.

T41D-0259 0830h POSTER

Impact of tectonic stresses on compaction in the toe thrust region of a Tertiary Delta

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Increased mean and shear stresses during toe-thrusting can accelerate compaction within thrust sheets, even away from bounding faults. Tectonic compaction in the toe-thrust regime is inferred when thrusted sediments appear to be anomalously consolidated compared to the same materials sampled from undeformed sections. Elevated mean stresses within thrust sheets can be estimated from the degree of overconsolidation of thrusted sediments relative to those compacted in near-uniaxial and neutral tectonic settings. Core data (sands) and well logs (shales) along a set of toe-thrusts of a Tertiary Delta have been used to describe the mechanism for compaction and estimate the magnitude of deviation from the normal trend in undeformed areas. Compaction mechanisms within thrust sheets appear to be dominated by grain rearrangement rather than cataclasis, which appears to occur only locally in thrust fault zones based on core data. Estimates of horizontal/vertical stress ratios (<1.5) compare favorably with estimates based on the low thrust angle and mechanical rock property ranges assuming relatively weak rocks in this shale-prone section. Results based on physical properties provide a narrower stress range than would be derived from the potential range of mechanical properties and structure inputs alone.

T41D-0260 0830h POSTER

Fundamentally Different Failure Mechanisms Around Boreholes in two High Porosity Sandstones

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We compare the shape and mechanism of failure around vertical boreholes drilled in blocks of two high-porosity sandstones subjected to unequal far-field principal stresses. Tablerock sandstone has a porosity of 28%, and is composed of 55% quartz and 37% weaker feldspar grains. Grain cementation is substantial through microcrystalline quartz. Critical far-field stresses induce failure around boreholes in the form of V-shaped (dog-eared) breakouts, the result of dilatant intra-and trans-granular microcracking subparallel to both the maximum horizontal far-field stress and to the borehole wall. No localized deformation ahead of the breakout tip is observed. On the other hand, boreholes in Mansfield sandstone, which has similar porosity (26%), but contains mainly quartz grains (90%) held together primarily by spot-sutured contacts, fail by developing fracture-like breakouts. These are long and very narrow (several grain diameters) tabular failure zones perpendicular to the maximum stress. Evidence provided mainly by SEM observations suggests a failure process initiated by localized grain-bond loosening along the least horizontal far-field stress springline, the packing of these grains into a lower porosity compaction band resembling those discovered in Navajo and Aztec sandstones, and the emptying of the loosened grains by the circulating drilling fluid starting from the borehole wall. Although the immediate several grain layers at the breakout tip often contain some cracked or even crushed grains, the failure mechanism enabled by the formation of the compaction band is largely non-dilatant, a major departure from the dilatant mechanism considered typical for rocks. The experimental results suggest that unlike our previous assertion, the type of grain bonding and mineral composition, and not the porosity, are major factors in the formation of compaction bands and the ensuing fracture-like breakouts.

T41D-0261 0830h POSTER

Potential field Modeling of the 3-D Geologic Structure of the San Andreas Fault Observatory at Depth (SAFOD) at Parkfield, California

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Gravity and magnetic data, along with other geophysical and geological constraints, are used to develop 2-D models that we use to characterize the 3-D geological structure of the San Andreas fault (SAF) zone in the vicinity of SAFOD near Parkfield, CA. The gravity data, reduced to isostatic anomalies, comprise a compilation of three different data sets with a maximum of 1.6 km grid spacing for the scattered data and closely spaced (∼40 m) stations along one SW-NE profile crossing the SAFOD pilot hole. Aeromagnetic data were flown at a nominal 300 m above the terrain along SW-NE flight lines perpendicular to the San Andreas Fault. Data were recorded at ∼50 m spacing along flight lines approximately 800 m apart. Ground magnetic data recorded every 5 m along lines ∼300 m apart cover a 3 x 5 km area surrounding the SAFOD pilot hole. Previous modeling showed that magnetic granitic basement rocks southwest of the SAF are divided by an inferred steep fault sub-parallel to the SAF. We compute 2-D crustal models along 5 km-long southwest-northeast profiles, one of which extends through the SAFOD pilot hole near and along the high-resolution seismic refraction/reflection survey completed in 1998 (Catchings et al., 2002). Our models are constrained by pilot hole measurements, where we see a boundary between sediment and granitic basement at ∼770 m and an order of magnitude increase in magnetic susceptibility at ∼1400 m, possibly the same depth at which the SW dipping Buzzard Canyon Fault intersects the pilot hole. Regional gravity, magnetic and geologic data indicate two very distinct basement blocks separated by a steeply dipping SAF. The shallowly dipping sedimentary section SW of the SAF coincides with the low velocity zone observed with seismic measurements. Shallow slivers of magnetic sandstone on the NE side of the SAF explain higher frequency features in the magnetic data. In addition, we show a flat lying, tabular body of serpentinite sandwiched between 2 blocks of Franciscan rock on the NE side of and truncating at the SAF. The Salinian granitic rocks to the SW of the SAF contain a magnetic body of unknown origin further to the SW and overlay a high density granitic root, possibly a deeper, denser phase of granitic rock. Furthermore, a shallow magnetic body SE of the SAF, possibly a sliver of granitic rock or serpentinite, gives rise to a significant NW trending high on the ground magnetic map parallel to the SAF. We use 2-D models both NW and SE of the profile that extends through the SAFOD pilot hole to explore the 3-D nature of the unknown magnetic bodies SW of the SAF and their significance to future drilling at SAFOD as well as to other faults sub parallel to the SAF. Our models are the basis for a 3-D digital model of the upper crust surrounding SAFOD that will act as a tool for directly comparing quantitative subsurface interpretations based on various methods including seismic refraction and reflection, seismicity, magnetotelluric, gravity, magnetic, and geologic techniques throughout the lifetime of the SAFOD project.

T41D-0262 0830h POSTER

"Intelligent design" of a 3D reflection survey for the SAFOD drill-hole site

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SAFOD seeks to better understand the earthquake process by drilling though the San Andreas fault (SAF) to sample an earthquake in situ. To capitalize fully on the opportunities presented by the 1D drill-hole into a complex fault zone we must characterize the surrounding 3D geology at a scale commensurate with the drilling observations, to provide the structural context to extrapolate 1D drilling results along the fault plane and into the surrounding 3D volume. Excellent active-2D and passive-3D seismic observations completed and underway lack the detailed 3D resolution required. Only an industry-quality 3D reflection survey can provide c. 25 m subsurface sample-spacing horizontally and vertically. A 3D reflection survey will provide subsurface structural and stratigraphic control at the 100-m level, mapping major geologic units, structural boundaries, and subsurface relationships between the many faults that make up the SAF fault system. A principal objective should be a reflection-image (horizon-slice through the 3D volume) of the near-vertical fault plane(s) to show variations in physical properties around the drill-hole. Without a 3D reflection image of the fault zone, we risk interpreting drilled anomalies as ubiquitous properties of the fault, or risk missing important anomalies altogether. Such a survey cannot be properly costed or technically designed without major planning. "Intelligent survey design" can minimize source and receiver effort without compromising data-quality at the fault target. Such optimization can in principal reduce the cost of a 3D seismic survey by a factor of two or three, utilizing the known surface logistic constraints, partially-known sub-surface velocity field, and the suite of scientific targets at SAFOD. Our methodology poses the selection of the survey parameters as an optimization process that allows the parameters to vary spatially in response to changes in the subsurface. The acquisition geometry is locally optimized for uniformity of subsurface illumination by a micro-genetic algorithm. We start by accurately establishing the correspondence between the subsurface area of the target reflector (in this case, the steeply-dipping SAF) and the part of the surface area whose sources and receivers contribute to its image using 3D ray-tracing. We then use dense acquisition parameters in that part of the survey area and use standard parameters in the rest of the survey area. This is the key idea that allows us to get optimum image quality with the least acquisition effort. The optimization also requires constraints from structural geologists and from the community who will interpret the results. The most critical parameters to our optimization process are the structural model of the target(s) (depth and geological dips) and the velocity model in the subsurface. We seek community input, and have formed a scientific advisory committee of academic and industry leaders, to help evaluate trade-offs for the community between cost, resolution and volume of the resultant data-set, and to ensure that an appropriate range of piggy-back experiments is developed to utilize the seismic sources available during the 3D experiment. The scientific output of our project will be a community-vetted design for a 3D reflection survey over SAFOD that is technically feasible, cost-effective, and most likely to yield the image and seismic parameter measurements that will best constrain the physical properties of the fault zone and their spatial variation.

T41D-0263 0830h POSTER

Comparison of SAFOD Pilot Hole phyllosilicate mineral assemblages to the Punchbowl fault: Recognizing post-faulting alteration in exhumed fault zones

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The chlorite assemblages in cuttings from two sampled intervals of the SAFOD Pilot Hole (488-914m and 1585-2012 m) can be separated into two populations based on X-ray diffraction characteristics. The first is characterized by peaks with a width of ∼0.1-0.3 $^{\circ}2\theta$ and a ratio of the area of the 002 chlorite peak to the 001 chlorite peak of ∼0.3-4.4, while the second exhibits peak widths of ∼0.2-1.0 $^{\circ}2\theta$ and a peak area ratio of ∼0.1-0.6. The first population occurs in the deeper interval, and rarely in the shallower, while the second population occurs only in the shallower interval. The difference in peak area ratio indicates a difference in chemistry (most likely in octahedral iron and magnesium), and the difference in peak width indicates that the deeper samples have larger crystallites and fewer expandable interlayers than the shallower population. The X-ray characteristics for the deeper population match those for samples from protolith and cataclasite for the exhumed Punchbowl fault, while samples from the intensely-deformed ultracataclasite are dissimilar to that population. This supports previously published findings, based on scanning and transmission electron

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 $\pm$ 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.

T41E-04 1105h

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

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