T32D-11 1620h

Initial Observations From the Talkeetna Arc Continental Dynamics Project

P Kelemen[1] (peterk@whoi.edu); N Christensen; P Clift; R Coleman; S DeBari; A Greene; B Hacker; S Hart; G Hirth; J Mattinson; L Mehl ; T Pavlis; M Rioux

[1]WHOI, Woods Hole, MA 02453, United States

The Jurassic Talkeetna arc section in Alaska lies north of the Border Ranges Fault in the northern Chugach Mtns, extending NW into the southern Talkeetna Mtns. Previous studies have demonstrated that the section formed in an island arc prior to accretion on the North American margin; mass balance estimates for a "1D" cross-section showed that it has a basaltic bulk composition; and garnet gabbros juxtaposed with pyroxenite overlying residual mantle harzburgite were interpreted as indicating a crustal thickness of about 30 km. Primary goals of this study are to extend mass balance calculations to 2D via mapping and thermobarometry, constrain the nature of primary magmas in the arc as a function of time during its (?) 20-30 Ma history, investigate the genesis of intermediate plutonic rocks, and evaluate the liklihood of lower crustal, convective instability ("delamination"). The project is designed to provide constraints on the evolution of continental crust via arc processes.

After reconnaissance in 2000, 2001 field work focused on additional sampling for thermobarometry and laboratory based seismic velocity studies near the base of the section, mapping and sampling in the Klanelneechina klippe (gabbros in a thrust sheet overlying a metamorphosed accretionary complex south of the Border Ranges Fault, with uncertain affinity to the Talkeetna arc), extensive sampling of mid-crustal gabbros for petrological and ion probe analysis, detailed stratigraphic studies in the volcanic section, and investigating the relationship of extensive, Jurassic quartz diorite and granodiorite in the southern Talkeetna Mtns (K/Ar ages 160-170 Ma) to dominantly gabbroic plutonic rocks in the arc further south and east (K/Ar and our new U/Pb and Ar/Ar ages 170-195 Ma).

Our preliminary thermobarometric estimates suggest that the crustal thickness may have been 20 to 25 km. This is important since an apparent discrepancy between the 30 km crustal thickness estimate and the 15 km structural thickness estimate in the eastern part of the arc section led earlier workers to suggest that roughly half of the section was missing.

We found that the Klanelneechina klippe includes garnet gabbros; the presence of garnet gabbros only 50 km apart, on both sides of the Border Ranges Fault, suggests that the Klanelneechina gabbros are part of the Talkeetna arc section, and that post-Jurassic strike slip displacement along the Border Ranges Fault has been small. We await additional geochronology data to corroborate this hypothesis.

Initial ion probe analyses of igneous clinopyroxene indicate a variety of different REE patterns for primitive magmas that formed pyroxenites near the base of the crust in the eastern part of the arc. However, new trace element data on gabbroic rocks and volcanics further west in the section have very uniform REE patterns. We sampled the easternmost volcanics and mid-crustal gabbros this summer in an attempt to resolve this apparent discrepancy.

New data on amphibolite lenses at mid-crustal depths, including garnet amphibolite, show that they were andesites with clear arc trace element signatures. Thus, they are not relicts of oceanic crust into which the arc was emplaced. They could be relicts of an older arc, or foundered Talkeetna volcanics that were buried early in the history of the arc, and then intruded by mid-crustal plutonic rocks.

T32D-12 1635h

Continental Crust Formation in Costa Rica and Nicaragua.

Thomas A Vogel[1] (517-353-9029; vogel@msu.edu)

Lina C Patino[2] (517-432-6319; patinoL@msu.edu)

Guillermo E Alvarado[2] (gainduni@cariari.ucr.ac.cr)

[1]Michigan State University, Department of Geological Sciences, East Lansing, MI 48824, United States

[2]Escuala Centroamericana de Geologia, Universidad de Costa Rica, Apdo. 35, San Jose, Costa Rica

Much work has been done in Costa Rica and Nicaragua on relating the variation in modern arc volcanism to variations in crustal type and thickness, sediment input and nature of the mantle wedge. However, little work has been done on the origin of the voluminous silicic ignimbrites in these sections of the arc. This is important because of the unusual abundance of silicic volcanism in a mature island arc environment where no continental crust occurs. The southern part of the Central American arc is the Chorotega block, which has developed on thickened oceanic crust. The boundary between the Chorotega block and the northern continental Chortis block is still a matter of debate. What is clear is that the Paleocene-Eocene island arc of the Chorotega block was built on a primitive basaltic crust (perhaps oceanic plateau?), which has evolved to the modern arcan evolutionary process that has led to the development of abundant silicic magmas.

In most island arc settings, abundant, high-silica volcanic deposits are not common, and this is generally attributed to the absence of continental crust. However, in Costa Rica and parts of Nicaragua, there are extensive silicic ignimbrite deposits. Because there is no recycling of continental crust in these sections of the arc, these silicic deposits represent the formation of new continental crust. This is in contrast to the northern part of the Central American Volcanic Arc where silicic magmatism is associated with older continental crust.

In Costa Rica the extensive ignimbrite sheets erupted from the Miocene to Pleistocene and occurred in three main areas: the Guanacaste province in the northwestern Costa Rica, Cordillera de Tillaran and Valle Central in central Costa Rica. In Nicaragua widespread ignimbrites developed from Eocene to as young as 6,000 yr bp (Ehrenborg, 1996). An important observation is that trace element ratios of these silicic volcanic deposits mimic the trace element ratios of basaltic to andesitic deposits from the modern arc. For example in southeastern Nicaragua and northwestern Costa Rica, samples from both the modern arc (basalt to andesite) and the ignimbrites have low Ce/Pb and high Ba/Nb ratios, indicating a large input from slab fluids. In Central Costa Rica samples from the modern arc (basalt to andesite) and the silicic ignimbrites have high Ce/Pb and low Ba/Nb ratios indicating a lower input from slab fluids. We interpret these data to indicate that the silicic melts were produced from partial melts of rocks chemically similar to the modern arc lavas, thus preserving the incompatible element ratio signatures (e.g. Ce/Pb and Ba/Nb ratios). There are no systematic variations of these trace element ratios in the different units with respect to age.

There are differences in the chemical and mineralogical composition among the ignimbrites and these differences most likely resulted from differences among source rocks and to crystallization processes. For example, although all of the samples are enriched in light rare earth elements, some units display positive Eu anomalies, whereas others do not. In addition, there are differences in the behavior of heavy REEs. These data most likely reflect the variability of hornblende and plagioclase in the sources for the melts, indicating to us that melting took place at the base of a thickened arc crust near the stability limit of plagioclase. Processes that formed the silicic volcanic rocks in this overthickened island arc or ocean plateau may be similar to processes that formed continental crust in the Archean.

T32E MC: Hall D Wednesday 1345h

Deformation, Fluid Flow, and Seismic Characteristics of Sedimentary Rocks

(joint with H, S, V, MR)

Presiding: **N Brodsky,** Sandia National Laboratory**; J Wheeler,** University of Liverpool

T32E-0904 1345h POSTER

Strain Localization in Sandstone

Xavier Du Bernard[1] (650-725-0573; xduberna@pangea.stanford.edu)

Peter Eichhubl[1] (650-725-0573; eichhubl@pangea.stanford.edu)

Atilla Aydin[1] (650-725-4296; aydin@pangea.stanford.edu)

[1]Stanford Rock Fracture Project, Department of Geological Environmental Sciences 450 Serra Mall, Bldg 320, Stanford, CA 94305-2115, United States

Based on petrographic and SEM observations of deformation mechanisms in sandstones of different compositional and petrophysical properties, we distinguish four types of deformation processes. All four deformation processes lead to the development of macroscopic deformation bands that appear similar in outcrop but differ significantly in microstructure. These four types of deformation bands are as follows: - In weakly consolidated to unconsolidated sand that has undergone limited mechanical compaction during burial we observed deformation bands that lack evidence of grain breakage but where porosity reduction is caused by grain sliding and rotation. Bands that are parallel to the tectonic shortening direction exhibit pure dilatation as revealed by an increase in porosity.

- In weakly- to well-cemented sandstone of high to intermediate porosity, deformation bands are composed of crushed grains that are compacted with or without shearing. As described by previous workers, porosity and permeability are strongly reduced within this kind of deformation bands.

- In a well-compacted sandstone of low porosity, fragmentation and formation of deformation bands are preceded by the formation of transgranular opening-mode fractures that occur in sets subparallel to the developing deformation bands. Unlike the first two types of deformation bands, these deformation bands have sharp boundaries to undeformed host rock. - In clay-rich sandstone, deformation bands are composed of elongated domains of finely crushed quartzo-feldspatic grains that are separated by clay-rich domains. In cathodoluminescence microscopy, these deformation bands resemble S-C fabrics with shear concentrated along the clay-rich domains.

The type of deformation is likely to depend on initial porosity, mineralogical composition, grain size, host rock cementation, and on stress boundary conditions. The specific mechanism of deformation band formation is likely to affect the permeability of these bands thus controlling the hydraulic properties of sandstone.

T32E-0905 1345h POSTER

Stress-Induced Acoustic Anisotropy in Sands: Preliminary Experiments and Models Comparison

Sandra Vega[1] ((650) 725-7037; sandra@pangea.stanford.edu)

Manika Prasad[1] (manika@pangea.stanford.edu)

Gary Mavko[1] (mavko@stanford.edu)

Amos Nur[1] (anur@stanford.edu)

[1]Geophysics Department. Stanford University, 397 Panama Mall, Stanford, CA 94305, United States

Stress anisotropy can affect the stability and induce mechanical failure in uncemented or poorly cemented sediment formations. Indirect and conventional methods such as seismic and sonic logs provide the potential to monitor stress changes and to reveal insights into the rock and sediment microstructure. Despite this fact, acoustic anisotropy in naturally occurring unconsolidated sediments has been neglected. The present work introduces an experimental study of stress-induced acoustic anisotropy in two different dry sand samples.

Induced acoustic anisotropy was detected using uniaxial stress tests. We acquired and processed acoustic wave signals in orthogonal directions. We measured the strains and stresses in the three Cartesians directions. Induced stresses in the planes orthogonal to the axial stress were higher in the unloading processes, and the strains showed a ductile behavior. We found considerable velocity anisotropy in both sands, i.e. velocities in the direction of the major stress were consistently faster than the velocities in the other two directions. The acoustic anisotropy was 71% to 99% for stress anisotropy of 12% to 33% in the coarse grain size sand, and the acoustic anisotropy was 66% to 89% for stress anisotropy of 12% to 27% in the fine grain size sand. The general trend of velocity anisotropy with stress was the same for both sands. The velocity hystereris was more notable in the directions of the induced stresses than in the applied stress. Also, we compared our results with four theoretical models based on the Effective Medium Theory and the Hertz-Mindlin contact model. There is an acceptable match of these models with our acoustic anisotropy data under certain conditions and adjustments except for an over-prediction of the induced stresses. We inferred that the main limitations of these models are the assumptions of identical spheres and non-slip between grains, which have to be substituted for better approximations. However, our results indicated that using acoustic velocities we can detect induced stress anisotropy in sands.

T32E-0906 1345h POSTER

New Insights Into the Elastic Moduli-Porosity Relationship in Sandstones

Franz LAHAIE[1] ((353) 1 716 2079; Franz.Lahaie@ucd.ie)

Chris Bean[1] ((353) 1 716 2140; Chris.Bean@ucd.ie)

[1]Department of Geology, University College Dublin, Belfield, Dublin 4, Ireland

The problem of inverting rock properties from seismic data is of paramount importance in a range of geophysical problems. In particular, attention has been focussed for many years, especially in petroleum industry, on the relationship between the seismic wave velocities (or elastic moduli) and the porosity of sedimentary rocks. The task of finding a simple universal relationship between those parameters has proved very difficult since the rock elastic moduli depend on many parameters other than porosity including mineralogy, grain shape and arrangement, degree of cementation, clay content, fluid composition, pore and confining pressure. Nevertheless, the most popular relationship between the elastic moduli and the porosity is

linear, joining the elastic moduli of the solid phase at zero porosity to the elastic moduli of a suspension at a 'critical' porosity (Nur et al., 1995).

Here, we test this model on a set of ultrasonic dry measurements carried out on 22 sandstone samples of low-to-medium porosity at varying confining pressures (Khaksar et al., 1999). We show that for all confining pressures a linear model describes fairly well the shear modulus-porosity relationship but can be statistically rejected for the bulk modulus-porosity relationship. Instead, the data are consistent with a hyperbolic model that assumes that the pore space compressibility remains unchanged with decreasing porosity, in contrast with the more intuitive idea (implicit in the linear model) that the pore space stiffness increases when the porosity decreases. We discuss several mechanisms of porosity reduction that could account for these observations.

T32E-0907 1345h POSTER

Numerical modeling of coupled pressure solution and fluid flow in quartz sandstones

Heather Anne Sheldon[1] (44-151-7945201; sheldonh@liverpool.ac.uk)

John Wheeler[1] (44-151-7945172; johnwh@liverpool.ac.uk)

Richard Worden[1] (44-151-7945184; R.Worden@liverpool.ac.uk)

[1]Department of Earth Sciences, University of Liverpool, Jane Herdman Laboratories, Brownlow Street, Liverpool L69 3GP, United Kingdom

Pressure solution in quartz sandstones can be envisaged as a 3-stage process, involving dissolution along grain contacts, diffusion of the solute along the grain contact to the pore space, and removal of the solute from the pore fluid by a combination of diffusive and/or advective transport and chemical reactions (e.g. precipitation of dissolved silica on free grain surfaces).

A number of authors have developed mathematical models of pressure solution in order to assess the impact of this process on porosity and permeability in sandstones. However, such models have always been based on a simplified subset of the governing equations, in order to reduce the computation time to an acceptable level. For example, some models assume diffusion through the grain contact zone to be the rate-limiting step, with all the dissolved material precipitating locally in the pore space. Other models assume that the rate of removal of solute from the pore fluid, by diffusion and precipitation, is rate-limiting.

It is now possible to solve the full coupled system of equations on a PC, without such simplifications. This enables us to investigate the coupling and interactions between pressure solution, chemical reactions in the pore spaces and macroscale advective/diffusive transport in the pore fluid. Preliminary results of such modeling will be presented, highlighting the importance of modeling pressure solution in an open system, where there is a strong coupling between macroscale transport in the pore fluid and the rate of porosity loss due to compaction and cementation.

T32E-0908 1345h POSTER

Pressure and Sorting Effects on Velocities in Sands: Measurements and Modeling

Michael A Zimmer[1] ((650) 725-5835; mzimmer@pangea.stanford.edu)

Manika Prasad[1] (manika@pangea.stanford.edu)

Gary Mavko[1] (mavko@stanford.edu)

[1]Rock Physics Laboratory, Geophysics Department, Stanford University, 397 Panama Mall, Stanford, CA 94305-2215, United States

In order to establish the effects of pressure and sorting on the seismic velocities of sands, we have conducted compressional and shear wave velocity measurements on reconstituted sand and synthetic glass bead samples at effective pressures from 100 kPa to 20 MPa. Both the P and S-wave velocities were fit with power law relationships, and both were found to be proportional to the pressure to approximately the one-third power. The experimental velocity results were fit remarkably well by the Walton infinitely smooth model, a Hertz-Mindlin type contact model that assumes that there is no tangential stiffness at the contacts. In general, the model tends to over-predict the velocities at effective pressures below 5 MPa, and to under-predict them at higher pressures. We interpret this behavior to indicate that at lower pressures the loose frame of grains results in a normal contact stiffness below that predicted by Hertz-Mindlin theory, as well as a near-zero tangential contact stiffness. At higher pressures the frame appears to be stiffer, preventing the grains from rotating or sliding as freely, and resulting in a full Hertz-Mindlin normal contact stiffness and a non-zero tangential contact stiffness.

We varied the initial porosity of the samples by mixing sands or glass beads of two or more particle sizes. The decrease in the sorting quality, which produces lower porosities, had a limited effect on the velocities. The effect of the sorting was found to be well modeled by a Reuss average between the moduli of pure quartz and those of the highest porosity samples, calculated from the velocities and density on the initial loading curve.

The porosity was also reduced through compaction of the samples. We ran each sample through up to 8 pressure cycles with an increased peak pressure for each cycle, and made velocity measurements at several pressure steps in each cycle. This compaction driven porosity reduction did not have a consistent effect on the velocities. In the sands, the compaction resulted in small increases in P-wave velocities, but very little change in the S-wave velocities. In the glass bead samples, the velocities were fairly constant for the lower pressure measurements through all the cycles, but decreased with increasing preconsolidation pressure at the higher pressures. We suspect that this behavior is due to damage to the grains in the glass bead samples, and might not be representative of natural sediments.

T32E-0909 1345h POSTER

An Experimental Investigation of the Effect of Stress Magnitude, Grain Size and Pore Fluid Type on the Time-Dependent Deformation of a Carbonate Sand

Catherine E Stafford[1] (+81 (0) 22 217 7523; catherine@rift.mech.tohoku.ac.jp)

Philip G Meredith[2] (+44 (0) 20 7387 7050; p.meredith@ucl.ac.uk)

[1]Fracture Research Institute, Faculty of Engineering Tohoku University Aoba 01, Aramaki, Aoba-ku, Sendai 980-8579, Japan

[2]Department of Geological Sciences, University College London Gower Street, London WC1E 6BT, United Kingdom

Oolitic sands are commonly forming today and commonly occur in the geological record, often forming significant hydrocarbon reservoirs. Hence, understanding the deformation behaviour of this geological material is important. In addition, ooids are a naturally forming carbonate grain with a uniquely spherical shape. Thus, they present an interesting laboratory material to study as the grain shape can essentially be considered a constant. Relatively few previous experimental studies have systematically investigated the effect of lithological and environmental variables on the time-dependent behaviour of particulate sediments at upper crustal stress conditions. Here, we report results from an experimental investigation of the effect of stress magnitude, pore fluid type and grain size on the time-dependent deformation of oolitic sand. By nature of formation, oolitic sands are very well-sorted and one particular locality yields grains of very similar grain size. Hence, we sampled from three different ooid shoals, all adjacent to Abu Dhabi Island, to give samples with grain sizes of 212 μm (212 >300 μm), 300 μm (300>425 μm) and 425 μm (425>600 μmm). Using each of these three different grain size samples, constant stress uniaxial compaction creep experiments were conducted, in oedometric cells, to effective axial stresses of 7, 31 and 60 MPa. Samples were saturated with distilled water, simulated seawater or an inert hydrocarbon. Experiments were conducted for periods ranging 14 to 148 days. Even after the longest test durations, the deformation never reached steady state creep, although it was possible to describe a quasi-steady state creep regime towards the end of the longest tests. Results indicate that creep deformation is enhanced by the application of high stresses, the presence of an aqueous pore fluid and a small grain size. From microstructural studies, we deduce that at effective stresses of 7 MPa, creep strains are accommodated by time-dependent frictional grain boundary sliding, whereas at the higher stresses, creep strains are accommodated by time-dependent grain fracturing, micro-fracturing at grain-to-grain contacts and frictional grain boundary sliding. In all samples, aqueous fluids enhance creep strains at stresses of 32 and 60 MPa but not at 7 MPa. This pore fluid effect is attributed to stress corrosion, which is enhanced at higher stresses. A general grain size trend is not found in all samples. This is attributed to the individual nature and different micro-porosities of each grain-sized sample. An empirical power law equation is proposed which describes the time-dependent behaviour of oolitic sands.

T32E-0910 1345h POSTER

Effects of Pore Fluid Chemistry on Pressure Solution in Calcite at Room Temperature: an Experimental Study

Xiangmin Zhang[1] (zhangxm@geo.uu.nl)

Janneke Salemans[1]

Chris J Spiers[1] (Cspiers@geo.uu.nl)

[1]High Temperature and Pressure Laboratory, Faculty of Earth Sciences, Utrecht University, PO.Box 80.021, Utrecht 3508 TA, Netherlands

Uniaxial compaction experiments have been carried out on fine-grained, super-pure calcite and crushed limestone (<100 micrometer) at ambient temperature, using applied effective stresses from 0.5 to 4 MPa. All samples were first loaded dry at an axial stress of 8 MPa, to obtain a well-controlled initial porosity and to minimize the contribution of grain re-orientation and sliding to subsequent wet compaction. Wet compaction creep experiments were performed by adding pre-saturated solution with varying concentration of Mg^{2+} and $HPO_4{}^{2-}$ (0.001 to 2 $mol.l^{-1}$ and 0.0001 to 0.1 $mol.l^{-1}$ respectively). Control experiments were carried out dry or using a chemically-inert pore fluid. All experiments were performed "drained". Compared with dry samples or samples flooded with inert fluid, samples tested using saturated solution showed significant compaction. Compaction strain rate decreased with increasing strain, increasing grain size, and increased with increasing applied stress. The presence of the magnesium and hydrogen phosphate ions in the pore fluid dramatically inhibited compaction. When the concentration is larger than of 0.01 $mol.l^{-1}$ for Mg^{2+} or 0.001 $mol.l^{-1}$ for $HPO_4{}^{2-}$, compaction is almost totally stopped and the effects of the solution are similar to that of an inert fluid. From the literature, it is well known that Mg^{2+} and $HPO_4{}^{2-}$ significantly inhibit calcite precipitation. This, together with a comparison of the observed mechanical behavior with pressure solution theory, suggests that pressure solution is the mechanism of deformation in our wet experiments and that precipitation on pore walls is likely the rate-limiting step.

T32E-0911 1345h POSTER

Elastic Properties of Clay Minerals

Tiziana Vanorio[1] ((650)723 7910; tvanorio@pangea.stanford.edu)

Manika Prasad[1] ((650) 723 8547; manika@pangea.stanford.edu)

Amos Nur[1] ((650) 723 9526; nur@stanford.edu)

[1]Stanford Rock Physics Laboratory, Stanford University 397 Panama Mall Mitchell Bld, Stanford, CA 94305-2215, United States

We present ultrasonic P- and S-waves velocity measurements on pure clay samples using three different experiment setups. These experiments provided petrophysical and acoustic properties of clay minerals as a function both of mineralogy and compaction. In the first experiment, acoustic measurements were performed on cold-pressed clay aggregates at ambient and at hydrostatic pressure conditions. Porosity and grain density values of the different clay mineralogy aggregates ranged from 4 to 43% and 2.13 to 2.83 g cm^{-3}, respectively. In the second experiment, we measured P-wave velocity and attenuation in a kaolinite-water suspension in which clay concentration was increased up to 60%. In the third experiment, P- and S- wave velocities were measured during uniaxial stress compaction of clay powders. Results from all three experiments revealed low bulk (K) and shear (μ) moduli for kaolinite, montmorillonite, and smectite; the values range between 6-12 GPa for K and 4-6 GPa for μ, respectively. Using these clay moduli values in effective medium and granular porous media models, velocity is predicted in saturated pure kaolinite samples, kaolinite suspension and shaly sandstones fairly well. Experimental results also showed that water interlayers play an important role in the compaction and strength of clay aggregates. Clay minerals carrying on water interlayers in their structure showed high compaction and strength. This study is relevant for a more reliable assessment of the seismic response in reservoirs and/or basins characterized by clay-bearing formations.

T32E-0912 1345h POSTER

Observations of a Water Induced Transition from Brittle to Viscoelastic Behavior in Nanocrystalline Swelling Clay

Daniel L Farber[1] (1-925-422-2256; farber2@llnl.gov)

Brian P Bonner[1] (1-925-422-7080; bonner1@llnl.gov)

Mehdi Balooch[1]

Brian Viani[1]

Wigbert Siekhaus[1]

[1]Experimental Geophysics Group Lawrence Livermore National Laboratory, PO Box 808 MS L-201, Livermore, CA 94550, United States

The elastic properties and time-dependent response of clay are of critical interest for many geophysical and geotechnical problems. These include, slope stability, seismic strong motion, the stability and detection of cap rock in oil reservoirs and consolidation of clay-bearing soils in the vadose zone. Here we report the first direct measurements of elasticity and time dependant mechanical response of a nanocrystalline material. Because smectites have the property of accommodating water between the 1 nm aluminosilicate sheets making up the crystallites, they provide a convenient means for studying the effects of water of hydration on mechanical properties. At ambient temperature, the number of water layers intercalated in smectites can be controlled between 0 and 4 depending on relative humidity. Suspensions of smectites (Crook Co, WY and Belle Fourche, MT montmorillonites) were dried on optically flat fused silica substrates to create thin films in which the 1 nm sheets are predominantly oriented parallel to the substrate. The mechanical response of the films was measured at different relative humidities using depth-sensing nanoindentation. Samples were tested in dry nitrogen and 30 % RH air and the effective Youngs modulus decreased from about 11 GPa to 3 to 5 GPa. The character of force penetration curves changed, indicating local softening (probably cracking) in the dry case and nearly ideal viscoelastic response in humid air. Force modulation experiments indicate that strong frequency dependent damping appears for the hydrated sample. X-ray diffraction measurements are underway to confirm that a single layer of water is incorporated in the smectite structure, as expected from previous measurements.

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T32E-0913 1345h POSTER

Discrete Element Models of the Micromechanics of Sedimentary Rock: The Role of Organization vs. Friction

David F Boutt[1] (505 835-5108; dboutt@nmt.edu)

Brian J.O.L. McPherson[1] (brian@nmt.edu)

[1]New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801, United States

The micromechanics of sedimentary rock deformation are a fundamental aspect of many research fields, ranging from geotechnical engineering to petroleum recovery and hazardous waste disposal. Laboratory triaxial tests yield information concerning macroscopic behaviors but are not capable of quantifying micromechanical processes such as microcracking and localization. Thus, to quantify micromechanical processes we employed the discrete element method (DEM) of rock deformation, calibrated with triaxial test results. This DEM simulates rock using rigid disc shaped particles bonded at contacts between particles. Previous studies demonstrated that this type of DEM can qualitatively and quantitatively mimic macroscopic behaviors of triaxial tests. An important conclusion of these studies is that a number of particles must be bonded together with higher bond strengths than the surrounding particles to achieve a steeper strength envelope of rocks. This process, termed clustering, is the focus of this study.

We hypothesize that since clusters posses a more complicated geometry, they may increase failure strength at elevated confining pressures by interlocking and creating a higher apparent friction. An alternative hypothesis is that the clusters change force chain development by allowing chains to persist longer in specimens. This ultimately causes failure to occur at higher strengths compared to unclustered material. A systematic study comparing effects of cluster shape, particle friction, and force chain development was undertaken. Several model simulations with various cluster shapes and sizes were compared with each other as well as single particle models with high friction coefficients (> 1). Preliminary results suggest that the organization of the particle clusters play a key role in increasing the strength envelope. Particle friction coefficients needed to increase slopes of the strength envelopes are well beyond those of geological materials measured in the laboratory. We conclude that models of rock using the DEM with single spherical and disc shaped elements do not fully capture the appropriate physics of most sedimentary rocks.

URL: http://www.nmt.edu/~dboutt/AGUFall01/

T32E-0914 1345h POSTER

Dynamics of Particle Size Distribution in Slide-Hold Tests on Laboratory Gouge Zones

Sankar K Muhuri[1] (405 325 3255; smuhuri@ou.edu)

Thomas A Dewers[1] (405 325 4430; tdewers@ou.edu)

Thurman E Scott[2] (405 325 2900)

[1]School of Geology and Geophysics, University of Oklahoma, 100 E. Boyd Street, Rm. 810, Norman, OK 73019, United States

[2]Rock Mechanics Institute, University of Oklahoma, 100 E. Boyd Street, Rm. P119, Norman, OK 73019, United States

Slide-hold tests using triaxially-loaded precut forcing blocks and artificial gouge examine contrasts in gouge particle size dynamics during frictional sliding and annealing or healing stages. A series of room-dry sliding experiments were conducted to various shear strains using dry gypsum gouge in between precut steel forcing members. A separate series of experiments saturated with distilled water was conducted at a pore pressure of 6.9 MPa (effective pressure of 13.8 MPa identical to the dry tests). The latter experiments were taken to a constant shear strain but were held under shear loading for various lengths of time (0.01-10 hours) after slip. Pore-volume change was monitored during hold periods. Particle size distribution (PSD) of gouge was measured using a laser particle size analyzer with a measurement range of 0.4-2000 microns. Stress-strain behavior for both dry and wet tests revealed multiple stress drops or stick-slip events and were similar suggesting no marked strengthening or weakening effect due to presence of water over the time scale of sliding.

Gouge PSDs were fit to a log-normal distribution function and then analyzed in terms of the moments of mass-size distributions. The best log-normal fits were obtained in the coarser fraction of the gouge (larger than peak size). PSD means decreased with shear while higher moments such as skewness increased with shear. Particle number-size relationships computed from the mass-size distributions revealed a fractal nature of the gouge with excellent fits obtained for fine and intermediate fractions (smaller than peak size). A fractal dimension (D) around 2.6 consistent with previous work on both natural and experimental fault gouge was obtained. There appears to be a correlation between D and the amount of shear strain and an inverse relationship between D and the maximum particle size. Empirical distributions such as the Weibull, Rosin-Rammler distribution functions and others provide good approximations of the data but physical justification for use of such functions to model fragmentation are absent as yet.

The time-dependent evolution of PSD during hold phases contrasts with evolution during sliding. Means, skewness, and computed D values all increase with time. Previous workers have observed a correlation between critical-slip distance in the rate- and state-dependent friction model and mean gouge particle size or with D, but there have been no systematic investigations of PSD dynamics during time-dependent healing. Inasmuch as this influences critical slip distances, it should be incorporated into earthquake models.

T32E-0915 1345h POSTER

Estimation of Thermal Transport Properties of Lithophysal Tuff at Yucca Mountain, Nevada

Nancy S Brodsky[1] (505-844-3408; nsbrods@sandia.gov); Carl L. Axness (505-284-4791; claxnes@sandia.gov); Cliff L. Howard (702-294-5744; clhowar@sandia.gov); James T. George (505-284-3956; jtgeorg@sandia.gov); David R. Bronowski (505-845-9013; drbrono@sandia.gov); James L. Ramsey (505-844-1331; jlramse@sandia.gov)

[1]Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185, United States

A suite of field tests is being conducted within the Exploratory Studies Facility at Yucca Mountain, Nevada, to determine in-situ values of thermal transport properties and the influence of gas and liquid flow. The field tests are being conducted in a cross drift that passes through the Tptpll (Tertiary, Paintbrush, Topopah Spring Tuff Formation, crystal poor, lower lithophysal) lithostratigraphic unit. Each field test requires at least two boreholes drilled into the drift wall: one to accommodate a 5-m long heater, and an orthogonal borehole to house a set of 30 thermocouples emplaced along a 5-m span. Data have been obtained from the first field test, comprised of a single heater and single thermocouple set. Data and analyses will be presented for this test, and data are expected from a second field test comprising three heater boreholes and three thermocouple boreholes.

The field data are modeled using two approaches to obtain the thermal transport properties. The first is a conduction-only analytic model in which a simple inverse technique is used to obtain thermal conductivity and thermal diffusivity. The second approach uses NUFT (Nonisothermal Unsaturated-Saturated Flow and Transport model), a multiphase-phase, multi-component flow and transport integrated finite difference model. Simulations with NUFT indicate that consideration of vapor transport alone yields thermal property estimates that are similar to those obtained using the conduction-only model. Consideration of air, steam, and liquid flow at near-saturated conditions significantly increases calculated heat flux and therefore lowers the estimated thermal conductivity. Both analysis methods provide thermal property values that are reasonably consistent with those expected based on laboratory results.

T32E-0916 1345h POSTER

Distinct Element Modeling of the Large Block Test

Steven R Carlson[1] (925-422-0722; carlson27@llnl.gov)

Stephen C Blair[1] (925-422-6467; blair5@llnl.gov)

Jeffrey L Wagoner[1] (925-422-1374; wagoner1@llnl.gov)

[1]Lawrence Livermore National Laboratory, PO Box 808, L-201, Livermore, CA 94551, United States

The Yucca Mountain Site Characterization Project is investigating Yucca Mountain, Nevada as a potential nuclear waste repository site. As part of this effort, the Large Block, a 3m x 3m x 4.5m rectangular prism of Topopah Spring tuff, was excavated at Fran Ridge near Yucca Mountain. The Large Block was heated to a peak temperature of 145°C along a horizontal plane 2.75m below the top of the block over a period of about one-year. Displacements were measured in three orthogonal directions with an array of six Multiple Point Borehole Extensometers (MPBX) and were numerically simulated in three dimensions with 3DEC, a distinct element code. The distinct element method was chosen to incorporate discrete fractures in the simulations. The model domain was extended 23m below the ground surface and, in the subsurface, 23m outward from each vertical face so that fixed displacement boundary conditions could be applied well away from the heated portion of the block. A single continuum model and three distinct element models, incorporating six to twenty eight mapped fractures, were tested. Two thermal expansion coefficients were tested for the six-fracture model: a higher value taken from laboratory measurements and a lower value from an earlier field test. The MPBX data show that the largest displacements occurred in the upper portion of the block despite the higher temperatures near the center. The continuum model was found to under-predict the MPBX displacements except in the east west direction near the base of the block. The high thermal expansion model over-predicted the MPBX displacements except in the north south direction near the top of the block. The highly fractured model under-predicted most of the MPBX displacements and poorly simulated the cool-down portion of the test. Although no model provided the single best fit to all of the MPBX data, the six and seven fracture models consistently provided good fits and in most cases showed much improvement over the other three models. Both provided particularly good fits to the east west displacements in the upper portion of the block throughout the entire test. This exercise demonstrates that distinct element models can surpass continuum models in their ability to simulate fractured rock mass deformation, but care needs to be taken in the selection of fractures incorporated in the models.

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T32E-0917 1345h POSTER

Effect of Initial Distribution of Two Fluids on Relative Permeability using Lattice-Boltzmann Method

Youngseuk Keehm[1] (650-725-5835; keehm@stanford.edu)

Tapan Mukerji[1] (mukerji@pangea.stanford.edu)

Amos Nur[1] (nur@stanford.edu)

[1]Stanford University, 397 Panama Mall, Stanford, ca 94305, United States

We present results on two-phase flow simulation by Lattice-Boltzmann method (LBM). The Lattice-Boltzmann method can handle complicated pore geometries, such as porous media. We have shown the single-phase LBM estimates absolute permeability of porous media very accurately and efficiently. We extended the method to two-phase flow and will show some characteristics of the two-phase LBM method. We particularly focus on one aspect of two-phase flow the effect of initial fluid distribution on relative permeability. We found our code for two-phase LBM honors laws of fluid dynamics and simulates corresponding physical parameters, such as capillary pressure and contact angle of the interface between solid and fluids. The simulated physical parameters showed very good agreement with theoretical predictions. After verifying that the two-phase LBM can simulate two-phase fluid flow through porous media, we applied the method to more complicated digital pore geometries; a Finneys random dense pack of spheres and samples from X-ray tomographic Fontainebleau sandstone. These were binary digital models describing the complex pore space. We used a steady state simulation that mimics a steady state measurement in laboratory. We experimented with four different kinds of the initial distribution of two fluids; (1) uniform distribution (fine mixture), (2) random distribution, (3) coating the grains with the wetting fluid, and (4) patch distribution. We found small differences in relative permeability with various initial distributions of two fluids. Although the final distributions were a little different due to different initial distributions, the relative permeability, which is a macroscopic value, was not much different. The difference at intermediate wetting-phase saturation was greater than one at low or high wetting-phase saturation. The patch type initial saturation showed the biggest difference among the initial distributions of two fluids.

T32E-0918 1345h POSTER

Petrophysical Controls on Fault-Zone Deformation in Ash-Flow Tuffs – Deformation Bands versus Fractures and Implications for Fluid-Fault Interaction

Jennifer E Wilson[1] ((505) 838-9038; jenw@nmt.edu)

Laurel B Goodwin[1] ((505) 835-5178; lgoodwin@nmt.edu)

Claudia J Lewis[2] ((505) 665-7728; clewis@lanl.gov)

[1]Dept. of Earth Environmental Science, New Mexico Tech, 801 Leroy Place, Socorro, NM 87801, United States

[2]Los Alamos National Laboratory, EES-9, MS D462, Los Alamos, NM 87545, United States

Fault-zone deformation processes and resulting structures vary both laterally and vertically in the Bandelier (New Mexico) and Calico Hills (Nevada) Tuffs. Primary controls on deformation processes include degree of welding and vapor-phase alteration of individual units within the tuff sequences. We have identified 5 fault-zone types based on outcrop-scale observations: faults with fractures, simple deformation-band faults, cemented faults, clay-rich faults, and complex deformation-band faults. Faults with fractures, similar to those found in low porosity rock, are most common in welded tuff units, but are also found in nonwelded tuffs that have experienced vapor-phase alteration. In contrast, faults in glassy, non-welded tuffs have a zonal architecture in which mesoscopic fractures are absent. Instead, deformation bands dominate the fault-zone structure. Petrographic and microprobe observations show evidence for cataclasis through distributed microfracturing of volcanic glass, pumice, and phenocrysts in the deformation bands. Simple deformation-band faults consist of these deformation bands, with or without silica cementation. Faults in non-welded tuff also commonly show alteration of fault-zone material to clays, recording fluid-fault interaction. Varying degrees of fluid-fault interaction during or subsequent to deformation are suggested by the presence of a range of structures, from simple, clay-rich fault zones with little internal zoning to complex fault zones with anastomosing compositional banding. In the absence of such alteration, complex deformation-band faults may develop by progressive reduction in pore and grain size, resulting in a mode-of-failure transition and development of a through-going slip surface. This type of fault is unique to tuff units in which there is only incipient welding, with moderate vapor-phase alteration. These observations indicate that faults in tuff sequences cannot be modeled as simple fracture networks, but must instead be considered as complex structures, in which fracture networks may extend into zones of deformation bands and/or clay-rich fault zones as they cut through different units. Thus, these faults are both mechanically and hydrologically heterogeneous structures.

T32E-0919 1345h POSTER

A Numerical Study of the Initiation and Propagation of Anticracks in Stressed Elastic Materials

bjorn jamtveit[1]

Daniel Koehn[1] (daniel.kohn@geologi.uio.no)

Anders Malthe-Soerenssen[2]

[1]Dept. of Geology,University of Oslo, PO Box 1047 Blindern, Oslo N-0316, Norway

[2]Dept. of Physics, University of Oslo, Blindern, Oslo N-0316, Norway

Dissolution-precipitation creep is an important deformation mechanism in the upper crust of the earth. It can lead to a variety of microstructures or spatio-temporal patterns ranging from veins to dissolution seams, stylolites and anticracks. In order to attain a better understanding of the development and characteristics of these patterns we studied the dissolution of a stressed solid. An elastic spring network with discrete particles describes the solid. The model is quasi-static in the sense that after each time step the particles are moved until they reach an equilibrium position with respect to the forces acting on each particle. The simulations are 2-dimensional on a triagonal lattice consisting of 200 x 200 particles. We examine dissolution on the surfaces of a fluid-filled cavity located in the centre of the model. The cavity is oriented like a mode I crack and has varying axial ratios. The particles defining the surface of the cavity are in contact with the fluid and can dissolve. The fluid pressure and solute concentrations are assumed to remain constant so that the stressed system is constantly undersaturated. The particles' probability to dissolve is calculated using a linear rate law and is a function of the Helmholtz free energy of the cavity's stressed surface. The Helmholtz free energy is the sum of the surface energy and elastic energy of the wall-particles where the elastic energy is calculated from the strain tensor of the elastic material. This system develops a variety of patterns which change with varying compressive stress, fluid pressure, axial ratio of initial cavities or cracks and absolute size of particles given by the surface energy. The dissolution-controlled patterns evolve in time from anticrack formation on tips of cracks (wing-anticracks) to roughening of crack surfaces leading to secondary and tertiary anticracks that have distinct spacings with respect to each other and to the wing-anticracks. For high surface energies and low compressive stress/fluid pressure-ratios the formation of anticracks becomes increasingly suppressed. This results in a flat dissolution surface and development of large uniform cavities. We present the different patterns in phase diagrams and analyse the phase boundaries.

T32E-0920 1345h POSTER

Thomas Etzel[1] (thomas.etzel@ruhr-uni-bochum.de)

Guntram Jordan[1] (guntram.jordan@ruhr-uni-bochum.de)

Klaus Roeller[1] (klaus.roeller@ruhr-uni-bochum.de)

Wolfgang Schmahl[1] (wolfgang.schmahl@ruhr-uni-bochum.de)

Bernhard Stoeckhert[1] (bernhard.stoeckhert@ruhr-uni-bochum.de)

[1]Institut fuer Geologie, Mineralogie und Geophysik, Ruhr-Universitaet Bochum, Bochum 44780, Germany

Dissolution precipitation creep (dpc) is a prominent deformation mechanism in sedimentary environments and at very low to low grade metamorphic conditions. Natural microstructures suggest that dissolution of quartz, carbonate, feldspar and olivine is enhanced at interfaces with sheet silicates. This phenomenon has also been observed in experimental studies: heterogeneous contacts are active sites of dpc, e. g. halite and quartz, while contacts between crystals of the same material, e. g. halite and halite, seem to be stable in time [1].

There are several concurrent models for the interface structure. The fluid film model assumes a continuous thin fluid film at the grain boundaries. The film is postulated to be controlled by a disjoining pressure [2], and its thickness would be in the order of a few nanometers. The island and channel structure model assumes a complex interface, which is composed of dry contacts between the crystals and free fluid in the channels. In any case the dissolved matter diffuses out of the boundary into some reservoir, from which the sinks are fed. The inherent length scales remain poorly constrained. Diffusion along the stressed interface (with source or sink control as alternatives) may be the rate controlling step for dissolution precipitation creep.

To gain new insight into the elementary processes of dissolution precipitation creep we have set up a monochromatic phase shifting interferometer to observe free and loaded faces of a crystal while undergoing dissolution or growth under uniaxial stress in a fluid cell. The vertical resolution of the phase shifting interferometer is a few nanometers and it is possible to measure the solid-liquid interface in situ. The advantage of this set up compared to scanning force microscopy is the non-contact and non-destructive technique.

First measurements of halite in contact with titanium oxide immersed in a brine at 30 degrees C at an uniaxial stress of 0.6 MPa reveal an inhomogeneous dissolution of the crystal. Locations with a high elastic strain energy density dissolve, while the free surface does not show any significant growth or ablation. The dissolved material was probably transported to new small crystals observed to grow elsewhere in the cell. More insight into the structure of the interfaces is crucial for the understanding of the process, and the influence of the type of interfaces.

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T32E-0921 1345h POSTER

Predicting Seismic Velocities in Marine Sesiments Using Clay Content

Anastasia Stroujkova[1] ((860) 402 8191; ana@vaino.geo.duke.edu)

Damian Herrick (damian@geo.duke.edu)

Lincoln F Pratson[2] ((919) 681 8077; pratson@eos.duke.edu)

[1]Department of Geology and Geophysics, University of Connecticut, Storrs, CT 06269, United States

[2]Division of Earth and Ocean Sciences, Duke University, Durham, NC 27708, United States

The ability to calculate seismic velocity accurately over the extent of a survey is a problem of interest to the seismic record. Velocity and other lithologic properties can be well resolved in boreholes, but due to structural and stratigraphic variations, these measurements are limited to very near the borehole. Clay content is shown to be the chief variable that affects velocity in sand/shale systems. It controls porosity and bulk density, and plays a major role in determining seismic wave velocity. Despite its importance, high-resolution measurements of clay content are frequently unavailable for many boreholes. As such, a proxy for clay content, such as gamma ray measurements, must be used in estimating clay volumes near a borehole.

A forward model is presented that calculates lithologic and acoustic properties of sediment using several petrophysical formulations. The models primary input is clay content (or gamma ray measurements), and modeled values include porosity, bulk density, overburden pressure, elastic moduli, and wave velocity. Seismic velocities are estimated based on self-consistent elastic moduli by Berryman (1980). The unknown geometric factors needed for Berrymans model are found using simulated annealing optimization.

The model is then applied to five wells from the Amazon Fan with measured gamma, porosities, bulk densities and P-wave velocities. The model performs well for porosity, bulk density and velocity predictions for binary mixtures with high contrast in particle sizes (sand/clay). However, if a significant volume of silt or intermediate size particles are present (for example for mass flow deposits), the models fails to predicts these properties.

T32E-0922 1345h POSTER

Porous Material Characterization Using Large Ultrasonic Beams: Velocity and Attenuation Estimates of the Biot Fast and Slow P-waves

Youcef Bouzidi[1] (780-492-4125; ybouzidi@phys.ualberta.ca)

Douglas R Schmitt[1] (780-492-3985; doug@phys.ualberta.ca)

[1]Institute for Geophysical Research, Dept. of Physics, Univ. of Alberta, Edmonton, AB T6G 2J1, Canada

A new method of probing porous materials has been developed using a large area (10-cm X 7.5-cm) ultrasonic transducer as an acoustic source. This transducer generates a wide, flat beam with central amplitudes remaining stable to up to at least 40-cm in water filled tank. The advantage of such a beam is that geometrical wave-field spreading is small and as such these effects may be neglected. This greatly simplifies measurements that rely on accurate amplitude determination in, for example, the measurement of attenuation or reflectivity. Synthetic water-saturated porous media are characterized by passing the beam through a plate of the material at incidence angles between -50° and 50° in a manner similar to that of earlier experiments by other groups. The initial pulse in the water is converted to fast-P, slow-P, and S-waves at the water-sample interface. Each of these arrivals is detected on the far side of the plate by small near-point receiver (∼ 1-mm diameter) and is recognized on the basis of easily discriminated travel-time versus angle of incidence images of the recorded waveforms. The velocity of the various modes are measured and modeled. The porosity, permeability, and tortuosity that are measured in separate experiments along with the velocities allow a good characterization of the porous sample. These measurements assist in the interpretation of a series of measurements of acoustic reflectivity from a saturated porous solid. A description of the experimental method and the methodology used in velocity estimates will be given.

URL: http://www-geo.phys.ualberta.ca/∼ybouzidi

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T32E-0923 1345h POSTER

Seismic Imaging of Subsurface Porosity

Valeri A Korneev[1] (510-486-7214; vakorneev@lbl.gov)

Roland Gritto[1] (510-486-7118; rgritto@lbl.gov)

[1]Lawrence Berkeley National Lab, 1 Cyclotron Road, MS 90-1116, Berkeley, CA 94720, United States

Reliable estimates of subsurface porosity is an important problem in the geosciences. Transport processes such as heat and water flow, or migration of particles are studied in many environmental applications, and rely on accurate porosity estimates. Furthermore, seismic site response studies, which determine a change in ground displacement due to stress changes during earthquakes, depend on porosity of the material under investigation. Yet current methods to determine subsurface porosity rely on point or line measurements in boreholes which are extrapolated to larger distances. It is clear that this method is very limited and produces questionable results at best. Therefore, an approach is needed that provides in-situ porosity measurements at larger scales and dimensions. In the current study, we present a method to estimate porosity over large areas based on scattered seismic energy.

Subsurface porosity occurs on all scales from micropores to large cavities. If information on the background material is available (e.g. the seismic velocity of the background matrix) it is possible to image the concentration of the larger pores in space. In this model the background information already contains the effect of micro-scale porosity and possible fracturing. Examples of larger pores are present in volcanic deposits where cooling processes have introduced gas inclusions that vary in size between a few inches up to one foot or more. Limestone deposits may also exhibit a high degree of porosity created by leaching or washout mechanisms. These voids represent strong scatterers and the application of linearized methods like the Born approximation, for example, will produce doubtful results. We explore a possibility to apply scattering theory to estimate the porosity without considering interaction between scatterers (single scattering theory). The voids in the medium affect the amplitudes as well as the phases of the scattered seismic waves , and in the Rayleigh regime the relationship between the concentration of porosity and phase shift becomes attractively simple. Thus porosity can be directly estimated from travel time measurements. We present modeling results based on laboratory data that estimate the distribution of porosity from travel times of seismic waves. A general finding is that the relative change in seismic velocity is approximately equal to 50% of the porosity value.

T32E-0924 1345h POSTER

Frequency Scaling for Evaluation of Shale and Mudstone Properties from Acoustic Velocities

Roberto Suarez-Rivera[1] ((801)584-2484; rsuarez@terratek.com)

Stephen M Willson[2] ((281) 366-5842; willsonsm@bp.com)

Seiji Nakagawa[3] (snakagawa@lbl.gov)

Olav Magnar-Ness[4] (olav-magnar.ness@iku.sintef.no)

[1]TerraTek, 400 Wakara Way, Salt Lake City, UT 84108, United States

[2]BP, 501 Westlake Park Blvd, Houston, TX 77079-269, United States

[3]Ernest Orlando Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, Ca 94720, United States

[4]Sintef Petroleum Research, S.P. Andersens vei 15 B, Trondheim N-7465, Norway

In subsurface oil and gas exploration, seismic wave (stress wave) measurement is one of the most important tools for determining the properties of overburden and predicting reservoir conditions such as pore pressure, fracture gradient, and stress distribution. To achieve detailed and reliable knowledge of the reservoir, an integrated analysis can be performed on the seismic properties of rocks measured at different scales ranging from laboratory core, boreholes (well logging) and reservoir itself (surface seismic). However, particularly for sedimentary rocks containing a large amount of clay minerals, such integration is not a straightforward task because of velocity dispersion that makes waves of different frequencies travel at different velocities.

The ultimate goal of this study is to devise a methodology for frequency scaling based on laboratory measurements of wave propagation at different frequency ranges. To this end, we have examined the mechanical and acoustic (seismic) properties of strongly dispersive sedimentary rocks. Shales were selected as principal rocks of interest for their predominance in the overburden and the direct impact on the well construction cost. Two types of shales were cored from outcrops(Pierre I and Mancos) and tested under varying conditions of loading (hydrostatic versus uniaxial-strain), orientation to bedding (parallel, perpendicular and oblique). Wave measurements were conducted under four ranges of frequency: Static and quasi-static (seismic frequency, approximately 7 Hz) data was obtained from high-accuracy, low-speed stress-strain measurements, and sonic data (0.4 kHz-9 kHz) was obtained from gas-confined resonant bar tests. For ultrasonic data (150 kHz-1 MHz), a frequency-domain phase analysis was applied to compute frequency-dependent phase and group velocities. Over these ranges, both Pierre and Mancos shales showed a smooth and monotonic increase in compressional and shear wave velocities with frequency. Strong velocity dispersion occurred in the range from 10 kHz to 1 MHz for Pierre shale, and 1 kHz to 1 MHz for Mancos shale. However, for both shales, resonance measurements were representative (within 20%) of static and quasi-static measurements. In contrast, velocities from the ultrasonic measurements were approximately 45% higher than the static and quasi-static measurements.

T32E-0925 1345h POSTER

Discrete Element Models of Seismic Wave Propagation in Sediments

David W. Sparks[1] (979-458-1051; sparks@seaver.tamu.edu)

Richard Gibson[1]

Einat Aharonov[2]

[1]Dept. of Geology and Geophysics, Texas AM University, College Station, TX 77840, United States

[2]Weizmann Institute of Science, P.O. Box 26, Rehovot 76 100, Israel

The propagation of seismic waves through heterogeneous sediments is a topic of major importance , particularly in reservoir exploration. In order to develop a better understanding of wave propagation through sediments, we employ a numerical model based on the discrete element method (DEM) used in modeling granular materials. An advantage of this method is that one can readily explore a large range of heterogeneity in grain properties, such as size and bulk modulus, as well as a variety of spatial distributions of those properties.

Discrete element models (e.g. Cundall and Strack, 1979) have been used to study the deformation of granular materials under a wide variety of conditions. In this method, a small (10^3 to 10^4) set of simple (2D circular) model grains is defined. The pore space between the grains is taken to have zero bulk modulus, so these models represent drained sediments. Grains interact with specified elastic and frictional forces. The elastic forces can be both repulsive and attractive, allowing simulation of both non-cohesive and cohesive sediments. The position, velocity and acceleration of each grain is tracked through time, in response to external loads. One side of the sample is subjected to a single time-dependent pulse in normal force, sending a compression wave into the sample. The subsequent accelerations of the opposing side give the acoustic wave speed in the granular material as well the attenuation of the wave form.

Initial experiments were conducted with non-cohesive grains in a system with a limited range of grain sizes (factor of 3). In such a system, the 2-D porosity is 18-19%. This system shows significant attenuation of the input wave and yeild a velocity that is about 15% slower than the acoustic velocity within a grain. We will examine the effect of pressure on seismic velocity and compare this with theoretical models. We will also explore the relationship between applied non-hydrostatic stresses and anisotropy.

T32E-0926 1345h POSTER

In situ Experimental Investigation on Rock Strength; Consequences for vertical stress profiles

Francois H Cornet (cornet@ipgp.jussieu.fr)

Inst. de Physique du Globe de Paris, 4 place Jussieu, Paris cedex 05 75 752, France

It is widely assumed that vertical profiles of stress magnitude in the upper crust are controlled by friction along preexisting faults. This is mostly based on stress determination in deep boreholes together with results from lab experiments on friction. Another approach to this problem is the analysis of failure processes induced in situ by water injection at sufficiently large flow rates. Such an experimentation has been conducted in granite at depth ranging from 2800 m to 3600m. The injection rate was increased every other day until pressure stabilized for about three days. Induced seismicity was observed in particular with downhole accelerometers. Principal stress directions are well constrained by borehole observations. Four different steps are observed: for injection pressure lower than 4 Mpa, no induced seismicity; for wellhead injection pressure ranging between 4 to about 8 Mpa, roughly axisymmetrical growth around the injection zone; from about 8 Mpa to 10 Mpa growth in a direction inclined about 30° to the maximum principal stress direction; once pressure stabilizes at 10 Mpa, growth in the maximum horizontal principal stress direction and upward. It is proposed that the initial growth of the seismic cloud is linked to the percolation of fluid through the intact rock mass. The second phase involves the failure of the rock mass in shear. The third phase, when pressure stabilizes, is associated with the growth of a zone normal to the minimum principal stress direction. Hence, clearly, in this experiment the growth of the seismic cloud cannot be linked uniquely to the permeability of the intact rock nor can the inception of induced seismicity be taken as the sign of large-scale failure inception. By analogy with results from the laboratory, the three induced seismicity phases yield clews for identifying the limit of elasticity of the rock mass and the criterion of failure that satisfies best the inception of failure. Again, by comparison with results from the laboratory, it is concluded that failure has extended throughout the rock mass and not through a single preexisting structure. At the scale of this experiment, about 800m high and 500m wide, it is concluded that the failure process is not dominated by the strength of a few well identified preexisting zones of weakness. Hence, at this scale, vertical stress profiles are not likely linked simply to frictional characteristics of weakness zones.

T32E-0927 1345h POSTER

In Situ Measurement of Electrical Resistivity of Deep Sea Sediments: Results From Cascadia Basin, Eastern Flank of Juan de Fuca Ridge.

Heinrich Villinger[1] (49-421-2184509; vill@uni-bremen.de); Bernd Heesemann[1]; Daniela Jansen[1]; Marion Pfender[1]; Andreas Rosenberger[2] (andreas@arescon.com); Christian Spindeldreher[3]

[1]Fachbereich Geowissenschaften Universität Bremen, Postfach 330 440, Bremen 28334, Germany

[2]arescon ltd, 9706 First St., Sidney, B.C V8L 3C7, Canada

[3]Sun Microsystems GmbH, Lankwitzer Str. 19, Berlin 12107, Germany

The electrical properties of deep sea sediments are linked to other physical properties through a series of empirical relationships. They allow the calculation of thermal conductivity from porosity which is derived from electrical resistivity using Archie's Law. In order to complement in situ thermal conductivity measurements made with our violin-bow type heat probe, we designed and built a sensor which is attached to the tip of our probe and allows to measure a continuous profile of electrical resistivity - and therefore porosity and calculated thermal conductivity - as the heat probe penetrates the seafloor.

The operating principle of our sensor is based on two identical 4-point electrode arrays arranged on the circumference of the sensor tip and separated by 10 cm. They are mounted in an electrically insulating, highly abrasion resistant plastic material. Both arrays are operated independently. A DC constant power source delivering 10 mA is reversed with a frequency of 1000 Hz to provide a 500 Hz alternating rectangular waveform current. The resulting signal at the electrodes is measured in a time-multipexed fashion with a final frequency of 250 Hz. Data are digitized and stored on a hard drive under control of a Tattletale data logger. Penetration is monitored by a pressure and acceleration sensor. The signal of the latter is used to convert the recorded electrical signals from time to depth.

We will present results from multi-penetration measurements along profiles located at the Eastern flank of the Juan de Fuca Ridge and also from a site on Cascadia Margin, where on previous cruises Canadian colleagues cored gas hydrate bearing sediments. The measurements were made during cruise SO-149 (fall 2000) on the German research vessel SONNE. Our data show that we are able to measure high resolution resistivity profiles over a depth range of 3 - 4 m which allow to characterize the overall porosity of the sediments and to identify turbidite layers present everywhere in Cascadia Basin. The calculated porosities are compared with existing porosity data from the same area. The developed instrument worked very reliably and delivered data of very good quality. Of course the sensor and its electronics can also be used separately for spatially detailed geotechnical work in shallow water.

URL: http://www.geophys2.uni-bremen.de