the break-up. The weak zone would facilitate reactivation of the faults if tensional stresses were produced by possible reorientation of the spreading direction of the North Atlantic Ocean in the future. The reactivation of the faults would create a free boundary condition at the hinge zone, allowing further bending of the lithosphere beneath the basin and juxtaposition of that to the mantle beneath the continent. This may provide a favorable situation for initiation of slow subduction due to subsequent compressional forces.

T42G-07 1520h

Subduction Initiation: Criticality by Addition of Water?

Klaus Regenauer-Lieb[1] (++4116332057; klaus@tomo.ig.erdw.ethz.ch)

Dave A. Yuen[2] (6126241868; davey@krissy.msi.umn.edu)

Joy Branlund[2] (joye@msi.umn.edu)

[1]Institute of Geophysics, ETH Hoenggerberg, Swiss Federal Institute of Technology, Zurich 8093, Switzerland

[2]Minnesota Supercomputer Institute and Dept. of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55415, United States

We have employed high-resolution finite-element (100k) models based on new rheological data of the lithosphere to investigate the role played by water on initiating subduction. Models of subduction require the formation of a weak zone to initiate subduction. This first instability ruptures the mechanical coherence of the lithosphere by localized plastic yielding. With plastic failure, fluid-dynamical approaches have succeeded in producing near vertical slab like features of negatively buoyant viscous lithosphere. However, the yield strength of the lithosphere has been assigned arbitrarily and the significance of elastic bending stresses has been neglected. Elasticity counteracts near vertical dripping slabs and creates distinct asymmetry. Hence, an elastic-fluid-thermo-mechanical instability is needed to drive a cold, stiff, and negatively buoyant lithosphere into the mantle. This instability can be triggered slowly by sedimentary loading over a time span of 100 Myrs. Our results indicate that subduction can proceed by a double feedback mechanism (thermo-elastic-rheological) promoted by lubrication due to water. An Atlantic-type continental margin would thus reach criticality upon the steady addition of sediments, if an average sediment load of 10 km thickness is reached. Plummeting of such a gravitationally and mechanically unstable lithosphere into the mantle is possible through many subsequent mechanisms.

T42G-08 1535h

Can Convective Instability of a Thickened Passive Margin Help Initiate Subduction?

M. Jull[1] (508 289-3248; jull@whoi.edu)

P. B. Kelemen[1] (508 289-2956; pkelemen@whoi.edu)

[1]Woods Hole Oceanographic Institution, Woods Hole Rd., Woods Hole, MA 02543, United States

A fundamental part of plate tectonic theory is that plates are generated at spreading ridges and consumed at subduction zones. High density phase changes in the subducting slab help to pull the plate into the convecting mantle. McKenzie (1977) formulated expressions for the driving and resisting forces at a subduction zone and showed that at least 130 km of slab, moving at a rate of at least 1.3 cm/yr, would be required to subduct before the process would be self-sustaining. It was unclear from this work, or in more recent studies, how subduction is initiated in the first place. We propose that initiation of subduction at a passive margin may be aided by convective instability of a thickened igneous crustal section that was emplaced during initial rifting of the margin, such as is observed along much of the eastern boundary of the North Atlantic. We performed calculations of subsolidus phase equilibria of mafic and ultramafic lower crustal compositions that show that at the base of the crust at a thickened passive margin, high density phase transitions cause the density of the crust to exceed that of the underlying mantle at sub-Moho pressures by 50-100 kg^3. Following recent work on convective instability of dense lower crust (Jull and Kelemen, JGR, 2001), we propose that colder temperatures at passive margins inhibit rapid convective removal of dense lower crust, and that initially only the deeper, ductile portions of the crust flow downwards via diffusion creep, allowing the density instability to continue. This results in subsidence and related sedimentation, which cause more and more of the lower crust to reach pressures where high density mineral phases form. Using a two-dimensional finite element model for the development of a convective instability, we evaluate this idea and determine the timescales and range of temperatures and pressures at which a thickened passive margin can produce a significant negative buoyancy force on the plate margin. A key component of this idea is that the phase transformations occur faster than the viscous root can "drip" off the bottom. This requires that the kinetics of reactions forming dense phases such as garnet are rapid compared to the time scale for convective instability, and that the reactions occur within geologically relevant times. Alternatively, if the lower crustal load cannot overcome the elastic strength of the plate (along with ridge push + sediment load), then the lower crust could eventually fall off and allow asthenospheric upwelling/heating/weakening, thus decreasing the elastic thickness of the plate so that ridge push and sediment load can overcome shear resistance at the plate margin and initiate subduction.

T42G-09 1550h

A Coupled Thermomechanical Model of Continental Collision in Alpine-Type Mountain Belts

Evgene Burov[1] (331 44 27 39 58; evgenii.burov@lgs.jussieu.fr)

Laurent Jolivet[1] (laurent.jolivet@lgs.jussieu.fr)

Laetitia Lepourhiet[1] (laetitia.lepourhiet@lgs.jussieu.fr)

Gisele Toussaint[1] (gisele.toussaint@lgs.jussieu.fr)

[1]Lab Teconique ESA 7072, University of Pierre and Marie Curie, Case 129, T26-16-1e, 4 Pl. Jussieu, Paris 75252, France

A fully coupled numerical thermomechanical model that accounts for strain localization, surface processes, phase changes and high viscosity contrasts is used to test different mechanisms of subduction in continental collision zones. The model considers various end member cases including low and high buoyancy of the subducted crustal material after metamorphic reactions. The low buoyancy model predicts steep subduction with early break-off and 3 levels of metamorphic rock exhumation for the same collision context: the classical corner flow LP-LT exhumation in the accretionary prism; deeper (70 km) HP-HT exhumation for the thickened subducting crustal-sedimentary wedge, and ultra HP-HT exhumation from the lower crustal chamber, forming at the depth of 100-120 km and separated from the upper one by a narrow crustal channel, which width can oscillate in the process of shortening, thus controlling the quantity of the crustal material exchanged between the crustal wedge and the lower crustal chamber. Although both zones of crustal accumulation and the narrow channel between them resemble a vortex-shaped nozzle, this nozzle appears to be too soft to produce any significant overpressures. From the upper crustal wedge, the material is exhumed following the ascending shear flow created by the overriding plate assisted by positive buoyancy of the heated crustal material. From the lower crustal chamber, the material is transported upwards to the upper crustal wedge by a flow induced by the asthenospheric traction and a small scale convective instability forming in the lower crustal chamber due to its heating by the overriding asthenosphere. In the case of high buoyancy, underplating may occur and the latter mechanisms become dominant resulting in fast exhumation of the crust to the surface, accelerated or slowed subduction in case of full or partial crustal decoupling, respectively, and upper plate extension. For all scenarios, the experiments demonstrate the primary importance of the pre- and post-metamorphic density contrasts as well as the importance of the lateral shear flow zones systematically created at the boundaries between the upper and lower crust and lower crust and mantle lithosphere (Moho zone). Shear strain localization is also predicted at the lithosphere asthenosphere boundary.

T42G-10 1605h

A Model for Wilson Cycles

Bernard Coakley (bcoakle@tulane.edu)

Department of Geology, Tulane University, New Orleans, LA 70118, United States

While the steady state tectonics of subduction are reasonably well understood, the initiation of subduction is not. Theoretical and modeling studies of subduction initiation require large, sustained in-plane stresses to break the continuous oceanic plate and drive the slab into the mantle before a new subduction zone can be self-sustaining. These studies have identified sediment loading and old, dense oceanic lithosphere associated with passive margins as factors favoring the localization of subduction. Old oceanic lithosphere is also quite strong, increasing the stress necessary to break the plate, making passive margins less appealing as a locale for initiation.

In contrast to breaking the plate in-plane, a subduction zone could grow laterally, by crack propagation, extending to join a passive margin. "Primed" by the bouyancy flux of the pre-existing subduction zone, progressive failure along a passive continental margin would disrupt the oceanic lithosphere and become self-sustaining as the dense plate sank into the mantle, accelerating the tear.

The Caribbean plate provides an example of how a micro-plate might nucleate a subduction zone through stress concentration. As the Caribbean plate advanced, the subduction zone at its leading, eastern edge was progressively channeled to the south as first Cuba and then Hispanola were jammed against the Bahamas platform. The Antilles arc is the current site of active subduction. The Caribbean plate is being over-ridden at the Muertos trough, south of Puerto Rico, and at the northern limit of South America and is over-riding the Pacific plate on the west and the North American plate on the east. The Caribbean plate is pinned between the three surrounding plates, which may provide the necessary stress concentration which could lead to the development of a new active margin on the East coast of North America.

Wilson cycle tectonics, as seen in the Phanerozoic history of North Atlantic passive margins, require that passive margins periodically become active. Since slab pull dominates all other plate boundary forces, changing the geometry of subduction alters the absolute motion of the plate, affecting adjacent plates. Rapid initiation of subduction may offer an explanation of rapid, large-scale re-orientation of plate motions.

T51A MC: Hall D Friday 0830h

The Physics and Mechanics of Compressive Failure: From Faulting to Ductile Flow II *(joint with S, MR, HG)*

Presiding: **C E Renshaw,** Dartmouth College**; E M Schulson,** Dartmouth College

T51A-0837 0830h POSTER

Compaction Localization, Fluid Flow and Acoustic Emissions in Porous Rock

David J Holcomb[1] (505-844-2157; djholco@sandia.gov)

William A Olsson (505-844-7344; waolsso@sandia.gov)

[1]Sandia National Labs, PO Box 5800 MS0751, Albuquerque, NM 87185-0751, United States

When subjected to non-hydrostatic, compressive stresses, in the brittle-ductile transition regime, sufficiently porous rocks exhibit non-uniform compaction. The compaction occurs as a localization process, analogous to shear localization, but results in a thickening, tabular zone of compaction as opposed to culminating in a shear fracture. Acoustic emission locations were used to track the evolution and propagation of the compaction front while continuous flow permeability measurements were carried out. These experiments showed that compaction localization produced a two-order-of-magnitude decrease in permeability. Because of the inhomogeneous nature of compaction produced by compaction localization, and its temporal evolution, a number of phenomena related to fluid flow are predicted to occur: compaction-induced fluid injection, locally increased pore pressures, and spatial changes in the effective permeability. Understanding these phenomena requires a knowledge of the time-dependent position(s) of the compaction front(s), obtained from acoustic emission locations and upstream and downstream fluid pressures and volumes, obtained from the continuous flow permeability measurements. These effects are analyzed and related experimental results are reported that show the evolution of effective permeability to be linear with respect to the distance the compaction fronts propagated. The presence of multiple compaction bands leads to locally increased pore pressures which will influence compaction localization in a manner similar to dilatancy hardening for shear banding.

T51A-0838 0830h POSTER

Dilational and Compactional Shear Failure: Application to Siliciclastic Petroleum Reservoir rocks.

Martin Casey[1] (00441132336626; m.casey@earth.leeds.ac.uk)

Quentin J Fisher[2] (00441132331920; quentin@rdr.leeds.ac.uk)

Robert J Knipe[2] (00441132335208; rjk@rdr.leeds.ac.uk)

[1]ES, School of Earth Sciences Leeds University, Leeds LS2 9JT, United Kingdom

T

[2]RDR, Rock Deformation Research Leeds University, Leeds LS2 9JT, United Kingdom

Investigations related to the exploitation of oil reserves provide examples of brittle shear failure in rocks with well known burial, stress, temperature, compactional and diagenetic history. In addition, particular emphasis is placed on the dilational or compactional nature of the failure mode because of the influence this has on the permeability of the fault rocks.

Microstructural investigations show that at shallow depths of less than 2.5 km failure during continued subsidence is by particulate flow and is usually compactional. At greater depths mechanical compaction may occur by particulate flow/ grain crushing or the rock may fail by dilational brittle failure. The main control on failure mode is the degree of cementation. At low cementation the rock fails by particulate flow (with or without fracture). Dilational shear failure occurs when the cementation has considerably reduced the porosity.

We developed a model of cementation rate based on temperature controlled precipitation rate and used this to plot product of porosity and grain radius (a measure of susceptibility of the rock to crushing) against effective stress for some North Sea Reservoir rocks during their burial history. We found that the initially the low cementation rate held the crushing strength constant, causing the rocks to approach the empirical failure curve, but that at greater depths the increased cementation rate rapidly increased the strength, taking the rock mechanical state away from the failure line. Some deeply buried rocks were observed to have lower than expected amounts of cement and we ascribe this to the inhibition of precipitation by clay films.

Deep, well cemented rocks, that failed by shear localised dilatant brittle shear were found to have higher permeabilities than expected on the basis of laboratory results. The natural specimens came from dilational jogs in a network of fault segments and we infer that the increased permeability is the result of deformation under conditions of lower effective confining pressure in the dilational jogs. Thus the application of laboratory results to nature requires a consideration of the possible heterogeneities in the natural deformation resulting from its inherently larger scale.

T51A-0839 0830h POSTER

Formation of Deformation Band Structures Normal to the Shear Plane

Clara M Balasko[1] (1-775-784-6134; clarab@unr.nevada.ecu)

Richard A Schultz[1] (1-775-784-4318; schultz@mines.unr.edu)

[1]Geomechanics-Rock Fracture Group, Dept. of Geological Sciences, University of Nevada-Reno, Mackay School of Mines/172, Reno, NV 89557-0138, United States

Recent fieldwork has shown that many of the geometric relationships previously observed in cataclastic deformation bands are based on a two dimensional view of a three dimensional structure. When the bands are viewed in the shear direction lenses and insosculating bands are seen, as first noted by *Aydin* [1978] and later by many others. When viewed normal to the shear direction "ladder structures" (linked mode II echelon stepovers or duplexes) and conjugate structures are seen [*Davis*, 1999]. *Davis* [1999] grouped these two geometries as different classes of deformation bands and many have interpreted the duplexes as strain localization in Riedel shear zones. Here we demonstrate an alternative explanation.

When viewed normal to the shear direction, deformation bands display either mutually crosscutting ("conjugate") sets or contractional stepovers ("duplexes") between interacting mode-II bands. Our field observations reveal that the principal difference between the two is the relative distance separating the parallel echelon bands. Bands that are sufficiently close interact mechanically to promote linking bands within the stepovers. These linking bands are younger than the bounding echelon bands. Because the orientations of bands within the stepovers are the same as that of "conjugate" bands that are more widely spaced, we infer that the magnitude of stress within the stepovers was increased somewhat over background values, but that stress rotations within the stepovers were negligible. To accomplish this, the echelon deformation bands must be strong relative to the host rock and accommodate only small offsets, leading to only minor perturbations of the local stress state in their vicinity.

Ladder structure, "radiator rock" [*Davis*, 1999], and linked echelon stepovers demonstrate a progression from distributed to more localized strain of the sandstone, with the scale dependent on the size and offset magnitude of individual bands. Occurrence of linked echelon stepovers along both conjugate directions in spaced arrays argues against Riedel shearing as a mechanism for localizing this class of deformation bands.

Aydin, A., Small Faults Formed as Deformation Bands in Sandstone, *Pure and Applied Geophysics, 116*, 913-930, 1978

Davis, G., *Structural Geology of the Colorado Plateau Region of Southern Utah: With Special Emphasis on Deformation Bands*, GSA Special Paper 342, 157 pp., 1999

URL: http://www.mines.unr.edu/geo-eng/geomech

T51A-0840 0830h POSTER

Yves Bernab[1] (yves.bernabe@eost.u-strasbg.fr)

Fethi Saidi (33 3 90 24 00 87; fethi.saidi@eost.u-strasbg.fr)

Thierry Reuschl (33 3 90 24 0048; thierry.reuschle@eost.u-strasbg.fr)

[1]Bernab, 5.rue ren descartes, Strasbourg 67000, France, Metropolitan

In order to investigate separately the effect of grain size, cementation, and bimodal grain size distribution on the mechanical behaviour of poorly consolidated granular rocks, we prepared synthetic materials in which these structural parameters could be varied. We mixed various proportions of two well-sorted sands with different grain sizes, Portland cement, and water. The mixture was left pressure-free during curing, thus insuring that the final material was poorly consolidated even when the cement content was large. The samples were mechanically tested in an uniaxial press. As expected, the uniaxial compression strength increased significantly with increasing cement content. In addition, static Young's modulus was measured during the tests by performing small stress excursions at discrete intervals along the stress-strain curve. We observed a strongly non-linear elastic behaviour in all the samples. Furthermore, we observed a transition from a grain-size sensitive behaviour (i.e., strength and elastic moduli depended on grain-size) at low cement content (i.e., <20%) to grain size independence above this value. The mechanics of rigid inclusions embedded in a soft matrix is consistent with the observed grain-size independence at high cement content. At low cement content, the observed grain-size sensitivity is maybe due to microstructural differences between fine and coarse grained materials. Finally, we also investigated the behaviour of samples, in which, fine and coarse sands were mixed in different proportions at varied cement content. The experimental data shows that for the cement content the behaviour is quite similar to that depicted above (i.e., strength and elastic moduli increased with cementation). At low cement content (i.e., 20%), the strength of samples increased as the proportion of fine grains was increased to 40%, and it remained nearly constant between this point and 100% fine sands. This result suggested that when the proportion of fine-grain phase is lower then 40% it acts as a cementing phase. Above this value, the behaviour becomes independent on the proportion of fine grains, and depended only on cementation.

T51A-0841 0830h POSTER

The Microstructural Record of Synseismic Loading and Postseismic Creep in the Uppermost Plastosphere

Claudia A. Trepmann[1] (+49 234 322 3235; claudia.a.trepmann@ruhr-uni-bochum.de)

Bernhard Stöckhert[1] (+49 234 322 7254; bernhard.stoeckhert@ruhr-uni-bochum.de)

[1]Institut für Geologie, Mineralogie und Geophysik, Sonderforschungsbereich 526, Ruhr-Universität Bochum, Bochum 44780, Germany

Failure of the upper continental crust in major earthquakes is suspected to cause short-term deformation at very high differential stress and high strain rates in the uppermost plastosphere, at temperatures of 300 to 350°C, and with marked fluctuations of pore fluid pressure. The microstructural record of such events has been identified in exhumed metamorphic rocks of the Sesia Zone, Western Alps [1, 2], and provides insight into the deformation processes related to synseismic loading and postseismic creep. Garnet crystals embedded in a quartz matrix are intensely fragmented, with the fragments displaced by sliding along the fractures, and finally slightly pulled apart with quartz and feldspar precipitated from the fluid phase in the open cracks. Jadeite crystals reveal mechanical twinning. The quartz microstructures indicate a transient stage of deformation in the low-temperature plasticity field, followed by deformation in the dislocation creep regime during stress relaxation with a very small recrystallized grain size, and finally minor static grain growth in some samples. The peak magnitudes of differential stress achieved during synseismic loading exceed 0.5 GPa, as indicated by the orientation distribution of mechanically twinned jadeite [2]. Apparent flow stresses of 0.2 to 0.4 GPa are suggested by the dynamically recrystallized grain size of quartz, related to the subsequent stage of non-steady state deformation by dislocation creep, with rapidly decaying strain rates during stress relaxation. The mesoscopic structures reflect a highly inhomogeneous strain field. Strain is concentrated in cm- to m-scale zones (mylonites, ultramylonites, pseudotachylytes) and remarkably low in the intervening rocks. Branching quartz veins developed from open fissures reflect brittle failure, with subsequent plastic deformation and recrystallization of the precipitated quartz. These fractures propagating into a temperature range of 300 to 350°C during synseismic loading are suggested to cause a drop of pore fluid pressure to markedly sublithostatic values, which is prerequisite for plastic deformation at extreme differential stress. Restoration of a near-lithostatic pore fluid pressure in the final stage of postseismic creep is reflected by slight opening and sealing of the cracks in garnet. In summary, the peculiar microstructural record of the exhumed rocks indicates episodic plastic deformation in the uppermost plastosphere at temperatures of 300 to 350°C, with (1) very high peak stresses exceeding 0.5 GPa at the stage of synseismic loading, (2) concomitant drop of pore fluid pressure due to fractures propagating downward, followed by (3) stress relaxation primarily controlled by power law creep of quartz, and (4) eventual restoration of a near-lithostatic pore fluid pressure, reconciled with a major earthquake in the overlying schizosphere.

References:

Küster, M. and Stöckhert, B. (1999): Tectonophysics 303:263-277.

Trepmann, C. and Stöckhert, B. (2001): Int J Earth Sc 90:4-13.

T51A-0842 0830h POSTER

High-Temperature Microindentation Tests on Olivine and Clinopyroxene

Dorothée Dorner[1] (dorothee.dorner@ruhr-uni-bochum.de)

Martin Schellewald[2] (ms@wtech.ruhr-uni-bochum.de)

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

[1]Institute of Geology, Mineralogy and Geophysics, SFB 526, Ruhr-University Bochum, Bochum 44780, Germany

[2]Institute of Materials, SFB 526, Ruhr-University Bochum, Bochum 44780, Germany

The perspectives of microindentation techniques for the investigation of the mechanical behaviour of minerals at high temperatures are explored. The technique offers the following advantages: (1) natural specimens with small grain size can be used, (2) preparation is simple, (3) a reasonable number of experiments can be performed within a short period of time. The strength of single crystals as a function of orientation and the activated glide systems are studied using scanning electron microscopy (SEM) combined with electron backscatter diffraction (EBSD) facilities. Furthermore, the effects of compositional variations on the flow strength of solid solutions are explored.

The indentation hardness tests are performed on selected grains within natural polycrystalline aggregates. The surface of the specimen is polished mechanically and chemically. The orientation of the crystals is determined using EBSD. The indentation tests are performed with a diamond pyramid (Vickers indenter) at temperatures of 25 °C to 900 °C. Loading is done with a constant displacement rate up to a force of 0.5 N, followed by a creep period of 10 s at constant load. SEM is used to measure the size of the indents and to examine their morphology in detail.

The microhardness obtained for olivine depends on crystal and indenter orientation and decreases slightly with temperature. Slip steps are observed on the surface around the indents. Their orientation with respect to the crystal orientation indicates that the predominant glide system activated in the indentation process is {110}[001]. The Schmid factors for this glide system correlate with the observed orientation dependence of the hardness.

Indentation hardness of clinopyroxene solid solutions depends on composition with jadeite being stronger than diopside. This is inverse to what is expected for dislocation creep. The high yield stresses inferred from the hardness data and the weak dependence of hardness on temperature are consistent with plasticity being the deformation regime explored in indentation hardness tests.

T51A-0843 0830h POSTER

A Pore Crack Interaction Model for the Brittle Failure of Porous Granular Rocks

Emmanuelle Klein[1] (Emmanuelle.Klein@eost.u-strasbg.fr)

Thierry Reuschlé[1] (Thierry.Reuschle@eost.u-strasbg.fr)

[1]Institut de Physique du Globe, 5 rue René Descartes, Strasbourg 67084, France

Experimental rock mechanics studies have shown that the brittle failure of porous granular rocks is governed by the subcritical growth of microcracks. Under triaxial compression, at low confining pressures, the mechanical behaviour of rocks is usually compactive up to the onset of dilation, beyond which cracks start to nucleate and propagate. Macroscopic failure occurs when these cracks coalesce by mutual interaction.

This process is analysed by using a fracture mechanics approach applied on a 2-D pore crack model. Our approach is based on some microstructural characteristics of porous granular rocks since it considers the growth of axial cracks emanating from cylindrical pores. These cracks grow when their stress intensity factors reach the subcritical crack growth limit. As cracks get longer their mutual interaction no longer remains negligible. We focus on the interaction between a pair of neighbouring cracks by calculating their stress intensity factor as the sum of two terms: a component for an isolated crack and an interaction term computed using the method of successive approximations. The model depends on crack length, pore radius, pore density and stress. The simulation of crack growth from cylindrical pores, associated with a failure criterion based on the coalescence of interacting cracks, allows us to compare the theoretical critical stress to the experimental peak stress. The comparison is done using experimental data on various porous sandstone samples deformed in the brittle regime. The results show that the model is able to capture the general experimental trend: it gives quite a good agreement between theoretical and experimental failure stress when material parameters deduced from microstructural observations are introduced.

Nevertheless, in its present form, our approach only allows failure by the development of vertical fractures and thus it does not explain the appearance of experimentally-observed shear bands. Future improvements will account for cracks initially oriented at an angle to the direction of maximum principal stress, in which crack sliding is controlled by a coefficient of friction. A constitutive law will then be derived to describe the deformation of a porous granular rock by using microstructural and key mechanical parameters deduced from sample observations.

T51A-0844 0830h POSTER

Visco-Elastic Damage Rheology Model: Theory and Experimental Verification

Yunfeng Liu[1] (213-740-6754; yunfengl@terra.usc.edu)

Vladimir Lyakhovsky[2] (vladi@geos.gsi.gov.il)

Yehuda Ben-Zion[1] (benzion@terra.usc.edu)

Dave Lockner[3] (dlockner@usgs.gov)

[1]Department of Earth Sciences, Univ. of Southern California, Los Angeles, CA 90089, United States

[2]Geological Survey of Israel, Jerusalem, Jerusalem 95501, Israel

[3]U.S.G.S., MS 977, 345 Middlefield Rd., Menlo Park, CA 94025, United States

We present a visco-elastic damage rheology model to describe evolving elastic properties and accumulation of irreversible deformation under large strain. Following the damage rheology model of Lyakhovsky et al. [JGR, 1997], we add a third parameter γ to the parameters of linear Hookean elasticity λ and μ to account for the asymmetry of the response of rocks for loading under tension and compression conditions. These three parameters define the effective instantaneous elastic properties of rock and they are functions of an evolving damage state variable α. We also introduce an effective viscosity proportional to the time derivative of α (i.e., the rate of damage change) to account for gradual accumulation of irreversible deformation due to slip of evolving micro-cracks. We use six deformation experiments carried out at the USGS Rock Mechanics laboratory, Menlo Park, with different rock samples and confining pressures to provide experimental verification for the above visco-elastic damage rheology model. The analysis of data from the experiments employs the observed stresses and acoustic emissions as inputs, while the observed strains are compared with model predications. The latter are calculated with a procedure designed to invert the relations between the model stress and strain tensors. We find that the observed axial and transverse strain-stress curves start to deviate significantly from those predicated by Hookean elasticity when the rate of observed acoustic emission events has a sharp increase. The predications of the elastic damage model of Lyakhovsky et al. [1997] can fit the observations well beyond the range of linear elasticity, but not over the entire deforming range associated with distributed damage. The new model, with the additional effective viscosity, significantly improves the quality of the fitting results for all tests consistently. Both predicated axial and transverse stress-strain relations of the visco-elastic damage model fit the observations very well up to the final brittle failure.

T51A-0845 0830h POSTER

A Differential Scheme for Elastic Properties of Rocks with Dry or Saturated Cracks

James G Berryman[1] (925-423-2905; berryman1@llnl.gov)

Steven R Pride[2] (Steve.Pride@univ-rennes1.fr)

Herbert F Wang[3] (608-262-0693; wang@geology.wisc.edu)

[1]Lawrence Livermore National Lab, University of California, University of California, P. O. Box 808 L-200, Livermore, CA 94551-9900, United States

[2]Universite de Rennes 1, Campus Beaulieu, Bat. 15, Rennes 35042, France

[3]University of Wisconsin, Dept. Geology Geophysics, 1215 West Dayton Street, Madison, WI 53706, United States

Differential effective medium (DEM) theory is applied to the problem of estimating physical properties of elastic media with penny-shaped cracks, filled either with gas or liquid. These cracks are assumed to be randomly oriented. It is known that such a model captures many of the essential physical features of fluid-saturated or partially saturated rocks. Using an assumption that the changes in certain factors depending only on Poisson's ratio do not strongly affect the results, the equations for bulk (K) and shear (G) moduli decouple, so that analytic integration is possible. Validity of this assumption is then tested by integrating the full DEM equations numerically. The analytical and numerical curves for both K and G are in very good agreement over the whole porosity range. Justification of the Poisson's ratio approximation is also provided directly by the theory, which shows that, as porosity tends to unity, Poisson's ratio tends towards small positive values saturated samples. A rigorous stable fixed-point is obtained for Poisson's ratio of dry porous media, where the location of this fixed-point depends only on the shape of the voids being added. These theoretical results for the elastic constants are then compared and contrasted with results predicted by Gassmann's equations and with results of Mavko and Jizba, for both granite-like and sandstone-like examples. Analytical approximations derived here give very satisfactory agreement in all cases for both K and G.

T51A-0846 0830h POSTER

Simulation of Borehole Failure Phenomena Using Discrete Element Modeling

Moo Y Lee[1] (505-844-2366; mylee@sandia.gov)

Benjamin K Cook[1]

Anthony A DiGiovanni[1]

Eric D Perkins[2]

John R Williams[2]

[1]Sandia National Laboratories, P.O.Box 5800, Albuquerque, NM 87123, United States

[2]Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, United States

A computationally efficient numerical model based on the discrete-element method (DEM) is described and applied to simulate well-known borehole failure phenomena: hydraulic fracturing and borehole breakouts. Radially graded, two-dimensional DEM models of the near-wellbore region were created of bonded disk elements. Inspired by the molecular model of a fluid, source elements were used to simulate fluid pressurization of the model borehole subjected to far-field stresses.

The calibration and validation of these numerical tools will require extensive comparison against experimental and field data (Wawersik, 2000). To address this challenge, a joint experimental-numerical research effort has been undertaken to develop a robust simulation capability for the exploration and prediction of near-wellbore mechanics. A true-triaxial vessel has been designed and constructed to enable the realistic laboratory simulation of the three-dimensional stress conditions present in the field (Wawersik et. al, 1997).

The structural damage in the DEM models was analyzed using histograms of the angular distribution of bond damage; results obtained for various stress states showed qualitative reproduction of the gross failure mechanisms associated with both hydraulic fracturing and borehole breakouts. The results from the laboratory simulation of near-wellbore failures demonstrate the ability of DEM to capture the discontinuous failure processes under different stress conditions.

T51A-0847 0830h POSTER

Focal Mechanisms of Acoustic Emission Events During Fault Propagation and Frictional Sliding

Sergei Stanchits[1] (49-331-2881324; stanch@gfz-potsdam.de)

Arno Zang[1] (49-331-2881325; zang@gfz-potsdam.de)

Georg Dresen[1] (49-331-2881320; dre@gfz-potsdam.de)

[1]GeoForschungsZentrum Potsdam, Telegrafenberg D423, Potsdam 14473, Germany

Cylindrical samples of Aue granite with 50 mm diameter and 100 mm length were loaded to failure in triaxial compression tests. A localized shear fracture initiated at the sharp edge of a steel plate covering 2/3 of the top sample surface. Fault nucleation, propagation and post-failure frictional sliding were studied by monitoring the acoustic emission (AE) activity related to microcracking. Ten piezoceramic transducers were attached to the samples and used to locate events and determine focal mechanisms. The velocity of fault propagation and sliding was controlled by the AE rate. Crack microstructures of deformed samples were investigated using optical microscopy. Fault nucleation involves 10-30% of the total AE events observed up to stress drop. A localized process zone of AE surrounds the tip of the propagating fault. Spatial correlation of the AE is low during fault nucleation, but increases during failure propagation up to stress drop. In the sliding stage, spatial correlation remains relatively constant corresponding to D-values of 1.8-2.0. Initial P-axes orientation distribution of focal mechanisms from shear events is broad with two maxima during fault nucleation, but it narrows during fault propagation. For given time intervals, AE P-axes show a preferred orientation near the tip of the process zone, but are more irregular at the trailing edge. During experiments B-values range between 1.2-1.8, but are similar for different fault segments. After stress drop a single P-axis orientation dominates along the fault. The P-axis distribution corresponds to a preferred orientation of secondary shears at a small angle to the macroscopic fault. The shears develop during propagation at the fault tip and remain similar in orientation during sliding.

T51A-0848 0830h POSTER

Central Japan's Atera Active Fault's Wide-Fractured Zone: An Examination of the Structure and In-situ Crustal Stress

Ryuji Ikeda[1] (81-298-54-0638; ikeda@bosai.go.jp); Kentaro Omura[1] (81-298-54-0638; omura@bosai.go.jp); Tatsuo Matsuda[1] (81-298-54-0638; mtatsuo@bosai.go.jp); Yukihiro Mizuochi[2] (81-03-3827-6137; Mizuochi.Yukihiro@sumicon.co.jp); Daijiro Uehara[2] (81-03-3827-6137; Daijiro.Uehara@sumicon.co.jp); Akihiko Chiba[2] (81-03-3827-6137; Akihiko.Chiba@sumicon.co.jp); Akira Kikuchi[2] (81-03-3827-6137; Akira.Kikuchi@sumicon.co.jp); Toshiya Yamamoto[3] (81-03-3668-6261; yamamoto@gsct.co.jp)

[1]National Research Institute for Earth Science and Disaster Prevention, Tennodai 3-1,, Tsukuba 305-0006, Japan

[2]Sumiko Consultants Co. Ltd., Ikenohata 2-9-7, Taitoku,, Tokyo 110-0008, Japan

[3]Geophysical Surveying Co. Ltd., Nihonbashi 3-6-3, Hamacho,, Tokyo 103-0007, Japan

In-situ downhole measurements and coring within and around an active fault zone are needed to better understand the structure and material properties of fault rocks as well as the physical state of active faults and intra-plate crust. Particularly, the relationship between the stress concentration state and the heterogeneous strength of an earthquake fault zone is important to estimate earthquake occurrence mechanisms which correspond to the prediction of an earthquake. It is necessary to compare some active faults in different conditions of the chrysalis stage and their relation to subsequent earthquake occurrence. To better understand such conditions, "Active Fault Zone Drilling Project" has been conducted in the central part of Japan by the National Research Institute for Earth Science and Disaster Prevention. The Nojima fault which appeared on the surface by the 1995 Great Kobe earthquake (M=7.2) and the Neodani fault created by the 1981 Nobi earthquake, the greatest inland earthquake M=8.0 in Japan, have been drilled through the fault fracture zones. During these past four years, a similar experiment and research at the Atera fault, of which some parts seem to have been dislocated by the 1586 Tensyo earthquake, has been undertaken. The features of the Atera fault are as follows: (1) total length is about 70 km, (2) general trend is NW45Kwith a left-lateral strike slip, (3) slip rate is estimated as 3-5 m/1000 yrs. and the average recurrence time as 1700 yrs., (4) seismicity is very low at present, and (5) lithologies around the fault are basically granitic rocks and rhyolite. We have conducted integrated investigations by surface geophysical survey and drilling around the Atera fault. Six boreholes have been drilled from the depth of 400 m to 630 m. Four of these boreholes are located on a line crossing the

T

fracture zone of the Atera fault. Resistivity and gravity structures inferred from surface geophysical surveys were compared with the physical properties determined from the borehole logging data and core samples. These results were also compared with in situ stress data by the hydraulic fracturing stress measurements in the boreholes. We obtained characteristic states on crustal stress and strength of the fault from these investigations. Our findings are as follows: (1) The fracture zone around the Atera fault shows a very wide and complex fracture structure, from approximately 1 km to 4 km wide. The average slip rate was estimated to be 5.3 m /1000 yrs. by the distribution of basalt in age of 1.5 Ma by radioactive dating. We inferred that the Atera fault has been repeatedly active in recent geologic time; however, it is in a very weak state at present. (2) The stress magnitude decreases in the area closer to the center of the fracture zone. Furthermore the orientation of the maximum horizontal compressive stress was almost in a North-South direction, just reverse of the fault moving direction. These are important results to evaluate fault activity. We argue that the stress state observed in these sites exists only when the faults are quite "weak," and thus does not reach to a critical level of fault activation in the present situation.

T51A-0849 0830h POSTER

Coseismic Growth of Active Fault-Propagation Folds by Heterogeneous Shear, Kansai Region, Japan

Eric C Cannon[1] ((303) 492-2763; eric.cannon@colorado.edu)

Karl J Mueller[1] ((303) 492-7336; karl.mueller@colorado.edu)

Yuichi Sugiyama[2] (sugiyama@gsj.go.jp)

Naoko Kitada[3] (kitada@geor.or.jp)

[1]Dept. of Geological Sciences, Univ. of Colorado , Boulder, CO 80309-0399, United States

[2]Active Fault Research Center, Geological Survey of Japan, Higashi 1-1-1 AIST C7, Tsukuba 305-8567, Japan

[3]Geo-Research Institute, 4-3-2, Itachibori, Nishi-ku, Osaka 550-0012, Japan

We define the mechanisms that control growth of active fault-propagation folds in the Kansai region of Japan. Long-term growth over a 10^5 yr time scale of the 44 km-long Uemachi and 3.5 km-long Suminoe flexures is assessed by numerical trishear modeling of depth-corrected seismic profiles. Modeling suggests that the fault tip of the 30-70 degree east-dipping Uemachi blind thrust is located in basement beneath Osaka Basin Quaternary sediments (0.6 to 1.6 km thick). Trishear models of the Suminoe flexure suggest growth above a blind thrust whose tip is located at 1-2 km depth. Fault displacement to length ratios (D/L) for the Uemachi fault span 10^{-2} to 10^{-3} - the lower value suggests reactivation of a preexisting fault. Short-term growth of the Uemachi flexure is assessed with shear-wave seismic profiles that image 50 cm thick beds. Using the base of the flat-lying Holocene sequence deposited across the forelimb as a strain marker, we argue that growth of the fold at 10^4 time scales occurs by heterogeneous shear, apparently by growth of two narrow kink-bands. One kink-band is associated with bed-parallel slip faults that displace tilted strata beneath the Holocene unconformity in a sense opposite that of the master fault. Although strata are folded across the width of the forelimb of Uemachi flexure over 10^5 yr scales by progressive limb rotation, coseismic displacement is not evenly distributed within the forelimb at a 10^4 yr time scale. Heterogeneous shear is also evident on the Suminoe flexure where large shear strains measured in the core of the forelimb cannot be modeled with trishear methods that assume homogeneous shear.

T51A-0850 0830h POSTER

Strain Localization via Graben Development: Influences on Displacement-Length Scaling and Footwall Uplift

Scott J. Wilkins[1] (775-784-6464; swilki@unr.edu)

Richard A. Schultz[1] (775-784-4318; schultz@mines.unr.edu)

Nancye H. Dawers[2] (504-862-3200; ndawers@tulane.edu)

[1]GeomechanicsRock Fracture Group, Dept. of Geological Sciences, Mackay School of Mines/172, University of Nevada, Reno, NV 89557-0138, United States

[2]Department of Geology, Tulane University, New Orleans, LA 70118, United States

Strain localization by brittle faulting is characterized by the coalescence and linkage of small, distributed fractures into throughgoing faults that increase in both displacement (D) and length (L) with time. Although fault population scaling characteristics, such as D-L data and length distributions, are commonly used to interpret the magnitude of strain and degree of localization, the consequences of forming a graben versus an isolated normal fault have not been investigated within this framework. Grabens at Canyonlands, Utah, and the Tempe Terra Extensional Province, Mars, exhibit a systematic increase in maximum displacement with graben length. Three-dimensional elastic boundary-element models predict that slip along one graben-bounding fault will induce significant stress changes on the opposing fault to trigger frictional sliding. These results are supported by earthquake sequences that exhibit successions of antithetic and synthetic slip along graben-bounding normal faults within a single sequence of events. Therefore, graben-bounding faults develop as mechanically interacting structures and each set should be recognized as a single structure in fault scaling relationships.

Footwall uplift is directly related to scarp height, and thus the measured displacement along a fault. Traditionally, magnitudes of footwall uplift have been attributed to variations in effective elastic thickness and fault dip. Our elastic modeling of fault slip also suggests footwall uplift is an increasing function of fault dip and not dependent on fault depth. Importantly, differences in footwall uplift magnitude also occur in response to variations in modeled slip distributions. For a given fault dip, relative footwall uplift is predicted to increase (2.5-40% of throw) with the ratio of graben width to depth of faulting (0-5). These time-independent predictions are in agreement with structural data compiled from terrestrial rifts in East Africa, Russia, and the United States, as well as smaller extensional provinces in the Volcanic Tableland, CA, Canyonlands, UT, and Tempe Terra, Mars.

URL: http://www.mines.unr.edu/geo-eng/schultz/

T51A-0851 0830h POSTER

Brittle Strain Localization and Thrust Fault Geometry Within Thrust-Cored Folds: Causative Principal Stresses and Insights From Coulomb Stress Change

Chris H Okubo[1] (chriso@mines.unr.edu)

Richard A Schultz[1] (schultz@mines.unr.edu)

Michele L Cooke[2] (cooke@geo.umass.edu)

Jian Lin[3] (jlin@whoi.edu)

[1]Geomechanics-Rock Fracture Group, Department of Geological Sciences, Mackay School of Mines, University of Nevada, Reno, NV 89557-0138, United States

[2]University of Massachusetts, Amherst, Morrill Science Center, Amherst, MA 01003, United States

[3]Woods Hole Oceanographic Institution, Dept Geology Geophysics, Woods Hole, MA 02543, United States

Arrays of thrust faults, with intricate geometries of synthetic and antithetic thrusts of various inclinations, underlie the structure and topography of thrust-cored folds. Coulomb stress changes around a single slipped thrust fault can induce brittle strain localization within the surrounding fold and initiate formation of an array of secondary slip surfaces around the primary fault. We relate magnitudes and ratios of causative principal stresses to the geometry of the resulting thrust fault array by using numerical models of Coulomb stress changes around a slipped blind thrust fault.

Our analysis assumes that faults are localized in areas of enhanced Coulomb stress. Coulomb slip is evaluated for a range of friction coefficients from 1 to 0, which correlates to fault dips ranging from 45 degrees to 22.5 degrees. The magnitude of the principal stresses required for Coulomb slip is determined by evaluating the Coulomb failure criterion in principal stress form (assuming S1 is horizontal). Fault displacement due to Coulomb slip is determined by first resolving the critical principal stresses onto the fault plane. The resulting driving stress is then related to displacement by assuming elastic behavior for the wall rock, strong end zones bounding the fault tips, and maximum displacement at the center of the fault, tapering to zero at the tips with an elliptical slip distribution. A ratio of the maximum fault displacement to the down-dip fault length (Dmax/L) yields the value of critical shear strain that is required for thrust faults to form through Coulomb slip. Representative values of Dmax/L calculated here for a 30° dipping thrust fault on the Earth are 0.001, 0.0004 on Mars, and 0.0002 on the moon.

We use the COULOMB dislocation software to map the post-slip Coulomb stress changes that are induced around active blind thrust faults under these conditions. Our results show systematic, dip-dependent variations in the extent and magnitude of Coulomb stress localizations around a thrust fault. A prominent lobe of positive Coulomb stress change is predicted within the hanging wall of a thrust fault dipping at 22.5 degrees. The magnitude of this stress change is sufficient to predict Coulomb slip along additional failure surfaces (secondary thrust faults). At progressively steeper dips, this lobe of hanging wall deformation migrates toward the upper tip of the fault and significantly reduces in extent and magnitude. At a fault dip of 45 degrees, the hanging wall is dominated by negative Coulomb stress change (faulting in the hanging wall is inhibited). Thus, the locations of secondary synthetic and antithetic thrust faults within a thrust-cored fold correlate with the dip of the primary fault.

The Coulomb failure criterion shows that the dip of the primary fault is a function of the principal stress ratio. Therefore, the orientations of the secondary synthetic and antithetic thrust faults, as well as the primary fault, strongly depend on the principal stress ratio at the time of faulting. These results are consistent with field observations of thrust fault geometries within fault-cored folds. Furthermore, this analysis shows that the Coulomb failure criteria can be used to ascertain the horizontal driving stresses, and resulting strains, for mapped thrust faults that formed under known vertical loading conditions (e.g. lithostatic load).

URL: http://www.mines.unr.edu/geo-eng/geomech

T51A-0852 0830h POSTER

Shear Localization in Solnhofen Limestone at Elevated Temperature

Wenlu Zhu[1] (1-508-289-3355; wzhu@whoi.edu)

Xiaohui Xiao[2] (1-617-253-5810; xhxiao@mit.edu)

Brian Evans[2] (1-617-253-2856; brievans@mit.edu)

[1]Woods Hole Oceanographic Institution, Department of Geology and Geophysics, Woods Hole, MA 02543, United States

[2]Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences, Cambridge, MA 02139, United States

With increasing pressure and temperature, rocks undergo a transition in failure mode from localized brittle failure to non-localized plastic flow. Knowledge of the mechanics of this transition is essential in understanding many geological and geophysical problems. In this study, we deformed Solnhofen limestone with initial porosity of 4.5% at temperatures of 473, 523, 573 and 673 K, at confining pressures (argon) of 70 to 200 MPa, and a constant pore pressure (distilled water) of 50 MPa. In this pressure and temperature range, most of the limestone samples failed by dilatancy and localized deformation. The failure process is sensitive to both pressure and temperature conditions. The stress required for the inception of dilatancy and localization increases with increasing pressure and decreasing temperature. Furthermore, at low pressures and temperatures, significant amount of strain softening and an abrupt stress drop were observed during localization. However, at higher pressure and temperature, the localization process became rather progressive, with strain softening and dilatancy accumulating over large amount of axial strain (up to 6%). Following the localization model derived by Rudnicki and Rice (1975), we calculated the internal friction parameter, the dilatancy factor, and the hardening modulus to characterize the failure behavior of our samples. Our experimental data provide the pressure and temperature dependence of both the internal friction parameter and the dilatancy factor. To elucidate the mechanisms that controls the failure modes in Solnhofen limestone, SEM and TEM observations are being made to measure pore geometry and dislocation microstructure. Some interrupted strain tests will be conducted to constrain the evolution of the microstructure.

T51A-0853 0830h POSTER

Lack of Dilatancy and Brittle Failure in Long Valley Caldera Basement Rocks Subjected to True Triaxial Stress Conditions

Chandong Chang[1,2] (chandong@pangea.stanford.edu)

Bezalel Haimson[1] (608-262-2563; haimson@engr.wisc.edu)

[1]University of Wisconsin, 1509 University Avenue, Madison, WI 53706-1595

[2]Now at Stanford University, Mitchell 360, Stanford, CA 94305-2215

We conducted true triaxial compression tests in two metamorphic rocks, hornfels and metapelite, recovered from the Long Valley Exploratory Well, California, in order to determine their deformation and failure characteristics. The two rock types constitute the major lithology of the Long Valley caldera basement in the 2025-2859 m depth range. Both rocks are banded, extremely fine grained ($\sim$1 μm), and have very low porosity ($<$0.4%). Uniaxial compression tests at different orientations with respect to banding planes reveal

that while the hornfels compressive strength is nearly isotropic, the metapelite possesses distinct anisotropy. Conventional triaxial tests in these rocks revealed that their respective strengths increase approximately linearly with confining pressure within the range of 0 to 60 MPa. True triaxial compression experiments, in which the magnitudes of the least and the intermediate principal stresses (σ_3 and σ_2, respectively) are different but kept constant during testing while the maximum principal stress σ_1 is increased until failure, exhibit a behavior unlike that previously observed in crystalline rocks (Haimson and Chang, IJRMMS, 2000; Chang and Haimson, JGR, 2000). For a given magnitude of σ_3, compressive strength remains nearly constant in both Long Valley rock types, regardless of the applied σ_2, suggesting no intermediate principal stress effect. Strains measured in all three principal directions during loading were used to obtain plots of σ_1 versus volumetric strain. These are consistently linear almost to the point of rock failure, suggesting no dilatancy. The phenomenon was corroborated by SEM inspection of failed specimens that showed no microcrack development prior to the emergence of one through-going shear failure plane steeply dipping in the σ_3 direction. The strong dependency of compressive strength on σ_2 in crystalline rocks originates with the higher dilatancy onset levels as σ_2 rises. We infer that strength independence of σ_2 in the Long Valley rocks derives directly from their lack of dilatancy.

T51A-0854 0830h POSTER

Unique Grain-Scale Behavior Preceding Fracture-Like Breakouts in St. Peter Sandstone

Andrew R Klaetsch[1] (arklaets@students.wisc.edu)

Bezalel C Haimson[1] (608-262-2563; haimson@engr.wisc.edu)

[1]University of Wisconsin, 1509 University Avenue, Madison, WI 53706-1595

We are conducting tests in St. Peter sandstone (average grain size 0.25 mm, cementation by sutured grain contact) of various porosities (ranging from 11 to 19%), in which drilling of vertical holes into 130 x 130 x 180 mm blocks subjected to pre-determined true triaxial far-field stresses ($\sigma_H \neq \sigma_h \neq \sigma_v$) induce borehole instability resulting in breakouts. Unlike the typical dog-eared breakouts found in other rock types, and regardless of porosity, these are thin and tabular, i.e. fracture-like, can extend for lengths reaching several borehole diameters in the direction of the least horizontal stress σ_h, and retain constant widths of 10 to 15 grain diameters throughout. Analysis of the damage zone ahead of the breakout tip reveals two distinct modes of micromechanical behavior. In the higher porosity (n=15-19%) sandstone, breakouts are preceded by the development of a narrow band of debonded, but mostly intact grains, suggesting that failure is occurring at grain sutures, and is therefore non-dilatant. However, in the lower porosity (n=11-15%) rock, breakouts occur within a long narrow zone of crushed grains caused by extensive failure of sutured grain contacts and the grains themselves. The breakouts in both cases appear to result from the formation of compaction bands that are emptied by the circulating fluid. The distinct characters of the failed zones can be related to the respective grain sutures. The matrix of the higher-porosity samples contains small areas of grain-to-grain sutured contact; this contact is severed at relatively low stress levels, yielding debonded but intact grains. In contrast, the lower porosity samples reveal large sutured grain contacts relative to grain size. The stronger matrix requires a higher stress to initiate debonding, a level that is also sufficient to crush the grains within the compaction band that develops ahead of the fracture-like breakout tip.

T51A-0855 0830h POSTER

Compressibility and particle size effects of compacted granular quartz

Stephen L Karner[1] (979-458-3924; karner@geo.tamu.edu); F. M. Chester[1]; A. K. Kronenberg[1]; J. S. Chester[1]; S. C. Lenz[1]; A. Hajash[1]; W. He[1]

[1]Dept. Geology Geophysics, Texas AM University, College Station, TX 77843, United States

Numerous processes influence how porous materials deform within the Earth. These mechanisms are not only effected by tectonic and diagenetic history, but depend on the intrinsic properties of granular aggregates (e.g. material, porosity, size, sorting). To study grain size effects, we ran experiments in a triaxial testing apparatus on water-saturated cylindrical samples of loosely packed, granular quartz. We ran two types of tests: 1) effective pressure (Pe) was monotonically stepped at timed increments, and 2) samples were hydrostatically loaded as before except that Pe was periodically lowered to the initial conditions (Pe=2.5 MPa). All pressures (fluid=12.5 MPa, confining<300 MPa), pore volume, and acoustic emissions (AE) were continuously monitored. Samples consisted of two types: 1) St. Peter quartz sand of various size fractions (125-180 μm, 180-250 μm, 250-350 μm, >350 μm); and 2) Arkansas Novaculite (grain size$\sim$35 μm). Similar results were observed for all grain sizes studied. In terms of applied pressure, large volumetric strains occur at low Pe and gradually decrease to a quasi-linear trend at intermediate Pe (we denote this transition as P_0). At intermediate pressures, apparent compressibility values ($\beta \sim \Delta V/\Delta Pe$) are similar for all grain sizes tested. At larger Pe we observe a second transition to rapid compaction that correlates with a maximum in AE rates. Microstructural and AE data indicate grain fracturing and crushing is more pervasive at these pressures, consistent with previous observations of a critical effective pressure (P*) for cataclastic flow. We observe that both transition pressures (P_0 and P*) decrease via a power-law relationship as grain size increases, in agreement with previous work. Our second set of results from Pe load cycling steps show that volumetric strain decreases as Pe is lowered but does not fully return to the initial level. Thus, permanent porosity loss occurs even for low and intermediate pressures. During reloading, we observe lower compressibility values and less AE activity compared to data from constant hydrostatic loading tests. Thus, samples subjected to constant hydrostatic loading exhibit the combined effects of elastic deformation and irrecoverable porosity loss due to compaction.

T51A-0856 0830h POSTER

On the Transition From Coulombic to Plastic Shear Faulting in Ice

Erland M Schulson (1-603-646-2888; erland.schulson@dartmouth.edu)

Thayer School of Engineering, Dartmouth College, Hanover, NH 03755

A re-examination of the literature has revealed two kinds of compressive shear faulting in ice Ih. One kind, termed Coulombic faulting, occurs under lower degrees of confinement; the other kind, termed plastic faulting, occurs under higher confinement. Both processes mark terminal failure under higher rates of deformation. The transition from one to the other occurs when frictional sliding is suppressed and that happens when,to a first approximation, R=(1-m)/(1+m) where R is the ratio of the smallest(least compressive) to the largest principal stress and m is the coefficient of sliding friction. The criterion is limited to m less than unity. It is suggested, and supported by calculation, that plastic faulting is caused by adiabatic softening. The role of shear faulting in ice mechanics will be discussed.

T51A-0857 0830h POSTER

In the Initiation of Brittle Compressive Failure: Lessons From Ice

Carl E Renshaw[1] (603-646-3365; carl.renshaw@dartmouth.edu)

Erland M. Schulson[2] (erland.schulson@dartmouth.edu)

[1]Dept. Earth Sciences, Dartmouth College, Hanover, NH 03755, United States

[2]Thayer School of Engineering, Dartmouth College, Hanover, NH 03755, United States

Brittle failure limits the compressive strength of rock and ice when rapidly loaded under low to moderate confinement. Higher confinement or slower loading results in ductile failure once the brittle-ductile transition is crossed. It is well established that the macroscopic brittle failure of rock, concrete and other brittle materials under compression is preceded by the initiation and sliding of microscopic primary cracks, creating wing cracks at their tips. In laboratory samples, microcracks begin to nucleate more or less uniformly throughout the sample at compressions equal to about 1/5 to 1/3 the terminal failure stress. Under little to no confinement, wing cracks extend and link together, splitting the material into slender columns which then fail. Under low to moderate confinement, wing crack growth is restricted and terminal failure is controlled by the localization of damage along discrete bands of intense damage inclined by approximately 30 degrees to the direction of the most compressive stress. Earlier investigators proposed that localization results from either the linkage of wing cracks or the buckling of microcolumns created between adjacent wing cracks. Observations of compressive failure in ice suggest a new mechanism whereby localization initiates due to the bending-induced failure of slender microcolumns created between sets of secondary cracks emanating from one side of a primary crack. Analysis of this mechanism leads to a closed-form, quantitative model that only depends on independently measureable mechanical parameters. We show that model predictions for both the brittle compressive strength and the brittle-ductile transition are consistent with data from a variety of crystalline materials.

T51A-0858 0830h POSTER

Calculation of Scale-Dependent Curvatures of Geological Surfaces

Stephan Bergbauer[1] (stephan@pangea.stanford.edu)

Tapan Mukerji[2] (mukerji@pangea.stanford.edu)

David D Pollard[1] (dpollard@pangea.stanford.edu)

Peter H Hennings[3] (phhenni@ppco.com)

[1]Geological and Environmental Sciences, Building 320 Stanford University, Stanford, CA 94305

[2]Department of Geophysics, Stanford University, Stanford, CA 94305

[3]Phillips Petroleum Company, 510A Plaza Office Building, Bartlesville, OK 74004

A comparison between a spectral and a factorial kriging analysis is presented for the calculation of scale -dependent normal surface curvatures. Knowledge of scale -dependent curvatures of geological surfaces plays an important role in quantitative structural geology. Often, curvature analyses of geological surfaces, such as horizon tops, are performed to estimate the strain resulting from deformation. The final shape of the horizon, however, is a superposition of natural structures of different sizes ranging from the grain scale to the basin scale. Performing a curvature analysis on the raw data often leads to patchy, un-interpretable surface curvatures. Separating the surface curvature of the overall structure from the curvature of minor surface undulations can therefore be crucial in any quantitative structural analysis that uses the absolute value of surface curvature. The two methods are applied to a seismically mapped and depth-converted horizon of domal structures from the North Sea to investigate their applicability in a sub-surface context.

For the spectral analysis the surface is transformed into a discrete frequency spectrum. When the overall curvature of the horizon is of interest, only the low-frequency components of the spectrum are used for the curvature analysis. The frequency bin width is determined such that only those frequencies that make up the overall surface structure are used, and that aliasing is minimized. The remaining high-frequency spectrum can be added back to address quantitatively the alias introduced by this filtering.

In geostatistical factorial kriging analyses, the spatial covariance (variogram) is estimated from the data, and modeled as a sum of independent factors with different ranges. Short range variogram factors correspond to high frequency spectral components of the surface while long range factors contribute low frequency components. Using the modeled variogram, factorial kriging filters out the desired long range component of the surface. Factorial kriging works directly in the spatial domain and unlike spectral methods can handle irregularly sampled data with minimal wrap around. Regardless of the method used, the separation of the surface into different components must be supported by the underlying geological and physical model.

T51A-0859 0830h POSTER

Numerical Modelling of Thermal Effects of Compressional Faulting and Denudation: the Sierra de Guadarrama (Central Spain)

Marlies ter Voorde[1] (31-20-4447343; voom@geo.vu.nl)

Karen de Bruijne[1] (31-20-4447343; bruc@geo.vu.nl)

Sierd Cloetingh[1] (31-20-4447341; cloeting@geo.vu.nl)

Paul Andriessen[1] (31-20-4447340; andp@geo.vu.nl)

[1]Faculty of Earth Sciences, Vrije Universiteit, De Boelelaan 1085, Amsterdam 1081 HV, Netherlands

We present a two-dimensional numerical model for the thermal response on lithopsheric shortening. The model is fully time-dependent, and includes the effects of alternating fault activation in the upper crust. Furthermore, any denudation-history can be imposed, implying that erosion and uplift can be studied as independent factors.

The model is used to investigate possible tectonic scenarios for the Cenozoic development of the Sierra de Guadarrama in the Spanish Central System. In earlier work, based on fission track analysis, it was suggested that the southernmost part of the present-day Sierra de Guadarrama was part of the Madrid Basin during the Paleogene. This would explain coeval Paleogene heating of samples in the southernmost fault-block, and cooling of samples more to the north.

We use T-t curves obtained from fission-track analysis as constraints for our modelling, and test whether this scenario produces enough heating in the southernmost block to explain these data. Furthermore, we focus on the Pliocene accelerated cooling observed in all the samples, aiming to find out whether this reflects a

T

Pliocene phase of uplift, or rather a Miocene phase of uplift followed by Pliocene denudation.

The modelling demonstrates that uplift in the absence of erosion can cause already more than 50% of the total cooling of a rock sample after complete denudation.

Our results indicate that the scenario suggested above cannot explain the amount of Paleogene heating observed in the rocksamples. Extra strike slip deformation seems to have been important. The only scenarios resulting in Pliocene cooling as observed in the SdG are those incorporating uplift during this timespan.

T51B MC: Hall D Friday 0830h

Continental Rifting and Passive Margin Development: Modeling and Failed Rifting *(joint with S, V)*

Presiding: **B luyendyk,** Univ California**; E Choi,** Caltech

T51B-0860 0830h POSTER

Samuel L Butler[1] (306-966-5702; sam.butler@usask.ca)

Gary T Jarvis[2] (416-736-2100; jarvis@yorku.ca)

[1]Dept. of Geological Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, SK S7N 5E2, Canada

[2]Dept. of Earth, Atmospheric and Terestrial Sciences, York University, 4700 Keele St, Toronto, ON M3J 1P3, Canada

The question of the mechanism that is responsible for super-continent break-up has been a long-standing one. Active mantle plume upwellings, downgoing oceanic plates at continental margins, and passive upwellings due to continental insulation of the mantle have all been proposed as mechanisms capable of creating sufficient extensional stresses within super-continents to result in fracture and dispersal. Much work has subsequently been done using numerical models of the mantle convection process and many of the above-mentioned mechanisms have been demonstrated for different Earth-like convective regimes. For the most part, all previous studies have been performed in Cartesian geometry and in the absence of many effects such as compressibility, phase-transitions, and depth-dependent properties. In this contribution we investigate these effects in a spherical-axisymmetric model of thermal convection in the Earths mantle in which the effects of surface plates are also included. We demonstrate that the extensional stresses needed to fracture super-continents are significantly reduced in spherical geometry and that the active plume mechanism of super-continent fracture may be less viable when effects due to compressibility are included.

T51B-0861 0830h POSTER

Numerical modelling of rift-related magmatism and melt chemistry at passive margins

Simon M Dean[1] (+44 (0)2380 592260; smd9@soc.soton.ac.uk); Moritz M Fliedner[3] (moritz@esc.cam.ac.uk); Timothy J Henstock[1] (then@soc.soton.ac.uk); Timothy A Minshull[1] (tmin@soc.soton.ac.uk); Bramley J Murton[2] (bjm@socnet.soc.soton.ac.uk); Robert S White[3] (rwhite@esc.cam.ac.uk)

[1]School of Ocean and Earth Science, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, United Kingdom

[2]Challenger Division for Seafloor Processes, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, United Kingdom

[3]University of Cambridge, Dept. of Earth Sciences, Bullard Laboratories, Madingley Road, Cambridge CB3 0EZ, United Kingdom

Rifted continental margins comprise many of the margins around the world, and all the margins in the North Atlantic. Their formation is of significant interest to the understanding of plate tectonics and they are of commercial interest as a potential hydrocarbon resource, the economic value of which is influenced by how the margin evolved. The amount of rift-related magmatism at a rifted margin is intrinsically linked to how the margin formed and affects the postrift margin subsidence. Rift-related magmatism is influenced by a number of parameters that we can numerically model including the maximum degree of continental extension and the mantle temperature at the time of rifting.

Current geophysical rifting models predict little or no synrift decompression melt material has been intruded into, or accreted beneath, continental crust at 'non-volcanic' margins in the North Atlantic. These rifting models assume a normal mantle temperature of 1300°C, appropriate to regions away from a hotspot or mantle plume, and moderate degrees of continental extension (β<15) by a pure shear mechanism. However, recent geophysical data and basement sampling by the Ocean Drilling Program (ODP) has identified an ocean-continent transition zone (OCT), located between extended continental crust and earliest oceanic crust, which is thought to have formed by the exhumation of mantle material to the basement. To form the OCT, in current study areas a region up to 170 km wide, explicitly requires (β>>15, for which at least 3-5 km of rift-related magmatism is predicted by the current rifting models.

In addition to melt thickness, our model includes calculations for the major and trace element melt geochemistry. We compare the chemistry of the melt to the latest geochemical data, obtained from basement sampling, as a new constraint on the degree of rift-related magmatism. Although we have only applied the model to non-volcanic margins so far, it is equally applicable to many volcanic margins, which we will investigate in the future.

T51B-0862 0830h POSTER

Randell A Stephenson[1] (31-20-444-7347; ster@geo.vu.nl)

Andrey Ershov[2] (7-095-939-4928; and@geol.msu.ru)

[1]Faculty of Earth and Life Sciences Vrije Universiteit, de Boelelaan 1085, Amsterdam 1081 HV, Netherlands

[2]Geological Faculty, Moscow State University, Moscow 119899, Russian Federation

One way in which theoretical rheological models of the lithosphere can be constrained by geological data is through estimations of the lithosphere's integrated strength. When an applied force exceeds this, then the lithosphere should lose its integrity and undergo irreversible deformation (WLF - "whole lithosphere failure"). The geological expression of this kind of deformational regime is the development of rifts (in extension) and inverted structures (in compression). By considering intracratonic structures rather than marginal ones it is possible to exclude additional extraneous influences and infer the net effect of intraplate stresses. Here, actual intraplate structures are considered in terms of a rheological model in which the non-brittle part of the lithosphere deforms viscously (by creep) in response to applied forces. This is in contrast to conventional estimations of total lithosphere strength based on "yield stress envelopes" in which "ductile" deformation is taken to be time-invariant (plastic). Taking into account the implications of adopting a viscous rheology in place of a plastic one in evaluating the "strength" of the lithosphere, it is necessary to incorporate the time-dependence of stresses, strains and strain rates and also the dependence of the bulk strain rate on the total applied force. This means that the duration of loading of tectonic forces prior to eventual rifting or inversion is also an important model variable. The mechanism that controls strain rate and stress distribution in the lithosphere prior to WLF in the model is one of stress redistribution from ductile deformation zones into elastic ones, as determined by stress relaxation in the former and stress amplification in the latter given an assumed constant applied boundary force. A stable equilibrium regime of deformation occurs when, at each point within the lithosphere, the stress reduction effected by viscous relaxation equals the stress increase effected by the applied force. Studies of key structures - including the Tertiary Eurekan "Orogen" (large-scale inversion) in northern Canada, the Devonian Dnieper-Donets Rift in Ukraine and its inverted segment the Donbas Foldbelt, and the Late Cretaceous inversion of the Polish Basin - suggest that relatively short-lived periods (<10 My) of very high plate boundary forces may be sufficient to cause intraplate WLF. An elevated lithosphere geotherm (such as might accompany much rift development) is favourable to WLF though is difficult to invoke during most inversion events, which tend to occur synchronously over large continental regions, suggesting a plate-wide (intraplate stress related) causal mechanism.

T51B-0863 0830h POSTER

Numerical Models of Half-graben Inversion

Susanne Buiter[1] (+41 (0)31 6314738; susanne@mpi.unibe.ch)

Adrian Pfiffner[1] (Adrian.Pfiffner@geo.unibe.ch)

[1]Geological Institute, University of Bern, Bern, Switzerland

Inversion of extensional sedimentary basins occurs in regions where an extensional phase is followed by compression. Mild to moderate basin inversion has been identified on seismic profiles in the North Sea and the Alpine foreland, where Late Cretaceous and Permo-Carboniferous basins were inverted in Cenozoic times. Examples of strong or complete inversion can be found in the Alps and Pyrenees and are associated with complex deformational structures including folding, fault rotation, fault reactivation, extrusion of basin fill and the creation of new faults.

We examine the effects of compression of a sequence of half-graben basins. To this purpose, we use a two-dimensional, visco-plastic model. The choice for a half-graben geometry is motivated by seismic studies, which show that rifting often leads to a series of half-grabens, and reconstructions of pre-inversion geometry of inverted regions. The aim of our study is to investigate the effect of various factors which play a role in the development of fold and thrust structures forming during inversion of half-grabens. We focus on the sensitivity of evolving structures to inherited extensional geometry, syn-rift and post-rift competence contrast, the presence of weak decollement layers, and surface erosion. Results of our models are compared with examples from nature (seismic and field studies) and analogue studies.

We find that syn-rift sediments are uplifted in the initial stages of basin inversion. This uplift is accompanied by rotation of the basement blocks beneath the basins. In the post-rift sequence new shear zones form which are a continuation of basin-bounding faults. With continuing shortening, further inversion is difficult owing to relative strengthening of the half-graben region. Erosion facilitates inversion. The presence of a post-rift decollement layer tends to decouple deformation of post- and syn-rift sediments and facilitates extrusion of the basin fill.

T51B-0864 0830h POSTER

Three-dimensional finite element models of fault-controlled sedimentary basin formation

Andreas Henk (++49-761-2036471; henk@uni-freiburg.de)

Geologisches Institut, Universitaet Freiburg Albertstr. 23 b, Freiburg D-79104, Germany

Three-dimensional numerical models are used to gain quantitative insights into the spatial and temporal variations of stress and strain during the formation of fault-controlled sedimentary basins, i.e. rifts and pull-apart basins. The study utilizes finite element techniques and a coupled thermomechanical modeling approach to simulate extension on a lithospheric scale. Thermal modeling is based on three-dimensional heat transport by conduction and advection. Among others, temperature-dependent thermal conductivities and lithology-dependent radiogenic heat production rates are used to calculate the lithospheric temperature field and its variations through time. For the mechanical calculations deformation in the brittle domain is described by an elastic-perfectly plastic material law with a pressure-dependent yield strength while deformation in the ductile domain is approximated by temperature- and strain rate- dependent creep laws. Contact elements are used to describe pre-existing zones of weakness which become reactivated during basin formation. Either displacement rates or plate boundary forces can be applied as boundary conditions in order to simulate lithospheric extension. Modeling techniques are applied to the evolution of the Rhine Graben in Central Europe and the Hanmer Basin of New Zealand. The results of the numerical simulations illustrate how extensional deformation is partitioned within the lithosphere and document strong variations of the regional stress field in the vicinity of the basin-bounding faults and with depth.

T51B-0865 0830h POSTER

Hangingwall Deformation Above Inverted 3D Listric Fault Systems - Insights From Experiments and Section-Balancing Techniques -

Yasuhiro Yamada[1] (yamada@rc.japex.co.jp)

Ken McClay[2] (ken@gl.rhbnc.ac.uk)

[1]JAPEX, 1-2-1, Hamada, Mihama, Chiba 261-0025, Japan

[2]Royal Holloway University of London, Egham, Surrey TW20 OEX, United Kingdom

Fault geometry is a primary control on hangingwall deformation. In this study, a series of inversion analogue experiments was conducted by using rigid fault surfaces of spoon-like true 3D geometries. The hangingwall geometry on serial sections of the experiments was then examined with conventional 2D section balancing techniques.

To investigate the geometric and kinematic evolution of geologic structures, scaled physical experiments are excellent technique. In this paper, experimental results by Yamada (1999) were used. As the master detachment surface, two types of rigid footwall fault blocks were employed. One has a sinusoidal shape and the other has a double-concave shape in plan view, while both have a vertical profile of a simple concave listric. In each experiment, the hangingwall is uniformly extended by 10 cm, then uniformly contracted