temporal change, we could find subsidence in Okushiri island consistent with the observed one.

T42E MC: 310 Thursday 1330h

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

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

T42E-01 1330h

Coupled Evolution of Damage and Fluid Flow: A Unified Permeability-Porosity-Stiffness Relation.

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We present a formulation for mechanical modeling of interaction between fracture and fluid flow. The new model combines the classical Biot's poroelastic theory together with a damage rheology model. The theoretical analysis based on the thermodynamic principles, leads to a system of coupled kinetic equations for the evolution of damage and porosity. We generalize the widely used permeability (k)-porosity (ϕ) relation (k=k$_o\phi^n$), by accounting for the effect of damage intensity on the connectivity:
k=k$_o\phi^n\alpha^m$,
where α is the damage intensity variable. This new damage-permeability relation together with the coupled kinetics of damage and porosity evolution reproduces a wide range of realistic features of rock behavior. We constrain the model variables by comparisons of the theoretical predictions with laboratory results reporting porosity and permeability variation of rock samples during isostatic and anisotropic loading. The development provides an internally consistent framework for simulating coupled evolution of fracturing and fluid flow in a variety of practical geological and engineering problems such as: nucleation of deformation features in poroelastic media and fluid flow during seismic cycle.

T42E-02 1345h

Seismic and Micromechanical Studies of In situ Compressive Failure

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Our fundamental understanding of how microfractures progressively weaken rocks and in turn how this contributes to macro-deformation processes is limited. However, recent advances in particulate mechanics now mean fracture processes can be modelled dynamically to study the micro-mechanics of fracturing in rock. In addition, advances in recording and analysing very high frequency acoustic emissions (AE) allow for detailed examination of micro-cracking. We use these particle models and AE techniques to test specific hypotheses about natural and induced rock fracture processes at an intermediate scale (between classic lab and nature) by examining compressive failure in an underground laboratory in granitic rock.

During the excavation of the underground laboratory seismic activity was recorded using an array of 16 triaxial accelerometers positioned to give optimal focal coverage around a tunnel. The data collected on these sensors were processed to provide locations, magnitudes and source mechanism information about compressive failure around the tunnel. The dynamic excavation response was modelled in 2D using the Particle Flow Code (Itasca Consulting Group). The rock properties used in the model were first calibrated by undertaking a series of simulated uniaxial lab tests and comparing the results to actual laboratory tests undertaken on the granite. To simulate the time-dependent response of the tunnel a stress-corrosion mechanism was employed in the model. In the excavation simulation, we found that the spatial and temporal evolution of the seismicity and the magnitude distributions replicated the in situ seismicity. As part of the PFC modelling, source mechanisms (moment tensors) were also computed for the events recorded during the dynamic simulation. Although a direct comparison of the mechanisms cannot be made as the simulation was performed in 2D, the results are compatible with those that have been observed during processing of the real events.

Hazzard J.F., Young R.P., and Maxwell S.C., (2000). Micromechanical modelling of cracking and failure in brittle rocks. Journal of Geophysical Research, 105, 16,683-16,697.

URL: http://www.liv.ac.uk/seismic

T42E-03 1400h

Acoustic Emission Activity and Spatial Distribution of Damage Associated with Compaction Band Formation

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Compaction band has been observed as a localized failure mode in porous sandstones, at stress states that are associated with the transitional regime from brittle faulting to distributed cataclastic flow. Detailed microstructural observations were conducted on the Bentheim, Berea, Boise, Darley Dale and Rothbach sandstones with porosities ranging from 13% to 35% to delineate and quantify the spatial distribution of damage associated with the development of compaction bands. Significant grain crushing and porosity reduction are evident in the localized bands, with crack densities up to 5 times greater than those in areas outside the bands. Two different patterns of strain localization can be distinguished: diffuse conjugate shears at relatively high angles, and discrete compaction bands subperpendicular to the maximum compression direction. Whereas the development of diffuse bands is characterized by the continuous accumulation of acoustic emissions (AE), discrete bands are associated with episodic surges in AE that are characterized by an overall strain hardening trend punctuated by episodic stress drops. The number of discrete bands correlates with the number of AE surges and stress drops. Preliminary permeability measurements indicate appreciable reductions of permeability during compaction band development.

T42E-04 1415h

Deformation Bands as Linear Elastic Fractures: Progress in Theory and Observation

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Deformation bands (DBs) are thin, tabular, bounded features of highly localized shear and/or compaction that commonly occur as systematic and pervasive arrays in porous sandstone. They also constitute an active area of theoretical and experimental research into the compressive failure of granular materials. Based on our ongoing study of DBs in the field, we propose that they originate at stress concentrations and propagate as brittle fractures in a linear elastic medium. Furthermore, we suggest that individual DB morphology is largely dominated by the closing (anti-mode I) component of the displacement discontinuity accommodated.

The notion of DBs as "anti-cracks" akin to pressure solution surfaces is not new. But close examination of real DB arrays within the unifying context of linear elastic fracture mechanics is needed to add depth and bring quantitative rigor to our understanding of the phenomenon. Thus, we are building a body of detailed data based on field observation and thin-section analysis to substantiate and expand our central hypothesis, while also laying the foundation for an effort to replicate realistic DB arrays using numerical modeling techniques. Our field effort focuses on the Jurassic Aztec Sandstone as exposed in and around the Valley of Fire State Park, Nevada. This area offers expansive and varied DB exposures within a thick and relatively consistent sequence of dune-dominated aeolian sandstone.

We will present interim results, interpretations and conclusions specific to the elastic nature of DBs, in particular comparing our data to the three distinct fracture-tip models: the dislocation, and the crack with and without cohesive end zones. Each of these models predicts substantially different near-tip stress fields for the same material under the same remote loading conditions, leading to different expectations for basic DB shape, structure, and propagation and mechanical interaction behavior. These expectations will be compared to and judged against our field-based observations.

T42E-05 1430h INVITED

Predictions for Localized Compaction Bands

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Compaction bands are narrow, planar zones of localized pure compressive deformation (without shear) that form perpendicular to the direction of the maximum compressive stress. They have been observed in porous sandstones in the laboratory under conditions for which uniform (non-localized) compression is also a possible mode of deformation and in the field. Because the porosity and permeability in the bands is less than in the surrounding material, formation of these bands in reservoirs and aquifers can dramatically alter the character of the fluid flow. Olsson (*JGR*, 1999) has pointed out that conditions for the occurrence of compaction bands can be derived by the same approach used by Rudnicki and Rice (*J. Mech. Phys. Solids*, 1975) to predict the onset of shear bands: determining the conditions on the constitutive parameters for which localized deformation is an alternative to uniform deformation. This procedure is applied to the predict the onset of compaction bands in the axisymmetric compression test for a transversely isotropic material (with the isotropy axis coinciding with the specimen axis) described by a linear relation between stress-rates and strain-rates. Compaction bands are first predicted to occur when $E = -(9/2)r\nu K$, where E is the tangent modulus (slope of stress vs. strain curve), ν is the negative of the ratio of increments of lateral to axial deformation (at constant confining stress), r is the ratio of axial to lateral stress increments causing zero axial deformation and K is a modulus relating increments of lateral stress and strain. In axisymmetric compression experiments, compaction bands are typically observed on relatively flat portions of the stress-strain curve indicating that $E \approx 0$. Some experimental evidence suggests that the deformation is nearly uniaxial, $\nu \approx 0$ but the non-uniform deformation makes precise measurements difficult. Shear bands (sometimes at low angles to the specimen axis) are frequently observed in conjunction with or in the absence of compaction bands. The predictions of both depend sensitively on the constitutive formulation and, in materials modeled by both a shear yield surface and a "cap", on the intersection of the two surfaces.

T42E-06 1450h

A New Class of Microstructures Associated with Transformation-Induced Faulting

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Previously, experiments on transformation-induced faulting during the olivine to spinel transformation in Mg_2GeO_4 have provided an increasingly clear picture of the microstructural evolution of spinel-filled anticracks under loading and the coalescence of individual anticracks into through-going faults. We report here a new type of stress-induced transformation microstructure that also leads to bulk shear failure, discovered in a new Mg_2GeO_4 starting material with a larger average olivine grain size (150 μm) and much smaller average enstatite grain size (5 μm) than that used in previous studies. Electron microscopy shows thin (120-1000 nm) planar zones of nanocrystalline (10-40 nm) spinel which form by preferential transformation of low angle boundaries in deformed olivine. These zones develop rapidly after approximately 25% bulk strain. As these zones develop into a network with increasing strain, specimens weaken at an accelerating rate and ultimately can fail in shear. The rate of weakening preceding bulk failure correlates with the degree of development of the planar zones. In failed specimens and in those unloaded before bulk failure, individual zones show evidence of shear offsets, suggesting that the strain weakening may be due to localized failures

throughout the specimen. At 1.0-1.7 GPa, faulting due to planar transformation in this material occurs at T = 1250-1275 K, warm enough to allow transformation of high strain regions, but below where anticrack formation along grain boundaries becomes very rapid. At higher T, the overall transformation rate is too high to develop a shear instability; the experiments stably strain weaken with accumulating transformation. In experiments with finer-grained olivine, anticracks are the dominant microstructures which coalesce into fault zones. We hypothesize that at larger grain sizes, planar transformation is more efficient because anticrack development along grain boundaries is too slow to build a through-going network of weak material before the overall amount of transformation leads to stable strain weakening rather than faulting. Planar transformation compliments anticrack formation, and it is possible that both mechanisms can coexist in Earth in materials of differing grain sizes.

T42E-07 1525h

Dissolution and Replacement Creep:A Significant Deformation Mechanism in Mid-crustal Rocks

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Zoning patterns and zoning truncations in metamorphic minerals in a granodioritic orthogneiss from the Bronson Hill terrane, New England indicate that strain and S-C fabrics in these rocks were produced by dissolution, precipitation, and replacement processes, even at epidote-amphibolite facies metamorphic conditions. The metamorphic fabric is defined by alternating layers and folia dominated by quartz, feldspars, and biotite + epidote. Zoning patterns in most metamorphic plagioclase, orthoclase, epidote, and sphene are truncated at boundaries normal to the shortening direction, suggesting dissolution. Interfaces of relict igneous orthoclase phenocrysts that face the shortening direction are embayed and replaced by biotite, epidote and myrmekitic intergrowths of plagioclase and quartz. Metamorphic plagioclase grains are also replaced by epidote.

We interpret these microstructures to reflect strain-enhanced dissolution. The cores of many grains show asymmetric overgrowths with at least two generations of beards, all oriented on the ends of grains that face the extension direction. We interpret these textures to reflect precipitation of components dissolved by deformation enhanced dissolution. While biotite and quartz probably deformed by dislocation creep, the overall deformation was accommodated by dissolution perpendicular to the shortening direction, and precipitation parallel to it. These chemical processes must have been activated at lower stresses than the dislocation creep predicted from extrapolations of data from experiments in dry rocks. Thus wet crust is likely to be weaker than calculated from these experimental studies. Where such processes dominate, stress may not be high enough to reach brittle failure.

T42E-08 1540h

Faulting by Dissolution and Shearing in a Compressive Setting

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We present a new model demonstrating the initiation and growth of normal faults by hierarchical formation of pressure solution structures and their subsequent shearing in Cretaceous platform carbonates in a fold and thrust belt setting at Maiella Mountain, Italy. We have documented the detailed architecture of these faults through increasing slip values from a few mm to ~10 meters and identified the sequence of processes responsible for their evolution.

Faults develop by the following processes. (1) Bedding-parallel solution surfaces form during burial and define mechanical layer boundaries. (2) Within each layer two tectonic related orthogonal sets of bedding-perpendicular solution surfaces develop. (3) Shearing along bedding parallel solution surfaces, due to flexural slip of the layers forming an anticline, produces tail solution surfaces that extend from their terminations at oblique angles. Localized deformation also occurs at the termination of slip patches where tail solution surfaces and preexisting bedding-perpendicular solution surface sets form a zone of incipient shear. (4) The zones of localized deformation are consequently sheared in a normal sense, thereby generating a fifth set of solution surfaces that helps to fragment the rock. With increasing slip, further fragmentation and weakening of the rock occurs within adjacent mechanical packages. (5) Linking of high intensity damage zones within the adjacent mechanical packages results in fault growth. At this stage, the fragmented rock constitutes breccia with variable geometry and grain size from one mechanical layer to the next, depending primarily on the spacing of the bedding-parallel solution surfaces and/or the thickness of the mechanical layer. With larger amounts of slip, polished and striated surfaces form at the edges of the breccia zone and define fault boundaries.

We highlight two major points. First, whereas the interaction and linkage of opening (mode I) features such as joints or veins are commonly associated with fault development, pressure solution (anti-mode I) with subsequent shearing represents the sole deformation mechanism in this case. Second, it is intriguing that normal faults, whose overall geometry accommodates extension, form by the processes of dissolution and shearing in a contractional setting.

T42E-09 1555h INVITED

Evolution and Zonation of Host Rock Deformation During Faulting

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We analyze the zonation and evolution of host-rock deformation that are associated with a set of small faults developed in a quartz-syenite body in southern Israel. The work includes field mapping, in-situ measurement of mechanical properties, microstructural study and strain measurements. The faults range in length from 1mm to 100m and they are curved and segmented at almost all scales. Three deformation zones are recognized: (1) fault-core with width W = 0.005 L (L is fault length), and which includes breccia and networks of calcite-filled-fractures; (2) inner-zone with W = 0.1 L, and which includes intra-granular and intergranular fault-parallel fractures, reduction of Young modulus and uniaxial strength, and distorted lines; (3) outer zone with negligible fault related deformation. We determined the fault-related shear strain from measured displacements and geometry of fault-normal distorted lines and found nonlinear decrease of strain intensity from about 3.0 at the fault-core to less than 0.01 at the outer zone. The present analysis indicates that the fault-related deformation formed during two main stages. First, fault propagation stage during which intense deformation was localized in a process zone with W=0.001-0.005 L. Second, mature fault stage during which anomalous shear is associated with slip along the existing, weak fault. Fault-related deformation that preceded the faulting was apparently below the resolution of our methods. The self-similarity of the studied faults over five length orders and the outstanding lack of tensile microcracks suggest fault growth in shear mode.

T42E-10 1610h INVITED

Localized Failure Modes in a Compactant Porous Rock

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Since dilatancy is generally observed as a precursor to brittle faulting and the development of shear localization, attention has focused on how localized failure develops in a dilatant rock. However, recent geologic observations and reassessment of bifurcation theory have indicated that strain localization may be pervasive in a compactant porous rock. The localized bands can be in shear or in compaction, and occur as diffuse or discrete bands oriented at relatively high angles (up to 90 deg) to the maximum compression direction. Microstructural characterization of the spatial distribution of damage in failed samples have confirmed that localized failure modes involving such compaction bands and high-angle conjugate shears can develop in sandstones with porosities ranging from 13% to 35%. These failure modes are generally associated with stress states in the transitional regime from brittle faulting to cataclastic ductile flow. The laboratory results suggest that these complex localized features can be pervasive in sandstone formations, not just limited to aeolian sandstone in which they were first documented. They may significantly impact the stress field, strain partitioning and fluid transport in sedimentary formations and accretionary prisms. While bifuraction theory provides an useful framework for analyzing the inception of localization, our data rule out a constitutive model that does not account for the activation of multiple damage mechanisms in the transitional regime.

T42E-11 1625h

Two-Yield Surface Model for Compaction Band Formation in High Porosity Rock

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Compaction bands, a recently identified form of localized deformation found in high porosity rock, consist of planar zones of pure compressional deformation that form perpendicular to the maximum compression direction. They are characterized by reduced porosity and reduced permeability, and have been observed in both field and laboratory specimens. Experimental results (Wong, Baud and Klein, 2001) indicate that compaction bands and/or shear bands (at an angle to the maximum compression direction) occur in a transitional regime where multiple damage mechanisms may be active. Utilizing a two-yield surface constitutive model, which macroscopically represents two active damage mechanisms, conditions for localized deformation are examined. The first yield surface corresponds to a dilatant, frictional mechanism, while the second is a yield surface cap (shear stress required for further inelastic deformation decreases with increasing mean stress), which corresponds to a compactant mechanism. A bifurcation approach to localization (Rudnicki and Rice, 1975) reveals that localization conditions are strongly influenced by the choice of constitutive relation. For reported values of key material parameters, a single yield surface constitutive model predicts only shear bands, while both compaction bands and shear bands were observed. However, the two-yield surface model predicts both experimentally observed band types. The influence of the bulk hardening modulus (slope of the mean stress vs. inelastic volume strain curve at constant shear stress) on localization conditions is examined, as is the normality assumption commonly applied to the yield surface cap.

T42E-12 1640h

Grain-Scale Deformation in a Weakly-Cemented Analogue Reservoir Rock

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High-resolution field-emission scanning electron microscopy was performed to elucidate the micromechanics of compaction in Castlegate sandstone deformed in the laboratory under triaxial compression loading conditions. The microscopy reveals that compaction of this weakly-cemented sandstone proceeds in two phases: an initial stage of porosity decrease that is accomplished by breakage of grain contacts and grain rotation, and a second stage of further porosity reduction that is accommodated by intense grain breakage and rotation. This compaction sequence contrasts with that observed by other workers in more strongly indurated rocks such as Berea sandstone, where grain fragmentation coincides with the onset of inelastic compaction. Quantitative stereological measurements corroborate the decrease in intergrain spacing and increase in grain boundary contact area that the microstructural observations suggest occur during the first stage of compaction. In the second stage of compaction, image analysis further reveals a five-fold increase in the surface area per unit volume resulting from extensive microfracturing that occurs with a preferred orientation parallel to the primary loading axis. Acoustic emission (AE) detection and location measured during the experiment correlate with the microscopic observations in that rotation and breakage of grain contacts in the first compaction stage is marked by diffuse AE events whereas the regions of intense grain breakage and subsequent compaction are indicated by intensely concentrated AE. High-resolution (1.7 and 3.3 micron) synchrotron computed microtomography experiments performed on millimeter sized cores at the GSECARS beamline at the Advanced Photon are also analyzed and compared with the data obtained from the high-resolution scanning electron microscopy.

This work was performed at Sandia National Laboratories funded by the U.S. Department of Energy under Contract DE-AC04-94AL85000.