T13A CC: 516 A Monday 1330h

Visualizing the Evolving Fault Zone I

(joint with G, S, MR)

Presiding: **J F Hazzard,** University of Toronto**; K Mair,** University of Edinburgh

T13A-01 1335h INVITED

Defining the mechanical fault

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Simply defined, a fault is a fracture on which slip is localized during an earthquake. However, as the number of studies on fault zones grows, so too does our understanding of the complexity of fault structure and evolution. We examine the structure and evolution of faults related to the Landers and Hector Mine ruptures in the Mojave Desert, within the eastern California shear zone. Following both the Landers and Hector Mine earthquakes, we used trapped waves to delimit a 100-200 m wide zone of highly damaged rock and found significant velocity and shear modulus reduction within this zone to at least 5 km depth. In addition, we tracked the healing of these fault zones. Our study of both fault zones showed an increase in velocity in the years following the mainshocks. The Hector Mine earthquake shook and re-damaged the Landers fault zone resulting in a temporary reversal of healing. InSAR and shear-wave anisotropy studies complement the refraction wave studies by providing a regionally extensive view of the deformation field. Anisotropy studies show rotation in microcrack orientation along strike of the Hector Mine earthquake and also variable distribution of crack density. Post-seismic InSAR images indicate poroelastic rebound is a major player in the deformation fields following both the Landers and Hector Mine earthquakes. Localized zones of post-seismic deformation detected by InSAR correspond to regions of high crack density and velocity reduction observed by anisotropy and trapped wave studies. While we see healing of the fault zones within the first few years after rupture, long-term reduction in the fault-zone rigidity is evident from coseismic InSAR images spanning both the Landers and Hector Mine earthquakes. We see strain localized on compliant zones of nearby unbroken faults, i.e., the Pinto Mountain, Calico and Rodman faults, indicating that active fault zones are probably permanently softer than the surrounding more intact rock.

T13A-02 1355h

Comminution characteristics of quartz in natural and experimental faults; Implications for brittle shear localization

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We studied a number of faults in weakly cemented Aztec sandstone (92.6% quartz, 6.1% clay, 1.2% K-feldspar; well/sub-rounded grains; mean grain size 330μm; porosity 17-24%) from Valley of Fire (VOF) State Park in Nevada, USA, with true displacements 1.5 to150 cm. The deformation is typically asymmetric core/damage zone type microstructure with fault core thickness varying between the samples from 2 to 50mm. Digital optical and SEM images were used to obtain PSD, and fractal dimension (D) of the comminuted quartz with $\sim$4μm particle segmentation resolution. A shape descriptor algorithm (POL) was used for quantifying particle angularity. The VOF results were compared with those of quartz and feldspars in simulated Westerly granite gouge (WG) sheared at 25MPa pressure. Compared to WG samples of similar displacement, typical VOF fault gouge appears to be less isotropic and includes larger and more survivor particles. The incidence of D values >2.58 seems to correlate with shear localization microstructures regardless of total displacement on the faults. There is considerable reduction in particle angularity with increased displacement in the VOF samples, and higher D values correlate well with lower POL numbers, i.e. comminution results in rounding of quartz particles. Similar correlation of D and POL values is found for the quartz fraction in the WG samples in which feldspar particles become more angular with increased shear displacement. The results provide a tentative basis for relating the evolution of particle geometry to angle of internal friction in active bands within the fault gouge. Our observations support a model in which an episode of displacement on the fault initially generates series of dilatant oblique shears (e.g. a stack of R-shears). The dilatant shears should occur with diminishing frequency as further comminution reduces the band thickness via packing density increases. This process tends to lower the angle of internal friction by reducing the magnitude of dilatational component of friction, and is probably associated with the onset of localization of deformation in a shear-parallel orientation. Our data suggests that the proposed microstructural transition from R to Y shears might be affected, among other probable factors, by fracture properties of mineral constituents.

T13A-03 1410h

Comparative Laboratory and Numerical Simulations of Shearing Granular Fault Gouge

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Laboratory studies of granular shear zones have provided significant insight into fault zone processes and the mechanics of earthquakes, including important contributions to our understanding of earthquake nucleation, the seismic-aseismic stability transition, dynamic rupture, and fault interactions. Numerical simulations using particle dynamics methods can offer unique views into deforming fault zones, particularly regarding the micromechanisms of deformation in shearing materials. Recently, significant advances in our understanding of granular shear have been gained by integrating these two approaches to better model the frictional behavior of tectonic faults. We describe a series of comparative laboratory and numerical experiments of granular shear carried out under identical initial and boundary conditions, using idealized granular materials, i.e., glass beads and rods. Phenomenologically, the two sets of experiments are very similar, demonstrating shear strength fluctuations that can be related to variations in particle size distribution, shear zone thickness, and imposed normal stress. Observed discrepancies in absolute shear strength and stress-strain behavior, then, allow us to calibrate and update the numerical interparticle contact laws to gain improved fits to the laboratory results. The numerical simulations serve to clarify the active deformation processes, demonstrating the role of shear localization, and partitioning between deformation mechanisms, including grain boundary sliding, rolling, and changes in particle size distribution. This integrated study offers great promise to improve our understanding of fault mechanics and earthquake physics. We describe results of the combined study and development of the next generation of particle-based numerical models, including realistic, physico-chemically based contact laws.

T13A-04 1425h

Visualising stress-chain morphology during granular shear

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Active faults often contain distinct accumulations of granular wear material. During shear, this granular material accommodates stress and strain in heterogeneous manner that may influence fault stability. We present new work to visualise evolving stress distributions during granular shear. Our 3D numerical models consist of granular layers subjected to normal loading and shear, where gouge particles are simulated by individual spheres interacting at points of contact according to simple laws. During shear we observe the transient microscopic processes and resulting macroscopic mechanical behaviour that emerge from interactions of thousands of particles. We track particle translations and contact forces to determine the nature of internal stress accommodation with accumulated slip for different initial configurations. We view model outputs using novel 3D visualisation techniques. Our results highlight the prevalence of transient force or stress chain networks that preferentially transmit enhanced stresses across our layers. We demonstrate that particle size distribution (psd) strongly controls the nature and persistence of the stress chain networks. Models having a narrow (or relatively uniform) psd exhibit localised stress chains with a dominant orientation, whereas wider psd models show diffuse stress chain webs that take a range of orientations. First order macroscopic friction, is insensitive to these distinct stress chain morphologies, however, wider psd models with diffuse stress chains are linked to enhanced friction fluctuations i.e. second order macroscopic effects. Our results are consistent with predictions, based on recent laboratory observations, that stress chain morphologies are sensitive to grain characteristics such as psd. Our numerical approach offers the potential to investigate correlations between stress chain geometry, evolution and resulting macroscopic friction, thus allowing us to explore ideas that heterogeneous stress distributions in gouge material may exert an important control on fault stability and hence the seismic potential of active faults.

T13A-05 1440h

POST-TERMINAL COMPRESSIVE DEFORMATION OF ICE: FRICTION ALONG COULOMBIC SHEAR FAULTS

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Coulombic shear faults characterize terminal failure when polycrystalline ice Ih is rapidly loaded under a moderate degree of confinement. Post-terminal deformation occurs through frictional sliding along the shear fault. To examine this latter stage of deformation, experiments were performed on freshwater S2 ice at -10o C. The ice was proportionally loaded biaxially across the column-shaped grains along a variety of all-compressive loading paths at four sliding velocities (8*10-1, 8*10-2, 8*10-3 and 8*10-4 mm/s.). At higher velocities sliding was noisy and the process exhibited velocity weakening. At a lower velocity sliding was quiet and fault healing occurred. The two kinds of sliding are indicative of brittle-like (at higher speeds) and ductile-like (at lower-speeds) behavior. At each velocity Coulomb's law describes the relationship between the shear strength of the fault and the normal stress across it, both at the onset of sliding and once sliding has progressed a few millimeters. The friction coefficient decreases with increasing velocity in a manner similar to that seen by Kennedy et al. (2000) in ice-on-ice experiments, but is higher by about a factor of two to four depending upon the sliding speed, owing perhaps to a greater degree of roughness.

T14A CC: 516 A Monday 1530h

Visualizing the Evolving Fault Zone II

(joint with G, S, MR)

Presiding: **J F Hazzard,** University of Toronto**; K Mair,** University of Edinburgh

T14A-01 1530h INVITED

Use of 2D and 3D Imaging Techniques to Understand Fracture Growth

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The monitoring of acoustic emissions (AE) is a valuable tool for studying the brittle fracture process in rock. With the improved characterization of transducer response, researchers are able to apply a broad

spectrum of seismological techniques to AE catalogues collected in the laboratory; i.e., moment tensor analysis, Vp/Vs ratios, attenuation, event clustering statistics, Gutenberg-Richter b-value and aftershock analysis. Since AE occurs spontaneously as a result of unstable microcrack growth during rock deformation experiments, it provides a non-destructive method to observe damage accumulation. I will give examples of visualization techniques that have proven helpful in the analysis of fracture nucleation and growth based on 3D event locations in granite and sandstone samples. These techniques are useful in interpreting the development of complex fracture systems in lab samples. Complementary measurements of wave speed anisotropy and heterogeneity are used to infer both the development of damage zones and the rate of infiltration of water during fluid injection experiments. Finally, spatial clustering of AE events is evaluated in terms of the surface roughness of reactivated faults during triaxial deformation experiments.

T14A-02 1550h

Damage and recovery of calcite rocks deformed in the cataclastic regime

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Compressional and shear wave velocities have been measured during the experimental deformation of Carrara marble and Solnhoffen limestone in the cataclastic regime using the newly installed triaxial apparatus at the ENS of Paris. Experiments were performed both in dry and wet conditions, up to 260 MPa confining pressure, 10 MPa pore pressure (wet conditions) and room temperature. We measured the elastic and mechanical properties under hydrostatic conditions, during triaxial loading (at the constant strain rate of $10^{-5}.s^{-1}$) and during stress relaxation. Our results show that the seismic velocities increase during hydrostatic pressure build up as well as during the first part of the axial loading. During cataclastic deformation, the velocities decreased progressively, indicating the stress induced damage in the rock. During stress relaxation tests, most interesting results was the increase of velocities with time, which suggested a 'recovery' of the microstructure. A substantial and rapid drop in the velocities occurred when reloading, suggesting that the previous 'recovery' was only a transient phenomena. Subsequent relaxation test showed other marked increases in velocities. These experimental results suggest that during the deformation of low porosity calcite-rich rocks, dilatant micro-mechanisms (crack opening and sliding, void creation) and compactive ones (pressure-solution, pore closure) interplay. Evolutions of elastic properties (mainly sensitive to crack density) and macroscopic volumetric strain (more sensitive to porosity) are not systematically correlated and depends on the strain rate, the solid stress conditions and the pore pressure, which promote the dominant deformation mechanisms.

T14A-03 1605h

Acoustic Emissions and Seismic Velocities in a Numerical Model of Rock Fracture

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Visualizing evolving fault zones in the laboratory involves monitoring of acoustic emissions, measuring seismic velocity changes and making physical observations. Dynamic, micromechanical numerical models can complement these observations by helping to explain some of the mechanics behind the geophysical measurements and relating these to the physical observations. In this study, a numerical model is created by bonding together thousands of elastic spheres at points of contact to simulate a competent rock. The rock model is subjected to mechanical loading, and seismicity is recorded' by observing the energy release when bonds between particles break. In addition, seismic velocity changes are measured by passing dynamic waves through the modelled rock at different stress states. A laboratory study is simulated in which sets of aligned fractures are created in a cubic sample of Crosland Hill sandstone subjected to true triaxial loading. The model exhibits similar patterns in acoustic emission locations, mechanisms and magnitudes to what is recorded in the laboratory test if frictional platens are used in the model. Patterns in velocity change are also similar. All velocities increase during hydrostatic loading however the magnitude of the velocity increase is smaller in the model due to a lack of pre-existing cracks. A significant decrease in velocity is observed during deviatoric loading for waves propagating through the opening fractures in both the laboratory sample and the model - with the magnitude of velocity decrease similar in both cases. The model provides the ability to directly examine the micromechanics behind the observed velocity changes and acoustic emissions. It is shown that the velocity changes in the model can be related directly to the formation and dissolution of particle contacts and the breaking of bonds. If each lost contact or broken bond in the model is considered a microcrack, then the crack density in the model corresponds closely to the crack density calculated from the seismic velocities.

T14A-04 1620h

Development of Shear Banding in Berea Sandstone

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Closed-loop, servo-controlled testing was used to investigate the development of shear failure in Berea sandstone under low confining pressure. The experiments were performed with the University of Minnesota Plane-Strain Apparatus, designed to allow the failure plane to propagate in an unrestricted manner. Deformation was imposed into the strain softening regime and controlled so that the specimens remained intact. Thin-section microscopy provided direct observation in, adjacent to, and around the tip of the rupture zone. The shear band appeared to initiate near a stress concentration, either the corner of the specimen or, when present, an imperfection ($3mm$ diameter hole) introduced into the specimen. Intragranular microcracking was the dominant observable failure mechanism. The intensity of grain cracking was greatest near the initiation point and decreased as the failure surface was traced towards the tip. Areas of high crack density also appeared to have the greatest amount of grain size reduction and there seemed to be a larger amount of pore space. In areas where intragranular microcracks were distinguishable, (e.g. near the tip of the rupture zone), microcracks showed very little or no shear displacement, suggesting the features were not reoriented after formation. Microcrack orientations showed a dominant direction of -16 degrees from the maximum principal stress direction and -26 degrees from the failure surface. A numerical imaging technique was developed to provide an efficient means for analyzing the relative porosity of epoxy-impregnated thin-sections. The code was set up to receive a digital image (*.bmp), where three parameters (R, G, and B) describe the color of each pixel. The intensity of the R channel consistently defined the boundary of grain and pore space and was used to differentiate blue pore space from the white grains composing the matrix. Porosity increase within the rupture zone was $3-4$ grain diameters wide. An absence of notable porosity change beyond the tip (last observable intragranular microcrack) of the rupture zone suggested the altered porosity developed contemporaneously with intragranular microcracks. A cohesive zone model with a linear distribution of traction to represent a process zone and a constant distribution of traction to represent the frictional resistance along the rupture surface were used to examine the stress field near the process zone, which showed similarities to principal compressive stress orientations interpreted from intragranular microcracks. Observations of the process zone and increased shear deformation along the rupture surface were consistent with a cohesive zone model of shear fracture.

T14A-05 1635h

Frictional Properties of Mylonite, Feldspar, and Quartz Under High-Pressure and High-Temperature Conditions

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In order to understand the earthquake generation process, we need to understand the frictional and rheological properties of fault zone materials under high-pressure and high-temperature conditions. Laboratory data on frictional properties of fault surfaces of fault zone rocks are useful for that purpose. We designed and constructed an original Japanese-type gas-medium deformation apparatus. Frictional properties of mylonite, feldspar, and quartz under high-pressure and high-temperature conditions were obtained. We carried out a series of conventional triaxial compression tests of mylonite at constant displacement rate. The strain rate of deformation was 5.5×10^{-6}. We analyzed the stress-strain relation and the frictional behavior of the fault surface formed in the tests. Mylonite samples taken from an exposed brittle-ductile transition zone, the Hatagawa fault zone, northeast Japan, are tested under the confining pressure up to 200 MPa and temperatures up to 600C both in the dry and wet conditions. Even under the same effective confining pressure, presence of pore water dramatically reduces the peak shear stress at the temperature regime higher than 600C. Frictional properties of fault surface formed during the deformation tests are investigated. In the dry conditions, stick-slip behaviors were observed at the room temperature and 200C. For the temperature range up to 600C, frictional forces are almost same level. In the wet condition, we didn't observe stick-slip behavior for all temperature ranges. The frictional force decreased as the temperature increased. Fluid such as water in the deep crust may play an important role in deformation process. We conducted frictional experiments by using albite, anorthite, and quartz gouges (about 3 micron diameter) under high-pressure and high-temperature in the wet and dry conditions. These experiments were conducted by the velocity-stepping test. Temperature varied from room temperature to 600C. In the dry conditions, experiments were conducted under the confining pressure of 150MPa. In the wet conditions, pore water pressure was applied up to 50MPa under the confining pressure of 200MPa. Sample was put between upper and lower sawcut alumina cylinders (20mm in diameter, 40mm long). The sawcut was oriented at 30 ^{o}to the loading axis. The values for a-b of quartz and albite were positive under the dry condition from room temperature to 600C. On the other hand, those values of albite and quartz were negative at the temperature of 200C and 300C under the wet condition respectively. Those values of quartz decreased as the temperature increased from 100C to 300C and increased as the temperature increased from 300C to 600C. Those values of albite were switched from velocity weakening to velocity strengthening between the temperature of 200C and 300C, and increased in the temperature range up to 600C. The frictional coefficient of albite decreased gradually not exponentially after velocity-step from the temperature of 250C to 350C. We will discuss these frictional properties with the texture of samples by the SEM observations.

T21A CC: 220 C-E Tuesday 0830h

Deep Structure of the Continental Lithosphere: Combining Seismic, Heat Flow, and Other Geophysical Data III Posters *(joint with G, GP, S, V, NS, MR)*

Presiding: **R D Hyndman,** Geological Survey of Canada**; N Shapiro,** University of Colorado

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T21A-01 0830h POSTER

The Use of Crustal Overtones to Constrain Crustal Structure in Central Asia

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We have constructed a new data set of observations of the dispersion of the first crustal overtone for about 500 paths crossing Central Asia.The number of reliable higher modes measurements is about thirty times less than reliable fundamental mode observations made on the same seismic recordings.This difference is largely due to the fact that the higher modes are excited less efficiently by shallow crustal