Previous observations quantifying subsidiary fault density, microfracture density, and particle size distributions across the Punchbowl fault zone are used to calculate the total fracture surface area of the fault zone. The Punchbowl fault is a large displacement (44 km), exhumed strand of the San Andreas system in the San Gabriel Mountains. The fault zone consists of a fault core containing a 0.3 m thick layer of ultracataclasite with cataclastic particles between 4 to 400 nm in diameter. The core is bounded by a 100 m thick zone of damaged host rock cut by numerous mesoscale subsidiary faults and microfractures. The total fracture surface area calculated for the ultracataclasite of the fault core, assuming an average grain diameter of 50 nm, is 3 x 10^7 m^2 per m^2 of the fault surface as defined at the 1:12,000 map scale. In the damage zone the density of subsidiary faults and microfractures decrease with increasing distance from the fault core reaching background levels at approximately 100 m. Assuming that the average thickness of subsidiary faults is 0.1 mm and that they consist of comminuted grains averaging 1 micron in diameter, gives a total fracture surface area for subsidiary faults of 1 x 10^7 m^2/m^2. Microfractures throughout the damage zone constitute another 8 x 10^6 m^2/m^2, which indicates that the total fracture surface area in the damage zone is about half that in the ultracataclasite layer. Taking 10 J/m^2 as a representative fracture surface energy gives a total fracture surface energy of the Punchbowl fault zone of 4.8 x 10^8 J per m^2 of the fault surface. This value is approximately 100 to 200 times greater than the fracture energy, G, for a single large earthquake. If G is attributed entirely to the creation of new fracture surfaces, then the observed damage of the Punchbowl fault could be produced by earthquake slip totaling less than approximately 1 km of cumulative displacement, consistent with previous interpretations that the overall structure of large-displacement continental faults are established early in faulting history (i.e., within 100 m to 1 km of total slip). These data also are consistent with suggestions that G for mature faults may be attributed to processes other than fracture of intact grains, such as those related to reworking within the fault core, including the rupture of grain boundaries that have healed during interseismic periods.

S21B-02 0855h

Rupture Sequence of Three Interrelated Earthquakes at Isparta Angle of Southwestern Turkey

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Three earthquakes with an interesting interaction occurred at the north tip of Isparta Angle of southwestern Turkey, a tectonic complex with triple plate interaction and with intersecting faults. The first was on December 15, 2000 (Mw=6.0, Event I), and the others were both on February 3, 2002 (Mw=6.5, Event II, and Mw=6.0, Event III). Their source rupture characteristics are determined based on observed surface faulting (limited data), aftershock distributions, and inversion of broadband seismic waveforms. For Event I, the rupture started at the NW end and unilaterally propagated in SE direction for 30 km. It lasted about 13 seconds, releasing a total moment of 1.3×10^{18} Nt-m. Event II had a very complex source process. The rupture started from the hypocenter and extended about 15 km in a NW direction, overlapping part of the fault zone of Event I. This step lasted about 10 seconds, releasing a total moment of 9.2×10^{17} Nt-m. Then, a westward propagation rupture was triggered with oblique left-lateral normal motion. It lasted more than 15 seconds and had a relative large moment of 3.5×10^{18} Nt-m, a prominent part of the source. This may explain why source mechanism solutions obtained from long period data gave an EW trending fault. Event III happened two hours later and ruptured on a SW trending fault, lasting 6 $\sim$ 7 seconds and releasing a moment of 1.2×10^{18} Nt-m. The occurrences of these three events demonstrate an example of rupture evolution in a tectonically complex fault system with different striking directions. The complex rupture process of second event may be explained in terms of dynamic fault branching (Kame, et al., JGR, Vol 108, pp 1-19, 2003).

S21B-03 0910h

Seismotectonics of the Central Denali Fault, Alaska and the 2002 Denali Fault Earthquake Sequence

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We analyzed the spatial and temporal variations in the seismicity and stress state within the central Denali fault system, Alaska, before and during the 2002 Denali fault earthquake sequence. Seismicity prior to the 2002 earthquake sequence along the Denali fault was very light with an average of four events with magnitude 3.0 and greater per year. We observe a significant increase in the seismicity rate prior to the M7.9 event of November 3, 2002 within its epicentral region, starting about eight months before the subsequent mainshocks. The majority of the aftershocks of the M7.9 event are located within the upper 11 km of the crust and form several persistent clusters with a few aseismic patches along the ruptured fault. The most active aftershock source is associated with the epicentral region of the M7.9 earthquake. The overall b-value of the aftershock sequence is 0.96 with the highest b-values within the epicentral region. We estimate that it will take 14 years for the seismicity rate to drop back to the background level. The stress regime across the region varies in space and time. The inferred stress regime prior to the 2002 sequence is predominately strike-slip. The maximum compressive stresses along the Denali fault rotated clock-wise by up to 30 degrees after the 2002 earthquake sequence. The greatest rotations correspond to the area of the rupture stepover from the Denali to Totschunda fault. The inferred stress regime after the 2002 sequence indicates an interchanging thrusting and strike-slip faulting along the ruptured fault. The thrust faulting is concentrated in the epicentral region of the M7.9 event and along the rupture segments with the largest measured surface offsets.

S21B-04 0925h

Extreme Earth tides strongly trigger shallow, thrust earthquakes

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We observe tidal triggering of shallow, thrust events by strong tidal stresses. Our dataset consists of the 9350 global earthquakes of M 5.5 or greater from 1977 to 2000 in the Harvard CMT catalogue. These events include 2823 reverse, 1040 normal, 3597 strike-slip, and 1890 oblique earthquakes. We examined the entire dataset and subsets of the data for correlations with Earth tides, taking into account the amplitude of tidal stress. Tidal stress calculations include both a direct solid-Earth term and an indirect ocean-loading term. Both components must be accurately determined to fully resolve tidal influences on earthquakes triggered globally. We sort the catalog by the average of the peak Coulomb stress amplitudes before and after each event, assuming a coefficient of friction of 0.6. For the 1% of events with the highest averaged peak stress, we find significant tidal correlation, with a corresponding phase near the peak stress promoting failure. The highest correlation is seen for thrust events at or above 20 km depth with peak tidal stresses above 0.14 bars. Schuster's test, used to find statistical significance of periodicity, gives a p-value of 0.68%, or in other words there is only 0.68% chance that the distribution is randomly distributed. A second test shows that the non-random distribution peaks near the peak Coulomb stress; with 39 out of 53 earthquakes (74%) occurring in half of the time of encouraging stress. A simple binomial test of significance shows that this distribution of events corresponds to a tidal correlation at the 99.96% significance level. This result demonstrates that the tides modulate the occurrence of earthquakes at stress levels similar to those observed for the triggering of shallow aftershocks by mainshock stress redistribution.

S21B-05 0940h

Source Characteristics of Mining-Induced Seismicity from Moment-Tensor Analysis and Spatio-Temporal Relationships

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Mining-induced seismicity represents the best environment for studying small events (moment magnitude $-2 \leq M \leq 3.5$) whose dimensions are at or below the detection threshold of most surface-based seismic arrays. The volume of data is enormous (thousands of events per day) and the events are recorded close to the source (stations are located 50 m - 5 km from the events). In addition, mining-induced seismicity includes events directly triggered by blasting that are assumed to involve fresh fracturing of rock as well as those induced over longer timescales that have been hypothesized to be dominated by frictional slip. These distinctions have so far been based on spatio-temporal clustering statistics and spectral signatures of these two types of events. We have inverted for the moment tensors of 15 events from the Far West Rand gold-mining region of South Africa that range in size from $1.0 \leq M \leq 3.2$. These events occurred at 1-4 km depth and were recorded locally by four networks of 102 three-component geophones installed at depth throughout the active mining environment as well as regionally by a two-year Passcal deployment of 80 broadband seismometers. This depth and magnitude range is comparable to borehole studies in California and to the target of the SAFOD experiment. The moment tensors of these events are consistent with purely double-couple solutions. Therefore, we assert that these events are indeed proxies for natural tectonic earthquakes that nucleate via friction-dominated slip on planar surfaces. From spectral analysis, scaling relations, and statistical analysis of the characteristic length scales between sequential frictional events we confirm earlier estimates by Richardson & Jordan (2002) of the critical slip length ($D_c \approx 100\,\mu$m) and critical patch size ($R_c \approx 10$m). We believe these dimensions represent the nucleation size of events in this hard-rock mine environment.

S22A CC: 516 A Tuesday 1030h

Insights Into Earthquake Nucleation and Rupture II *(joint with G, T, NS, MR)*

Presiding: **E Richardson,** Pennsylvania State University**; K Mair,** University of Edinburgh

S22A-01 1030h

Spatial and Temporal Patterns in the Seismicity of the Equatorial Pacific and Possible Earthquake Triggering at the East Pacific Rise

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We utilize hydroacoustic data collected since May 1996 by NOAA/PMEL's Equatorial Pacific autonomous hydrophone array to investigate the first order spatial and temporal variability of seismicity of the Equatorial Pacific within the array and in particular, the East Pacific Rise (EPR). Our statistical analyses reveal strong evidence of seismic clustering along the EPR. The majority of earthquakes are clustered in seismic swarms, in which individual events occurred within a few km and within minutes or hours of each other. We have examined the six transform faults contained within the hydrophone array: Clipperton, Siqueiros, Quebrada, Discovery, Gofar, and Yaquina transform faults. The calibrated seismicity rate of a transform fault, when normalized by the transform fault length, changes from one transform to the other. In particular, the Clipperton transform fault shows a relatively low seismicity rate, which we hypothesize might be linked to a possible mantle thermal anomaly in the region. Furthermore, there appears to be very little correlation of transform slip rate and transform length to the rate of seismicity along the oceanic transform faults within this region. Through correlating hydrophone data to teleseismically recorded events, we have located several moderate size earthquakes on the Siqueiros, Discovery, and Gofar transform faults. Some of these moderate size events occurred closely in space and time, suggesting the possibility of earthquake triggering. Stress calculations were carried out for several pairs of the moderate size events. The close correlation of the calculated Coulomb stress changes with the observed spatial and temporal variations in seismicity patterns provide strong evidence for possible earthquake triggering along the transform faults.

S22A-02 1045h INVITED

Insights Into Earthquake Nucleation and Fault Evolution Within Magma

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Volcanoes erupting highly viscous magma generate an exceptionally large amount of seismic energy per unit volume. Seismicity is unlike that generated on most tectonic faults, being characterised by repeated small events ($M_w < 3$) with identical waveforms and short inter-event times (from days to less than a second). Events occur in swarms with typical durations of hours to weeks and have anomalously low frequency content (dominant energy in the 1-3 Hz range). They also show no S-wave arrivals and occur within a small volume typically < 2 km from the surface. New field evidence suggests that these earthquakes may occur on small faults that nucleate by shear fracture of magma during conduit flow (Tuffen et al. Geology 31:1089-1092, 2003). Shear fracture occurs due to stress accumulation when strain rates are too high for purely viscous flow. The anastomosing fracture networks generated share many characteristics with "tectonic" pseudotachylites, including injection veins and evidence for fluidisation. Fracture networks evolve with continued slip into near-planar faults up to five metres in length that are rotated parallel to the magma flow direction. Cataclasite on fault planes bears the textural hallmarks of frictional stick-slip behaviour, with localised grain size reduction, slip localisation, and Riedel shear zones. Eventually, cohesive viscous deformation occurs due to frictional heating and strain rate decrease and completely heals the faults. This forms flow banding in obsidian, which is a kind of high-temperature pseudotachylite. This new evidence may help to explain some properties of the low-frequency earthquakes that occur during eruptions of high-viscosity magma: a) The short inter-event time may be due to high strain rates (10^{-6} to 10^{-2} s^{-1} are typical of eruptions of silicic magma). b) Similar events may be generated by multiple slip pulses on fault planes. c) The seismogenic lifetime of faults may be limited by the high temperature of the faulting medium (little slip is required for melting). d) The restricted magnitude range of events ($-2 < M_w < 3$) may indicate the restricted source dimensions. We combine field observations with numerical modelling of the stick-slip stability of high-temperature magma, which needs only a small temperature increase to heal and undergo viscous deformation. The magma viscosity is extremely sensitive to temperature, and frictional heating of only a few degrees can result in distributed viscous deformation rather than frictional stick-slip. Faulting in high-viscosity magma is therefore analogous to faulting elsewhere in the crust, but occurs on different spatial and temporal scales that reflect the high strain rates, high temperatures and small sizes of magma-filled conduits.

S22A-03 1100h

Mechanical Consequences of Metamorphism and Their Effects on In-slab Earthquakes

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The relatively few earthquakes deeper inside a subducting slab tend to have larger magnitudes than those just below the slab surface. For example, three recent damaging events (1999 Oaxaca, Mexico; 2001 Geiyo, Nankai; 2001 Nisqually, Cascadia) in warm slabs all occurred in the lower crust or mantle. We propose that this is controlled by slab metamorphic processes. The metabasalt-eclogite transformation of the subducting oceanic crust causes up to 15% volume reduction. Because of temperature and kinetics, the densification begins in a thin layer along the top of the slab. Volume reduction gives rise to an equivalent stretching force in the thin layer in all slab-parallel directions, activating existing faults and developing new fractures. The theory of fracture spacing predicts that the densified thin layer must be "shattered". The shattered upper crust may have numerous small earthquakes but does not favor large ruptures. In contrast, the much more uniform lower crust and mantle can host larger ruptures, although seismic ruptures may occur only in limited hydrated parts. Earthquakes that rupture the subducting mantle, such as the M 6.8 2001 Nisqually earthquake at Cascadia, appear to require serpentine dehydration along pre-existing deep faults.

S22A-04 1115h

Earthquake nucleation: rate and state friction or shear heating?

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Earthquake nucleation requires loss of frictional strength $\tau = \mu(\sigma - p)$ with slip or slip rate. For rate and state dependent μ at fixed $(\sigma - p)$ instabilities can occur when $d\tau_{ss}/d\log v = (\sigma - p)(a - b)$ is negative, where a measures direct velocity strengthening, and $b - a$ measures steady-state velocity weakening. Shear heating increases p and, if dilatancy and pore pressure diffusion are limited, will cause τ to decrease. We examine here how shear heating, dilatancy and pore-pressure diffusion compete to determine stability on a fault which may be intrinsically stable $(a > b)$ or unstable $(b > a)$. We consider a highly simplified fault model with a narrow fault core (thickness h) bordered by a relatively impermeable inner wall zone (thickness h_w), and an outer permeable damage zone. The fault zone responds adiabatically to perturbations, and the pore-pressure p obeys: $dp/dt = \tau v/\mu_0 L_p - (1/\beta) d\phi/dt - (p - p^{\infty})/t_p$, where v is slip speed, L_p scales with fault zone thickness and depends on the specific heat, compressibility, β, and thermal expansivity of fault zone materials, ϕ is inelasitc porosity, and t_p the characteristic time for pore-pressure diffusion across the impermeable wall zone. The terms on the right hand side represent shear induced thermal presurization, dilatancy, and pore pressure diffusion, respectively. If the drained behavior is stable, and wall zone permeability exceeds a critical value given by $\kappa_{crit} = \mu_0 v \eta \beta h h_w / 2(a - b) L_p$ fault slip is stable at *all wavelengths* (η = pore fluid viscosity). For reasonable parameters, the critical permeability ($\sim 10^{-21} m^2$) is less than that measured for materials of the Nojima Fault and Median Tectonic Line fault cores, even when subjected to effective stresses appropriate to 10 km depth. We conclude that shear heating can not generally nucleate slip instability; frictional weakening is required. Thus, time to failure and seismicity rate variations based on rate-state friction alone should be approximately valid. Shear heating effects become important at slip speeds of order $v \sim L_p/t_p$, ($\sim$ 1 mm/s) and displacements of $u_{crit} = -a/H \ln[v t_p/L_p], (\sim 0.001 - 0.01 m)$, where $H = b/d_c - k/(\sigma - p)$. Once slip and slip-rates exceed these values shear heating effects dominate. Thus, dynamic rupture may be insensitive to frictional variations and dominated by shear heating effects. Major uncertainies are dynamically induced permeability and dilatancy at high slip speeds.

S22A-05 1130h INVITED

Influence of Particle Characteristics and Surface Roughness on Friction in Granular Fault Gouge

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Particle characteristics (shape, size, and roughness) and surface roughness affect friction and the amount of shear localization that occurs within granular shear zones. In order to improve our understanding of grain-scale deformation mechanisms within fault gouge, we performed laboratory experiments using a double-direct-shear testing apparatus. This assembly includes three rigid forcing blocks with two gouge layers sandwiched between rough or smooth surfaces. Roughened surfaces had triangular grooves 0.8 mm deep and 1 mm wavelength machined perpendicular to the sliding direction. Grooves promote shear throughout the layer during cataclastic deformation. Smooth surfaces were mirror-finished hardened steel and were used to promote and isolate grain boundary sliding. Our experiments were conducted by controlling the displacement rate at which the center block was driven between the two side blocks to create frictional shear. We studied gouge layers 2 to 9 mm thick, consisting of smooth glass beads mixed with varying amounts of rough sand particles. We report on particle diameters that range from 0.050-0.590 mm. The experiments are run at room temperature, controlled relative humidity ranging from 5 to 60%, and shear displacement rates from 0.1 to 3000 microns per second. Experiments are carried out under a normal stress of 5 MPa or 10 MPa, a non-fracture loading regime where sliding friction for smooth spherical particles is measurably lower than for rough angular particles. We compare results from shear between smooth boundaries, where we hypothesize that grain boundary sliding is the mechanism influencing granular friction, to rough sample experiments where shear undergoes a transition from distributed, pervasive shear to progressively localized shear as a function of increasing net strain. For both the rough and smooth surfaces, we find that the frictional strength increases as the fraction of angular grains within a layer increases. For shear within rough surfaces, stick-slip instability occurs in layers that consists of less than 20% angular grains and begins once the coefficient of friction reaches a value of 0.35-0.40. Peak friction during stick-slip cycles is 0.40-0.45. Each stick-slip event involves a small amount of quasi-static creep prior to failure, which we refer to as pre-seismic slip. For unstable sliding regimes, we measure the amount of pre-seismic slip and the magnitude of dynamic stress drop. These parameters vary systematically with sliding velocity, particle characteristics, and bounding roughness. For shear within smooth surfaces, friction is very low (0.15-0.16 for spherical particles) and sliding is stable, without stick-slip instability.

S22A-06 1145h

A Parallel Implementation of the Lattice Solid Model as a Tool for the Study of the Rupture Process on Rough Faults

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The lattice solid model is a particle based model for the simulation of earthquakes and rock mechanics. The model consists of particles interacting by elastic-brittle and frictional forces. The current parallel implementation in 2D or 3D makes it possible to use powerful parallel computer systems to simulate the dynamics of large models consisting of several million particles.

For the study of rupture propagation, a fully dynamic fault model is used consisting of two blocks of densely packed, bonded particles with variable size. The particles along the fault between the two blocks interact by frictional forces. The roughness of the fault is determined by the size and geometric arrangement of the particles along the fault plane. To simulate fault slip, the model is loaded by a normal force and its outer edges are sheared, leading to a stick-slip motion of the fault.

This model allows the study of all aspects of the rupture process while controlling the parameters involved, such as geometric roughness, frictional inhomogeneities along the fault and different friction laws.