The existence (or confirmed non-existence) of velocity discontinuities in the lower mantle is critical for a number of first-order problems in geoscience, such as the style of mantle convection, and phase change and chemical composition in the lower mantle. So far positive identification of sharp lower-mantle discontinuities on a large scale is scarce. We hand-selected about 3000 high-quality receiver functions from shallow (80 km or less) earthquakes recorded by broadband seismic stations in California, made moveout corrections along the time of P-to-S converted phases, and performed an n-th root stacking to form a single depth image. About a dozen apparent arrivals have been imaged for the depth range of 700 to 2000 km. To identify and reject false discontinuities associated with non P-to-S phases, we generated a synthetic seismogram using CORE (Complete Ordered Ray Expansion, Clarke and Silver, 1993) for each of the 3000 seismograms by taking account the actual focal parameters. We then processed the synthetic seismograms using exactly the same procedure as what was used for the real data, and generated a synthetic depth image. Comparison between the observed and synthetic depth images suggest that about six of the 12 observed arrivals do not correspond to arrivals on the synthetic image, and are thus likely to represent real lower-mantle discontinuities. Those positively identified discontinuities are in the depths of about 1040, 1080, 1230, 1400, 1600, and possibly 2000 km. Comparison with previous observations and implications of those discontinuities will be presented.

S51A-07 0945h

Receiver-function imaging of the crustal and mantle structure beneath South Africa: a comparison of stacking and migration

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Receiver functions analysis has been widely used in imaging the crustal and mantle structure in recent years. Signal enhancement techniques have evolved from single-station to common-conversion-points (CCP) stacking of receiver-function traces. Kirchhoff and other migration techniques are also introduced in receiver-function imaging. It is generally believed that CCP stacking is suitable for horizontally layered structure, while, migration techniques are more favored but require denser receiver array for imaging complicated media. Here we present an investigation on the advantages and disadvantages of the two techniques using a high-quality dataset in a region with a relatively simple structure. The Kaapvaal Seismic Array we used in this study is approximately a linear array extending from southwest to northeast. We chose 6 shallow teleseismic events roughly located at the direction of the array. Both CCP stacking and Kirchhoff migration are performed with the same dataset. Due to the sparse distribution of (∼50 km), image above ∼200 km is not well reconstructed from migrations. The two techniques, however, produced very consistent images below ∼200 km, especially in the transition zone and lower mantle depths. The CCP stacking shows a very well-defined crust-mantle transition. Crustal thickness is found to be well correlated to geologic terranes, consistent to the previous studies. The crust beneath undisturbed Archean Kaapvaal craton is relatively thin (∼35 km), while the surrounding Proterozoic belts have thick crusts up to ∼50 km. The upper mantle in this region seems to be extremely transparent in the images, except some artificial structures between 100 and 200 km resulted from crustal reverberations. The 410-km discontinuity is extremely well mapped, with an apparent topographic relief of ∼15 km across the array (1400 km). Images also show a very clear 660-km discontinuity across the array, except for the ∼250 km section of the southwest end of the array, where the discontinuity is diffused by as much as 50 km. Compared to the 410-km, the 660-km discontinuity has less topography (∼5 km) except for the southwest end of the array. The transition zone thickness beneath the Kaapvaal craton is about 10-15 km thicker than those beneath the Namaqua-Natal and Limpopo belts. Although the observation could result from unmodeled velocity variations in the transition zone, a 10-15 km variation in transition zone thickness would need at least 3 to 4% variations in velocity, which are not observed by tomographic images. Lateral variations in the P to S conversion amplitude are also observed across the array, with the largest amplitude being found in the craton region. All the observations suggest that the distinction between the Archean craton and the Proterozoic belts in South Africa may continue to as deep as the transition zone.

S51B MCC: 3011 Friday 0800h

Jingle All The Way: Observed and Theoretical Fault Zone Processes

(joint with G, T)

Presiding: **R Anooshehpoor,** University Of Nevada, Reno; **T E Tullis,** Brown University

S51B-01 0800h

Influence of Grain Shape and Wall Roughness on Rock Friction in DEM Simulations

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Experimental data on rock friction for normal stresses up to 200 MPa are characterized by large scatter in the data, a result thought to be due to poorly constrained variations in the roughness of shear zone walls. Recent laboratory experiments have demonstrated that grain characteristics can also significantly affect the macroscopic friction of a granular material under shear. We have examined the effects of wall roughness on friction, and the variation of friction with normal stress and grain characteristics using a modified version of the Distinct Element Method (DEM), in which bonds are added between adjacent particles. In this way, grains of arbitrary shape and size can be generated to reproduce more realistic fault gouge, which can evolve by grain fracture during shear. Two types of grains, rounded grains composed of 7 close-packed particles and triangular grains composed of 6 close-packed particles were designed to simulate quartz gouge. DEM experiments were conducted by shearing identical granular assemblages, subject to the same wall surface roughness, over a range of normal stresses from 1 MPa to 100 MPa. Similar experiments were conducted on both types of gouge. The results show an inverse power law relationship between normal stress and friction. For the rounded grain assemblages, this relationship can be represented by a best fit equation: $\mu = 0.8569{\sigma_n}^{-0.2627}$. Base friction of the rounded-grain assemblages is around 0.4, similar to results of DEM simulations using unbonded, circular particles. Gouge composed of triangular grains is much stronger, with base friction of about 0.65, close to the results of laboratory experiments. At lower normal stresses, grain interlocking is a dominant deformation mechanism, particularly favored by triangular grains. Grain rolling becomes more significant, and effects of grain shape on friction becomes less important, with increase of normal stress. Our study confirms that friction of simulated granular assemblages with identical wall roughness obeys the power law friction relationship derived from Hertz's contact law, and that grain shape is a key factor that affects the magnitude of friction.

S51B-02 0815h

Low-Heat and Low-Stress Fault Operation in Earthquake Models of Statically Strong but Dynamically Weak Faults

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Observations suggest that San Andreas fault generates much less frictional heat that one would predict based on laboratory static friction coefficients of 0.6 to 0.8 for most rocks and effective normal stresses comparable to overburden minus hydrostatic pore pressure. Hence one concludes that earthquakes there happen under low shear stress. Two explanations are most commonly proposed: Either (1) effective normal stress is very low everywhere on the fault or (2) static friction coefficients are very low (less than 0.2) and so the laboratory values are not appropriate for real faults. There is another possibility, that of a statically strong but dynamically weak fault with small defect regions to nucleate ruptures. On such a fault, friction coefficients at low velocities and effective normal stress are high almost everywhere, except for small defect (weak) regions. However, frictional strength deteriorates significantly at high slip velocities or slips, making the fault dynamically weak. The idea is that the fault would then operate under low shear stress (and hence with low heat generation) as follows: Model earthquakes nucleate under low shear stress in a defect (weak) region and then propagate into strong regions due to significant dynamic weakening. We study this possibility in the framework of a 2D depth-averaged elastic model of a faulted crustal plate, slowly loaded via coupling to a steadily moving substrate. We use the classical Dieterich-Ruina rate and state friction law, but modified to permit much stronger weakening at high slip rates V than the logarithmic weakening of the standard rate and state formulation. In the new law with enhanced weakening, the steady-state strength varies, essentially, as 1/(1+V/constant) at high V. Such functional dependence is suggested by theoretical studies of flash heating of contact asperities at small slips and behavior of partially DRAINED, THERMALLY PRESSURIZED fault gouge, AND PERHAPS LIQUEFIED GOUGE, at larger slips. Note that other weakening processes of dynamic nature such as sliding between different materials or UNDRAINED THERMAL PRESSURIZATION may cause the fault to become dynamically weak, but their descriptions would be different. We find that this model can operate with much smaller heat generation than the one with the classical Dieterich-Ruina law. The static value of the friction coefficient is around 0.6 in our model. Even with no weak regions, the friction coefficient inferred from average shear heating stress can be as low as 0.2. This is due to the fact that most of the slip happens at high slip velocities when the friction coefficient is low, and hence there is little heat generated. However, with no defect regions, the average shear stress before model earthquakes is high, corresponding to the friction coefficient of about 0.5. When a defect region is introduced with much lower effective normal stress than for the rest of the fault, the average shear stress before model events reduces; the lowest we observed corresponded to the friction coefficient of about 0.3. At the same time, the heat generation further decreases, corresponding to the friction coefficient of less than 0.15. These numerical simulations are very challenging and we have not yet achieved full stability. We will report on our current attempts to find a set of parameters that allow for well-resolved simulations.

S51B-03 0830h

Fault Roughness and Matedness Suggest Significant Fault-Interface Dilatancy With Slip

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Pore pressure in a fault zone could increase during rapid coseismic slip due to thermal pressurization of pore fluid. However, the nearly self-similar topography of natural fault surfaces combined with their high degree of matedness suggests that a considerable increase in the volume of the space between opposing fault surfaces should occur with slip. Thus, pore pressure is likely to decrease rather than increase, and dilatancy hardening rather than thermal pressurization weakening seems a likely consequence of slip. To quantitatively explore how the gap between opposing fault surfaces could depend on slip, we have analyzed profilimetry data from a large well exposed normal fault in Dixie Valley, Nevada (Power and Tullis, 1992). The difference between the topographies of the presently well-mated fault surfaces was used to determine a progression of composite topographies as a function of offset of the surfaces in the paleo-slip direction. We assume that only the points of closest contact touch at each offset and that the remainder of the composite topography would constitute a gap between the surfaces. The average of this gap corresponds to a volume per area of the fault surface. As expected, this average gap increases with displacement and represents an increasing volume with slip. For the one fault surface analyzed to date, the volume increases by a factor of 7 after 10 mm of slip, an amount that would completely overwhelm any thermal expansion of the pore fluid, and, in fact, should cause pore pressure to decrease to nearly zero, assuming no flow of fluid into the interface. It seems reasonable to assume that fault surfaces do not remain mated during coseismic slip, because the deformation processes that cause matedness appear to involve pressure solution, and therefore the matedness probably occurs during slow interseismic creep (Power and Tullis, 1989). However, assuming that the opposing walls remain rigid during coseismic slip is presumably incorrect, because cataclastic processes could occur. Thus, our calculated increase of interfacial volume is presumably an upper bound. On the other hand, although cataclasis could cause the increase in volume along the interface to be smaller than our upper bound, significant overall dilatancy is still expected since the fragments produced by cataclasis will not fit together perfectly. It is difficult to make quantitative estimates

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of the likely volume increase in the presence of such cataclasis, but the dilatancy we calculate due to slip of mated surfaces is so large that it brings into serious question the likelihood that thermal pressurization could weaken the fault during coseismic slip; dilatancy hardening appears more likely.

S51B-04 0845h

Non-planar Fault Geometry and Stress Field around the Fault

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The distribution of asperities (i.e.large slip area during an earthquake) should be correlated with its initial shear stress distribution (or possible stress drops during the earthquake). If the surrounding stress field around the fault is known and rather uniform, initial shear stress distribution on the fault could be controlled by its fault geometry. This suggests that in order to detect the distribution of asperity prior to the earthquake, estimation of initial tectonic stress field applied to the fault becomes important. In this study, we examine if the final slip distribution can constrain the initial stress field when the constitutive relation on the fault and fault geometry are provided. We used a boundary integral equation method for triangular elements, which allows us to model an arbitrary shaped fault system with curvatures, branches and jogs. First, using a fault model with a complicated geometry and homogeneous constitutive law, we tried to invert the final slip distribution for the principal initial stress direction and its stress ratio (R) by a grid search method. This numerical test suggests that the principal stress direction can be estimated within an error of 5 degrees, but stress ratio R cannot be well constrained. Then we applied this technique to the 2000 western Tottori earthquake (Mw 6.6). The principal stress direction of the surrounding stress has already been estimated using a stress tensor inversion of aftershock moment tensors. The fault geometry is also estimated using relocated aftershock distribution by double difference method. The constitutive relations are also estimated from the slip rate function estimated by a waveform inversion. Using this model, we conducted a forward modeling to estimate the dynamic rupture history. We found that the principal stress direction obtained by the stress tensor inversion is the easiest angle for the dynamic rupture to propagate and we think this initial stress distribution is constrained by the fault geometry of this earthquake.

S51B-05 0900h

Flash Melting of Crustal Rocks at Almost Seismic Slip Rates

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Frictional heat is generated at microscopic contacts between rough surfaces in sliding contact. At high slip velocities over small displacements, as occurs during small earthquakes and at the onset of slip during larger earthquakes, heat generated at highly stressed, microscopic asperities on the fault surface can induce flash melting of the asperities. With continued slip, heat generated at contacts can raise the average fault surface temperature sufficiently to melt the entire fault surface. Both mechanisms may lead to a decrease in shear resistance during earthquakes, and thus have important implications for changes in dynamic stress drop and apparent stress with earthquake size. To investigate flash melting phenomena in rocks, friction experiments were conducted on monominerallic quartz and feldspar rocks, and granite, at near-seismic slip velocities (up to 360 mm/s) but short displacements (< 4.5 cm), i.e., at conditions conducive to flash, but not bulk, melting. Tests were conducted in rotary shear at ambient pressure and temperature at a normal stress of 5 MPa. Each experiment was begun by sliding slowly at velocity V=10 μm/s for 2 to 3 mm of slip, then at a velocity of up to 360 mm/s for $\sim$4 cm of slip. At 10 μm/s, the friction coefficient attains values of 0.6 to 0.8 for all three rocks. At higher velocities, the friction coefficient for quartz and feldspar rocks is purely velocity dependent and falls off as $1/V$ above a characteristic weakening velocity V_w. The lowest values of the friction coefficient, at 360 mm/s, were 0.25 and 0.45 for quartz and feldspar rocks, respectively. For quartz rocks, the onset of weakening occurs at V_w=105 mm/s and for feldspar rocks at 267 mm/s. In contrast, experiments on granite show no significant decrease in friction even at slip speeds of 360 mm/s. Results for quartz and feldspar rocks were compared with predictions of a theoretical model for flash heating/melting (*Rice*, 1999). In the model, the weakening velocity $V_w=(\pi\alpha/D)[\rho c(T_w\text{-}T_f)/\tau_c]^2$, where α is thermal diffusivity, D contact size, ρc specific heat, T_w a weakening temperature above which the contact shear strength τ_c is negligible, and T_f the average temperature of the sliding surface. Taking α=1.85 (mm)^2/s, ρc=2.9 MJ/m^3 K, D=25 μm, T_w-T_f=1700 and 1100 K (melting temperatures minus room temperature for quartz and albite, respectively), and τ_c=7 and 3 GPa for quartz and albite, respectively, yields values of V_w for quartz and albite of 118 mm/s and 270 mm/s, respectively, in agreement with experimental values. Thus, the onset of weakening in our experiments appears to be consistent with flash melting above V_w. The absence of weakening in granite may indicate that flash temperatures are limited by lower contact stresses due to the presence of micas.

S51B-06 0915h

MSLT, Multi Surface Light Table, a Tool for Viewing Faults Under Their Terrain

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The QuakeSim project [1] was created to develop a solid earth science framework for creating an understanding of active tectonic and earthquake processes and to construct a fully interoperable system of tools for studying these processes. QuakeSim framework includes a new federated fault database that defines earthquake faults. It also includes three major simulation tools: GeoFEST, PARK and Virtual California. Virtual California is a Monte Carlo simulation that generates simulated earthquakes on a network of fault segments that are mediated by elastic interaction. The most effective way to visualize the geographic parameters of the faults is to display them as surfaces with their associated terrain. With low cost, high performance graphics hardware, we are able to observe fault models with high-resolution terrain and elevation interactively. Moreover, we are able to visualize the dynamic characteristics of the faults, such as the time-varying slip and stress values generated by Virtual California. In addition to the visualization of faults in a 3D environment, mapping dynamic parameters with appropriate visual features would lead to intuitive understanding of time dependent fault interactions. We built the Multi Surface Light Table (MSLT) as an interactive tool to view earthquake fault segments underneath its associated terrain. The fault segments, represented as rectangular surfaces at a dip angle, are organized into collections, i.e., faults. An interface was built in MSLT to query and retrieve fault definitions from the QuakeSIM fault database. MSLT also reads time-varying output from the Virtual California simulation. The slip and stress are represented by color and intensity variation on the fault segments. MSLT's interactive controls provide a virtual trackball, pan and zoom, simulation playback, and simulation movie capture. In addition, MSLT also displays the geographical information of the fault segments and their collections on text windows. Because of the extensive viewing controls, faults can be seen in relation to one another and to the land as well as the ocean. These relations may be realized in simulations. Correlated slips in parallel faults are visible in the playback of Virtual California simulation. This is an example of the ability of the visual cortex to pick out complex relationships with ease when presented with an appropriate view. In this presentation, we will describe the technologies used to build MSLT, the hierarchical data structure we used to represent large terrain and image datasets in order to allow real-time pan and zoom, and the Java client used to interface the QuakeSIM database. We will also demonstrate the operation of MSLT using California faults and Virtual California simulation results. [1] http://www-aig.jpl.nasa.gov/public/dus/quakesim/

S51B-07 0930h

Average Dissipation Spectrum and Waveform Characteristics of Deep Low-frequency Earthquakes

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It is well known in regions operating dense seismic networks that the depths of almost all inland earthquakes are shallower than 15 km. However, anomalously deep events with depths ranging 20 km to 40 km have been observed beneath the Japan Island, and they have lower dominant frequencies for both P and S waves than corner frequencies expected from those magnitudes. These events are termed deep low-frequency earthquakes (DLF). Using high-density high-gain seismic data in Japan, it makes clear that DLF occur not only beneath the volcanic front but also beneath source regions of large inland earthquakes. Sometimes, DLF are characterized by large and long tailing coda parts of S-wave, and these waves represent the time evolution of DLF's source process directly. Based on the theory of KM2O-Langevin equation, we propose a new method to represent characteristics of coda parts of DLF. The most advantage of this theory is free from a prior information about data when the data satisfies stationarity, and we can deduce an stochastic difference equation producing the data without any parametric models before data analysis. If a specific physical process continues to excite seismic waves, it will be expected that the similar dissipation terms are obtained from the seismic waveforms. We propose a new algorithm to get an average KM2O-Langevin matrix function (LMav(X)) for plural local time series. Applying this method to the large and long tailing coda parts of S-waves excited by DLF on July 11, 2001, we calculate LMav(X) and get the linear difference equations using these dissipation matrices. The time series predicted by these difference equations can explain the dominant frequencies and the waveforms of DLF well. The fluctuation matrices of LMav(X) seem to be corresponding to the excitation of DLF. Using the inverse z-transformation, we solve the linear difference equations to obtain the discrete dominant frequencies with those attenuation factors and magnitudes. We term these quantities average dissipation spectra. We calculated the average dissipation spectrum of DLF on July 11, recorded at NIB, GJOH, and ANIH. The dominant frequencies and the attenuation factors at NIB, GJOH, and ANIH are (1.55 Hz, -0.37), (1.58 Hz, -0.31), and (1.59 Hz, -0.26), respectively. The frequencies and the attenuation factors with the second large magnitude also show the similar values each other. These results indicate that the average dissipation spectrum is useful method to reveal characteristics of long tailing coda parts excited by DLF.

S51B-08 0945h

Monitoring of fluid-rock interaction in active fault zones: a new method of earthquake prediction/forecasting?

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We propose a new method for earthquake forecasting based on the "prediction in hindsight" of a Mw 5.8 earthquake on Iceland, on September 16, 2002. The "prediction in hindsight" is based on geochemical monitoring of geothermal water at site HU-01 located within the Tjörnes Fracture Zone, northern Iceland, before and after the earthquake. During the 4 weeks before the earthquake exponential (<800%) increases in the concentration of Cu, Zn and Fe in the fluid, was measured, together with a linear increase of Na/Ca and a slight increase of δ^{18}O. We relate the hydrogeochemical changes before the earthquake to influx of fluid which interacted with the host rock at higher temperatures and suggest that fluid flow was facilitated by stress-induced modification of rock permeability, which enabled more rapid fluid-rock interaction. Stepwise increases (13-35 %) in the concentration of , Ba, Ca, K, Li, Na, Rb, S, Si, Sr, Cl, Br and SO_4 and negative shifts in δ^{18}O and δD was detected in the fluid immediately after the earthquake, which we relate to seismically-induced source switching and consequent influx of older (or purer) ice age meteoric waters. The newly tapped source reservoir has a chemically and isotopically distinct ice-age meteoric water signature, which is the result of a longer residence in the crust. The immediancy of these changes is consistent with experimentally-derived timescales of fault-sealing in response to coupled deformation and fluid flow, interpreted as source-switching. These precursory changes may be used to "predict" the earthquake up to 2 weeks before it occurs.