are not coupled. We use a slip-weakening fracture criterion and examine the effect on an earthquake rupture of material contrasts of up to 50 percent across the fault zone. We find a surprisingly good agreement between our earlier 2-D results, and our 3-D results for along-strike propagation. We find that the analytical solution presented in Harris and Day [BSSA, 1997] does an excellent job at predicting the bilateral, along-strike rupture velocities for the three-dimensional situation. In contrast, the along-dip propagation behaves much as expected for a purely mode-III rupture, with the rupture velocities up-dip and down-dip showing the expected symmetries.

S21G-05 1120h

Importance of Intermediate Principal Stress Magnitude in Dynamic Rupture Propagation in 3D

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Dynamic rupture process along non-planar faults has been progressively studied by several groups, but there are few studies that take into account the possibility that slip directions (rake) may change along the different segments. This may actually happen; for example, rupture started on an inverse fault and propagated far along several strike-slip faults during the 2002 Denali, Alaska, earthquake. We apply a 3D boundary integral equation method (BIEM) and numerically study dynamic rupture propagation along a few fault segments subjected to a uniform tectonic regime but with different strikes and dips. Their different geometry implies different rakes for each segment. Furthermore, not only the magnitude but also the direction of the dynamic stress perturbation is calculated since it may not be the same as that of the initial stress regime. Thus, compared to previous models, the occurrence of dynamic rupture jumps depends on the relative segment geometry, the relative value of the dynamic and static friction coefficients, but most importantly, on the relative value of the intermediate principal stresses.

S21G-06 1135h

Numerical Models of Stopping Ruptures on a Bimaterial Interface

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Using a cross-correlation earthquake relocation technique, Rubin and Gillard (2000) and Rubin (2002) found that the nearest aftershocks of microearthquakes on the San Andreas fault were much more likely (by a ratio of nearly 3:1) to occur to the NW of the mainshock than to the SE. They attributed this asymmetry to the material contrast across the fault and the resulting dynamical reduction in normal stress near the rupture front propagating to the SE (the front moving in the direction of slip of the more compliant medium). Specifically, it was hypothesized that regions of the fault far enough from failure to resist this extra dynamical "kick" would be that much farther from failure once those dynamical stresses decayed. However, analytical (steady-state) models of propagating slip on a bimaterial interface (Weertman, 1980) show that, as with the static stress field, normal stress changes occur only behind the rupture front. The proposed explanation works most simply if the region ahead of the SE rupture front experiences a transient stress favorable for slip. In principal this stress transient could be associated with either rupture growth or arrest. To investigate this further, we ran 2-D numerical models of slip on a bimaterial interface with slip-weakening friction, using the code of Cochard and Rice (2000). The ruptures spontaneously accelerate to the generalized Rayleigh wave speed of the medium, when such exists. During this growth phase, large tensile stresses are indeed restricted to regions of large slip velocity behind the SE-propagating rupture front. Ahead of the rupture front the normal stresses are smaller and compressive. If the rupture front is stopped abruptly, the short-wavelength tensile stress pulse continues to propagate at roughly the same velocity. The above comments also apply in an anti-symmetric sense to the NW rupture front, although there the slip speeds and normal stress changes are lower. If the rupture is stopped by a more gradual reduction in the loading stress, the moving tensile pulse can spawn a decaying slip pulse at the SE front but not the NW. If this slip pulse marks the furthest extent of slip, the resulting static stress field is quite asymmetric even for a symmetric initial stress, lying on the failure envelope at the NW end of the rupture but well below it at the SE end. These results are at least permissive of the explanation proposed by Rubin and Gillard. For weaker slip pulses (due to any of a number of factors contributing to smaller maximum slip speeds), the furthest extent of slip near the SE rupture front can be driven by the stopping phase arriving from the NW end of the crack. Under such conditions the final stress field is more symmetric. We will be running models using heterogeneous stress fields to explore these questions further, and hope to use rate-and-state friction to investigate the observed temporal decay of the aftershock asymmetry.

S22A MCC: Level 1 Tuesday 1330h

Mechanical Strength of the Continental Lithosphere III Posters

(joint with T, V)

Presiding: **J C White,** University of New Brunswick**; C W Holyoke,** Brown University

S22A-0407 1330h POSTER

Constraining the Vertical Coherence of Deformation in Central Asia Using GPS, Geologic, and Shear-Wave Splitting Data

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First-order constraints on the depth dependence of lithospheric strength are provided by the degree of vertical coherence between crustal and mantle deformation. We evaluate the level of vertical coherence for the Tibetan Plateau, and off-plateau region of Yunan, by comparing the strain-rate field that has been calculated for the surface, and the mantle field inferred from mantle anisotropy. A continuous surface strain-rate field is determined from GPS observations and Quaternary fault-slip rates that are interpolated using continuous bi-cubic spline polynomials. Point estimates of the mantle finite-strain field are inferred from measurements of the shear wave splitting fast polarization directions, ϕ , of core phases, which are assumed to denote the orientation of shear in the lithospheric mantle under transpressional deformation. We evaluate the surface field at the locations of splitting measurements, and calculate a surface-derived prediction of ϕ , ϕ_s, assuming that the finite-strain shear orientation corresponds to the no-length change orientation. We then use the difference angle $\Delta\phi_s = \phi - \phi_s$ as a measure of vertical coherence. On the Tibetan plateau, vertical coherence is remarkably high under left-lateral shear; the RMS value of $\Delta\phi_s$ is less than 10°, which approximately corresponds to the expected uncertainty in the splitting measurements. In contrast, $\Delta\phi_s$ is very large for the off-plateau region for either right (52°) or left lateral (43°) shear, signifying the absence of vertical coherence. We calculate the mantle strain-rate field assuming that the Indian plate, Tarim Basin, south China Block, Ordos block, and Sunda block, represent rigid lithospheric blocks. GPS measurements are used to define the rotations of these bounding blocks, and we solve for a continuous strain rate field in the deforming interior region. We calculate predicted values of ϕ, ϕ_m, where splitting measurements are available. The most dramatic change, compared to surface field, is that in Yunan, $\Delta\phi_m$ is less than 10°, suggesting that boundary conditions alone are enough to predict mantle deformation field off the plateau. For Tibet, the fit is degraded, compared to predictions from the surface field, with $\Delta\phi_m = 22^\circ$, suggesting a need for a second mantle deformational driving force, namely a contribution from body forces. Indeed previous dynamic modeling of Tibet shows that the surface deformation field (and hence the mantle field) requires a significant body-force contribution. Given that the crust and mantle have distinct strain-rate and velocity fields, at least in certain regions, we next seek to quantify the horizontal shear in the decoupling zone between the two. For this purpose, we determine a mantle velocity field consistent with the splitting observations by again applying the GPS-inferred rotations of the rigid blocks, and also impose the shear wave splitting measurements as directions of no length change in the inversion. With continuous surface and mantle velocity fields we can then calculate a differential velocity field between the crustal and mantle layers. By assuming different thicknesses and viscosity values for the decoupling zone, we calculate the shear strains and resulting shear tractions. These stresses are then compared to the observed surface deformation to place bounds on viscosity values within the decoupling zone.

S22A-0408 1330h POSTER

Convergence in a Model Viscous Lower Crust and its Surface Topographic Expression

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A 2-D analytic solution for the displacement of the upper surface of a viscous layer moving past a rigid body illustrates that such a system can produce measurable signals at the Earth's surface. This problem is best-known in the case of a rigid indenter intruding into a viscous fluid, often used to describe the case of rigid Indian lithosphere intruding into a fluid layer beneath Tibet. Similar geometry and distribution of mechanical properties may exist in other regions of convergent tectonics. In these cases, the indenter excites vertical velocity in the fluid, which drives displacement of the upper boundary at amplitudes and wavelengths related to the length scales of the fluid layer and the indenter. These displacements decay over time, but persist sufficiently to be expressed in real landscapes, such that observations of characteristic topography may serve as direct tests for the presence of flow in the lower crust. In particular, this model may be applied in cases such as Tibet where additional independent evidence for a channel of low viscosity exists in the distribution of seismic moment release or in observations of rheology from seismic wave velocities.

S22A-0409 1330h POSTER

Stress Magnitudes in Asia and North America: Implications for Strength Profiles

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We present dynamic models that incorporate lithospheric gravitational potential energy (GPE), coupling with deeper mantle circulation, and stress field boundary conditions. Our integrated modeling approach allows us to quantify the degree of coupling between the lithosphere and the mantle in western North America and throughout southern and central Asia. Although both regions undergo active continental deformation in broad diffuse zones, the relative roles of the forces contributing to the deformation of each region differ. In order to quantify the forces responsible for the continental deformation we estimate the contributions of lithospheric GPE, stresses associated with plate motions, and basal tractions resulting from mantle-lithosphere coupling. Internal density distributions inferred using seismic tomography and history of subduction drive our mantle circulation model that is constrained to match the geoid, topography, and plate motions. Our lithospheric models are solutions to equations for a thin sheet, with basal traction contributions, and allow us to solve for both the vertically averaged magnitudes and styles of the total deviatoric stress field that drives continental deformation. Initially we determine a kinematic strain rate and velocity field model based on interpolation of GPS velocity vectors and Quaternary strain rates. Results to date are consistent with significant coupling between lithosphere and deeper mantle circulation throughout deforming Asia. On the other hand, our results require a significant decoupling between deeper mantle circulation and the lithosphere in western North America. The magnitudes of vertically averaged deviatoric stress range from 5-40 MPa in Asia, and 5-20 MPa in western North America. We next use the magnitudes of the vertical averages of stress to investigate how strength

is partitioned within the lithosphere. Assuming Byerlee friction for the brittle portion of the lithosphere and flow laws for the rheology of regions below, we investigate the regional variations in thickness of the brittle, frictional portion of the lithosphere and compare this with the depth of seismicity. Results to date suggest that 50% or more of the lithospheric strength is contained within the brittle, seismogenic portion of the lithosphere.

S22A-0410 1330h POSTER

Rheology of the continental lithosphere

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The deformation of the continental lithosphere is associated with a combination of ductile and brittle processes. Ductile deformation is analyzed utilizing creep (Newtonian, non-Newtonian) and plastic rheologies. These can be extremely sensitive to composition and temperature. In some cases elastic stresses are relaxed, but in other cases elastic stresses are preserved over 108-109 years. The distinction between renewable stress (plate tectonic, bending) and nonrenewable (thermal, membrane) must be made. The concept of a yield stress is blurred. Brittle deformation tends to be much more complex. Displacements on faults certainly play an important role, but faults are present at all scales. Under some circumstances it is appropriate to treat these deformations in a continuum manner. An avenue for doing this is damage mechanics. The concept of damage mechanics have been utilized widely in engineering problems. We show that when damage mechanics is applied to the brittle deformation of the upper continental crust, a non-Newtonian, power-law viscous rheology is derived. There is a well defined yield stress that can be associated with the dynamic coefficient of friction. Below this stress the upper crust behaves elastically and can act as a stress guide. Above the yield stress the continuum deformations can be modeled as a power-law viscous fluid (with exponent l 10). This behavior is associated with aftershock sequences. A main shock suddenly increases the stress in regions of the upper crust. Stress relaxation is accomplished by the aftershock sequence and Omori's law for the decay of aftershocks quantifies the relevant fluid rheology.

S22A-0411 1330h POSTER

Evidence of Powerlaw Flow in the Mojave Desert Mantle

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Laboratory experiments suggest that rocks in the lower crust and upper mantle (shallower than ∼200 km) should deform by dislocation creep, leading to a powerlaw rheology characterized by a strain rate proportional to stress raised to a power, n. Powerlaw creep has not yet been confirmed by geodetic observations. We use GPS campaign and continuous time-series data associated with 1992 Landers and 1999 Hector Mine earthquakes to infer rheologic properties of the Mojave lithosphere in southern California. The coupled nature of these earthquakes (20 km and 7 years apart) makes them ideal for a stringent rheology study in that a candidate rheologic model must satisfy the postseismic observations associated with both events. To infer the nature of viscous flow we developed a finite element model of this earthquake sequence that simulates coseismic slip associated with both events, a regional background strain rate, and temperature dependent powerlaw rheologies. We consider a range of powerlaws (for felsic and mafic, wet and dry rocks) reflecting uncertainty in the mineralogy of the lithosphere and in the extrapolation from laboratory to geologic conditions. Thermal gradients are constrained from surface heat flow measurements and regional seismic velocities. For comparison purposes, we also consider models with a Newtonian (strain rate linearly proportional to stress) rheology. Our results show that the spatial and temporal evolution of transient surface deformation following the Landers and Hector Mine earthquakes can be successfully explained by powerlaw flow ($n = 3.5$), predominantly in a warm and wet upper mantle. We can rule out Newtonian flow as a reasonable explanation of both the spatial and temporal patterns of postseismic transient motions, implying that the common assumption of Newtonian flow in numerical models of ductile deformation within the crust and upper mantle may be invalid. These results suggest that recovery-controlled dislocation creep is the dominant mechanism of viscous flow following earthquakes. The model results also preclude significant flow in the lower crust, supporting the contention that, at least beneath the Mojave Desert, the mantle is the weaker region. The stress dependence of powerlaw flow inferred by our calculations means that the viscosity of the upper mantle changes as a function of time after an earthquake. This has implications for models of regional stress changes and fault interaction. For example, the influence of earthquake induced stress changes on neighboring faults will evolve more rapidly early on, but will last many decades longer than would be inferred from a Newtonian model. Furthermore, as viscosities are lowest where stresses are highest, a powerlaw rheology leads to a more localized shear zone beneath faults where coseismic stresses are highest. For example, our calculations show that a Newtonian model of post-Landers relaxation leads to a broad, diffuse shear zone in the mantle beneath the Landers rupture zone about 250-300 km wide. In contrast, post-Landers relaxation of a powerlaw rheology leads to a relatively narrow shear zone 70-90 km wide, with much of the shear concentrated in a central zone only 15 km wide.

S22A-0412 1330h POSTER

Rheology of an Extending Lithosphere From Postseismic Deformation of Large Basin-Range Normal-Faulting Earthquakes

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The effects of long-term viscoelastic loading and relaxation of the Earth's lithosphere and asthenosphere should be included to better model the complete earthquake cycle. An earthquake is assumed to generate coseismic stresses that cannot be sustained by the ductile lower crust and upper mantle, leading to postseismic relaxation of these materials. Stress and strain are in turn transferred to the upper crust, producing an observable transient geodetic signal. To investigate lithospheric rheology beneath the Wasatch fault zone where no large historic earthquake has been recorded, we first studied the change of surface deformation after the 1959 Ms = 7.5 Hebgen Lake, Montana, earthquake, measured by trilateration and GPS from 1973 to 2000 and the only postseismic observations of large normal-faulting earthquake in the Basin-Range. Time-dependent changes of baseline length across the fault were used to optimize rheological models beneath the Hebgen Lake fault zone. Our results are similar to the rheological structures of the eastern-Basin-Range lithosphere implied by the long-term deformation of the lacustrine shoreline caused by the Lake Bonneville rebound. Based on our optimized Hebgen-Lake rheological models, we then estimated combined postseismic responses caused by the most recent paleoearthquakes on the Wasatch and East Great Salt Lake faults and some Wasatch Front large ($M > 5.5$) historic earthquakes. Half-space and layered rheological models were used. Comparing these results with the contemporary GPS-observed velocities reveal how postseismic signals contribute to the current surface deformation in the Wasatch Front area.

S22A-0413 1330h POSTER

More Evidence for Strong Lithospheric Mantle: Mantle Earthquakes in Zambia

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The occurrence of intra-continental earthquakes in the mantle is a key evidence for strong mantle lithosphere. To this end, the most direct way to establish if intra-continental earthquakes occur in the mantle is to determine focal depths RELATIVE to the Moho. This approach bypasses the need for precise knowledge of both focal depths and local crustal thickness in the source region – often difficult requirements to meet simultaneously. We report preliminary results using underside reflections off the Moho directly above the source to ascertain that mantle earthquakes do occur away from the East African rift in Zambia. By matching observed, teleseismic P-waveforms with synthetic seismograms, we identified underside reflections off the Moho (pmP phase) based on its polarity and timing relative to the direct arrival, thus confirming the occurrence of mantle seismicity regardless of the actual crustal thickness in Zambia. By focusing on longstanding, quite receiver sites and on dense arrays, we are currently gathering a set of pmP data with short source-time functions and of exceptionally high signal-to-noise ratios. (Supported by NSF Continental Dynamics Program: Project Hi-CLIMB.)

S22A-0414 1330h POSTER

Earthquake Locations, Depths and Source Parameters From the Himalayan Nepal Tibet Seismic Experiment (HIMNT): Implications for Continental Lithospheric Strength.

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The Himalayan Nepal Tibet Seismic Experiment (HIMNT) included the deployment of 29 broadband IRIS PASSCAL seismometers in eastern Nepal and southern Tibet from October 2001 to November 2002. An initial catalog with hundreds of local earthquakes has been obtained by picking the first arrivals of P and S waves and locating the hypocenters using a weighted least squares algorithm. We find a dense alignment of seismic events along the front of the High Himalaya, following the general trend of the surface trace of the Main Central Thrust. Many earthquakes cluster at 15-25 km depth along the proposed mid-crustal ramp beneath the High Himalaya of northern Nepal, where interseismic accumulation is believed to take place. Earthquakes with depths between 70 and 85 km are found in northeastern Nepal and southern Tibet. The Sub-Himalaya of southern Nepal is almost free of seismicity, with the exception of a cluster of earthquakes in the vicinity of the 1988 magnitude 6.1 Udaypur earthquake. Many of these southern Nepal earthquakes are at depths very close to the crust-mantle boundary. A double difference algorithm has been utilized in order to relocate earthquakes, improving the ability of the seismicity pattern to image the active tectonic structures. Phase picks from 21 short period seismic stations of Department of Mines and Geology of Nepal (DMG) are combined with HIMNT picks in the relocations. After relocation, the alignment of earthquakes following the front of the High Himalaya becomes more clear, as well as the clustering of hypocenters along the inferred mid-crustal ramp. The alignment of the aftershocks of the Udaypur earthquake likely mark the fault plane along which the strike-slip motion occurred. Estimates of local crustal thickness from teleseismic receiver functions combined with hypocenter locations indicate an upper mantle origin for many earthquakes in southern Tibet and northeastern Nepal, which has important implications for the strength of the continental lithosphere. A full waveform moment tensor inversion is performed for the largest events, obtaining further constrain on earthquake depth as well as the mechanisms of faulting in the area.

S22A-0415 1330h POSTER

Pn inversion of the Tibetan Plateau from regional networks and INDEPTH experiments

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We perform an inversion of Pn travel times from the Chinese earthquake bulletins and the ISC bulletins as well as hand picks of the data from INDEPTH experiments and other digital stations. We invert for Pn velocity and anisotropy as well as station delays (which reflect primarily Moho depth variations). The use of the Chinese provincial and national stations increases the data coverage by an order of magnitude compared with previous studies. The inclusion of INDEPTH stations and Chinese stations in Tibet increases the azimuthal coverage of ray paths and allows us to examine crustal thickness variation across the plateau. Our results suggest that the Pn velocity in the northern Tibet is generally lower than in southern Tibet, consistent with previous studies. However, our model suggests a more complex structure. The low velocity anomalies can be traced from the northern Tibet across southwestern Tibet and south central Tibet to the India plate. Significantly, nearly all the reported intermediate depth, subcrustal earthquakes in the region in our areas of high Pn velocity in southern Tibet, western Kunlun or Pamir. This suggests that these high Pn velocity regions are cold enough to support brittle failure. Although limited by the number of subcrustal earthquakes, the result suggests that Pn velocity could be an excellent indicator of mantle lithosphere strength. Our preliminary results also suggest a significant change in crustal thickness and Pn anisotropy across the Banggong-Nujiang suture, which correlates with the observed changes in gravity anomaly and SKS splitting across the boundary.

S22A-0416 1330h POSTER

Earthquake source parameters determined using the SAFOD Pilot Hole vertical seismic array

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We determined source parameters of microearthquakes occurring at Parkfield, CA, using the SAFOD Pilot Hole vertical seismic array. The array consists of 32 stations with 3-component 15 Hz geophones at 40 meter spacing (856 to 2096 m depth) The site is about 1.8 km southwest of a segment of the San Andreas fault characterized by a combination of aseismic creep and repeating microearthquakes. We analyzed seismograms recorded at sample rates of 1kHz or 2kHz. Spectra have high signal-to-noise ratios at frequencies up to 300-400 Hz, showing these data include information on source processes of microearthquakes. By comparing spectra and waveforms at different levels of the array, we observe how attenuation and scattering in the shallow crust affect high-frequency waves. We estimated spectral level (Ω_0), corner frequency (f_c) and path-averaged attenuation (Q) at each level of the array by fitting an omega squared model to displacement spectra. While the spectral level changes smoothly with depth, there is significant scatter in f_c and Q due to the strong trade-off between these parameters. Because we expect source parameters to vary systematically with depth, we impose a smoothness constraint on Q, Ω_0 and f_c as a function of depth. For some of the nearby events, take-off angles to the different levels of the array span a significant part of the focal sphere. Therefore corner frequencies should also change with depth. We smooth measurements using a linear first-difference operator that links Q, Ω_0 and f_c at one level to the levels above and below, and use Akaike's Bayesian Information Criterion (ABIC) to weight the smoothing operators. We applied this approach to events with high signal-to-noise ratios. For the results with the minimum ABIC, f_c does not scatter and Q decreases with decreasing depth. Seismic moments were determined by the spectral level and range from 10^9 and 10^{12} Nm. Source radii were estimated from the corner frequency using the circular crack model of Sato and Hirasawa (1973). Estimated values of static stress drop were roughly 1 MPa and do not vary with seismic moment. Q values from all earthquakes were averaged at each level of the array. Average Q_p and Q_s range from 250 to 350 and from 300 to 400 between the top and bottom of the array, respectively. Increasing Q values as a function of depth explain well the observed decrease in high-frequency content as waves propagate toward the surface. Thus, by jointly analyzing the entire vertical array we can both accurately determine source parameters of microearthquakes and make reliable Q estimates while suppressing the trade-off between f_c and Q.

S22A-0417 1330h POSTER

Seismicity in the Central U.S. and Its Implication for Lithospheric Strength in the New Madrid Seismic Zone

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The depth histogram for seismicity is generally used in comparisons of seismicity and lithospheric strength models. Here, we examine the depth distribution of cumulative strain energy release (estimated from event magnitude) for seismicity in the central U.S. as a better physical indicator of the lithosphere's ability to store and release elastic strain energy. Seismic parameters in Central U.S. were collected and analyzed and include 5127 events occurred from 1974 to present. The analysis was performed with a focus to understand the difference of seismicity between the NMSZ and other Central U.S. areas so as to find constraints for construction of lithospheric strength models in the study area. The result shows that 82% of the 5127 events occurred in the NMSZ, but only accounted for 30% of total energy release, with dominant focal depth at 5 km and dominant energy release depth at 15 km. 18% of the 5127 events occurred in the other areas outside the NMSZ, accounting for 70% of total energy release, with dominant focal depth at 5 km and dominant energy release depth at 10 km. Even though there may be some artifacts for the event depth distribution introduced by the early earthquake location program, it is reasonable to conclude that the dominant energy release depth for the NMSZ is located at a lower depth than that for the other Central U.S. areas. It is noticed that most of the events with magnitude equal to or greater than 3.0 and depth equal to or greater than 15 km occurred in NMSZ. The deepest event with magnitude 4.0 occurred on 30 Apr 2003 with a focal depth at 23.8 km in NMSZ. Based on these analytic results, new lithospheric strength models are constructed for the NMSZ and Central U.S. respectively.

S22A-0418 1330h POSTER

Thermal Regime Inferred from Magnetic Anomaly Data in the Crust beneath the Japanese Islands, and its Relationship to Focal Depth

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One of the indicators of lithospheric strength is the focal depth distribution of earthquakes. Temperature has long been regarded as an important variable in determining the seismogenic portion of the lithosphere. The thickness of seismogenic crust layer correlates with surface heat flow in most interplate seismic areas of the world [e.g., Sibson, 1982]. However, heat flow measurements are often widely spaced, requiring an extrapolation of the data to estimate the thermal structure in the crust in some regions. The uncertainties associated with these extrapolations preclude improving on the general correlation between heat flow and depth of seismicity. We used another approach to estimate the thermal structure in the crust. The bottom of the magnetized crust determined from the spectral analysis of residual magnetic anomalies is generally interpreted as the level of the Curie point isotherm. We estimate the bottom of the magnetized crust, Z_b, of squares of 2.125^o subregions using the magnetic anomaly map of the Japanese Islands [Makino et al., 1992]. At the same region, the thickness of seismogrnic crust is estimated as the depth above which 90 percent of the earthquakes occur, D_{90}, using good quality hypocenters by JMA (Japan Meteorological Agency) data. Z_b and D_{90} range from about 11 to 32 km and 12 km to 28 km, respectively. This suggests that our analysis cannot catch a locally shallow depth. And it is consistent with the expected inverse relation between Z_b and the minimum heat flow values [Yamano et al., 1997] within the subregions. The inverse relation between Z_b and D_{90} suggests that this analysis is useful to estimate the regional thermal structure.

S22A-0419 1330h POSTER

Consequences of Removal of Cold Mantle Lithosphere: Uplift, Extension and Contraction in California (and Maybe Even Changes to the San Andreas)

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Volcanic rocks and associated xenoliths from the Sierra Nevada of California indicate that the entire mantle lithosphere was removed about 3.5 Ma, including about 30 km of eclogites and garnet pyroxenites. Such removal is surprising in that the Sierra has long been noted for its low surface heat flow, which, when combined with temperature information from xenoliths, indicates that this mantle lithosphere was very cold at the time of removal. One means of exploring the magnitude of this event is to examine the tectonic consequences. Replacing such a thick, dense body with more buoyant asthenosphere should drive uplift, which is consistent with uplift of the Sierran crest by more than 1 km between 3 and 8 Ma. Removal will also increase the gravitational potential energy of the Sierran lithosphere by at least 1.2 * 10^{12} N/m, which is capable of inducing extension. Such extension within 50 km of the east edge of the modern Sierra initiated between 5 and 3 Ma. If there are no changes in Pacific-North American plate motions [e.g., *Atwater and Stock*, 1998], then new extension must shut down extension elsewhere or increase compression. The California Coast Ranges date to about 3-5 Ma and largely have been created through shortening normal to the Sierran axis. Potentially this could influence San Andreas rates, as narrowing of the rigid Sierran block permits strike-slip motion to increase on the east side. A decrease of 12 mm/yr on the San Andreas at $\sim$ 4 Ma [*Dickinson*, 1996] suggests that slip on the Eastern California Shear Zone became viable about this time. All of these effects extend the length of the Sierra, indicating that removal affected the entire Sierra. If the removal occurred as a Rayleigh-Taylor instability, existing models can be reconciled with the cold temperatures if the high stress limit of *Evans and Goetze* (1979) is used and, probably, the top boundary of the lithosphere weakened prior to removal. However, the removal of the entire lithosphere is unexpected and suggests that the physics of these systems, including the lithospheric rheology, need additional study.

S22A-0420 1330h POSTER

Lithospheric and Upper Mantle Structure of the Rio Grande Rift: Implications for Pure Shear Extension

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Results from the Colorado Plateau-Rio Grande Rift-Great Plains seismic transect (LA RISTRA) experiment are consistent with a pure shear extension mechanism for the Rio Grande rift (RGR). LA RISTRA was a 950 km-long PASSCAL broadband seismic line with approximately 18 km station spacing deployed during 1999-2001 along a great circle from Lake Powell, UT to Pecos, TX, crossing the RGR near 34.5 degrees N. We image crust and uppermost mantle discontinuity structure along the transect by migrating receiver functions to produce a high resolution P-to-S converted phase image. Receiver function results show crustal thickness ranging from 45 to 50 km beneath both the Colorado Plateau and the Great Plains, thinning to a minimum of approximately 37 km centered beneath the RGR axis. The centering of the thinnest crust on the rift axis indicates that the deep crust has undergone primarily pure shear extension. Inversion of LA RISTRA surface wave data and tomographic inversion of teleseismic body-wave delay times for upper-mantle structure show a broad low velocity region, also centered beneath the rift axis. This low-velocity region is interpreted as rift-centered lithospheric thinning, indicating that lithospheric deformation, like that of the deep crust, is also primarily pure shear. A pure shear extensional mechanism for the RGR is consistent with geochemical evidence suggesting that the source region for rift related magmatism has evolved from predominantly lithospheric to asthenospheric mantle sources. This geochemical evolution of magmatism has been interpreted as lithospheric thinning, with the greatest thinning centered beneath the rift axis. Pure shear extension is further supported by processing regional gravity data to produce the decompensative gravity anomaly, which again shows symmetric thinning of the lithosphere closely tracking the rift axis. We conclude that while the upper crust along the RGR has undergone brittle deformation expressed as a series of asymmetric grabens, the lower crust and mantle lithosphere of the RGR have thinned symmetrically about the rift axis, indicating a pure shear mode of lithospheric deformation.

URL: http://www.ees.nmt.edu/Geop/Ristra/ristra.html

S22A-0421 1330h POSTER

Investigation of the Low Velocity Zone Beneath the Southern Basin and Range

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Following the work by Helmberger (1973), we use waveform recordings of P arrivals at distances from 6^o to 20^o to investigate the structure of the low velocity zone (LVZ) or asthenosphere. In contrast to the previous study, broadband data (TriNet and BDSN) is used at a much smaller station spacing providing higher along path and depth resolution. For this study, a well recorded earthquake in the central Gulf of California (M_w 6.3) produces transitions from P_{nL} to P_{410} across all of California and western Nevada. The nature of these transitions indicates the thickness and gradients of the LVZ and the lithosphere. Initial findings show large variations of lithosphere and LVZ structure from east to west below California. By varying the lithosphere compressional velocity and depth of the LVZ in 1-D models, a database of synthetics waveforms is created to guide the development of realistic 2-D (along path) and 3-D (against azimuth) description of the lithosphere and asthenosphere. The character of the P arrivals changes dramatically near 9-11^o with the emergence of a higher frequencies over-printing the longer-period P_{nL} arrivals. Coastal California stations show these arrivals at the shortest distances, 9^o indicating the lithosphere velocity and gradient below the LVZ are high. This is in opposition to those arrivals on the east which do not record the high frequency arrivals until 11^o. As the distances reach 13^o, a large amplitude, high frequency phase is present 10-15 seconds behind the initial P arrival. The emergence of the large secondary phase occurs at different distances across California with a pattern similar to before. At this distance, a change in the apparent velocity of the first arrival also occurs. Further in distance, the width of the initial P arrival and the energy following, or lack thereof, points to the shape of the underlying LVZ. Coastal stations and those in the central portion of California show larger amplitude arrivals following the initial P arrival than do those to the east. These large secondary arrivals may be due to larger than expected velocity jumps at the bottom of or just below the LVZ. Mapping the transition from the lithosphere to the asthenosphere, fine structure and lateral variation, should prove invaluable for tectonic reconstruction efforts, now in progress.

S22A-0422 1330h POSTER

Evidence for distributed lower crustal deformation within a continental strike-slip fault zone: Marlborough Fault System, South Island, New Zealand

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Teleseismic converted wave images from a passive seismic imaging experiment (2000-2002) across the Marlborough fault system, South Island, New Zealand show a continuous, unbroken Moho beneath the two northernmost faults of the fault system, suggesting that accommodation of lower crustal deformation occurs through distributed, ductile deformation and not by slip on a narrow vertical fault. Beneath the northernmost fault, the Wairau fault (450 km offset), the Moho dips between 25 to 30 degrees from a depth of 25 km northwest of the fault to a depth of 34 km southeast of the Wairau fault. Further to the southeast, the Moho arrival appears with a constant amplitude and depth of 34 km beneath the Awatere fault (30 km offset). Mid crustal arrivals appear to stretch across the Awatere fault at 10, 17, and 27 km depth but their continuation across the Wairau is not clear, possibly indicating a change in the depth of transition to ductile deformation north of the Wairau. Images derived using common conversion point stacking schemes will lose coherence and resolution in the presence of either large, lateral variations in seismic velocity or interface topography with wavelength similar to the smallest bin size of the stacking algorithm. To test the possibility that our image is actually produced by an offset in the Moho, we construct synthetic converted-wave images from seismograms calculated for models with either a Moho step or dip using the same station-event geometry as the processed data set. The synthetic image produced from the dipping Moho model matches our results, but that with a step does not. Large velocity variations associated with the terrain boundary represented by the Wairau fault could affect the coherence of the Moho conversion across the Wairau. Although, restacking with several different velocity models does not affect the lateral continuity of the Moho. The observation of a continuous but dipping Moho under the Wairau Fault and its 450 km of displacement implies distributed strain over a broader region of weak, ductile lower crust.

S22A-0423 1330h POSTER

How Sharp is the Base of the Lithosphere?

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Precisely determining the depth and the velocity gradient at the base of the continental lithosphere has proved challenging with existing body and surface wave tomography. Higher resolution imaging of this boundary can be achieved through the analysis of teleseismic P-to-S (Ps) converted phases generated at the discontinuity. In this study we have found a Ps phase which appears to emanate from the base of the lithosphere beneath eastern North America. We have used the timing, amplitude, and frequency dependence of the phase to invert for the properties of this discontinuity. To image the discontinuity, waveforms recorded at single stations were decomposed into their P and S components and migrated to depth through least-squares simultaneous deconvolution in each of 9 epicentral bins. Data from stations HRV in Massachusetts, LMN in New Brunswick, and PAL and BINY in New York reveal a negative velocity contrast at ∼90-100 km depth over a ∼450 km swath of the Appalachian orogen. This depth range is consistent with the thickness of the lithosphere found in previous surface wave tomography studies. At HRV, where the phase is most clearly observed, its amplitude decreases as the low-pass cut-off frequency increases, indicating that the velocity contrast occurs over a non-zero depth range. Crustal thickness and velocity and an observed mid-lithospheric discontinuity were first modeled to ensure that their effects on the phase of interest are accounted for. Finally, we inverted frequency-dependent waveforms containing the phase from the base of the lithosphere in different epicentral bins. The dominant period of the incident P-wave was constrained by comparing observed auto-deconvolved P-waves to synthetic data at various periods, and during the inversion the period of the incident waveform was allowed to vary within the error bars determined in the auto-deconvolution test. After each inversion iteration, the migration model was adjusted to match the best-fitting model, and the data were remigrated and reinverted to confirm that the last result remained identical to the preferred model. Initial inversions indicate a 7-10% velocity drop that occurs over no more than 5 km located at ∼95km depth. Such a strong and sharp velocity contrast at the base of the lithosphere is not consistent with a purely thermal gradient and suggests the influence of other factors such as volatile variations.

S22A-0424 1330h POSTER

Windows of Transient Creep and Rupture in Continental Lithosphere

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Factors influencing variations of mechanical strength with depth include the geothermal gradient (T, P), lithology and fluids, amongst others. In stratified models of the lithosphere, gross variations in lithology control partitioning of mechanical behaviour into strong versus weak rheologies as a function of the latter factors. In exhumed crustal section there exist large volumes of both highly deformed and relatively undeformed continental lithosphere that nonetheless record similar crustal conditions in their metamorphic mineral assemblages. This spatial and temporal heterogeneity of lithospheric deformation means that data on strength in nature come from rocks weak enough to deform, while those that remain undeformed must be inter alia strong. Field-based studies record deformation styles that are repeated within any large-scale variation in crustal lithology. These windows of transient deformation' are commonly associated with localization (fast strain rate, high-strength transient) and veins or melts (fluid input) that argue against steady-state behaviour. Comparison of experimentally imposed bounds with strength-related microstructures suggests that background ambient low stress/low strain rate response (bulk rheology) has imposed on it cyclic hardening and softening. These observations belie simple descriptions of P/T-related depth variations in strength and instead, deformation mechanisms appear to be critically sensitive to outwardly subtle variations in deformation environment. Such cycles of transient behaviour, including brittle deformation, are observed at all levels of the continental crust, and at least into the upper mantle.

S22A-0425 1330h POSTER

Creep: Long-term Time-Dependent Rock Deformation in a Deep-sea Laboratory in the Ionian sea: a Pilot Study

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Time-dependent brittle rock deformation is of first-order importance for understanding the long-term behavior of water saturated rocks in the Earth's upper crust. Interpretation of results from traditional laboratory brittle creep experiments have generally been in terms of three individual creep phases; primary (decelerating), secondary (constant strain rate or quasi-steady-state) and tertiary (accelerating or unstable). The deformation may be distributed during the first two, but localizes onto a fault plane during phase three. More recently, models have been proposed that explain the trimodal shape of creep curves in terms of the competition between a weakening mechanism and a strengthening mechanism, with the weakening mechanism eventually dominating and leading to localized failure. However, a major problem is that it is difficult to distinguish between these competing mechanisms and models given the lower limit of strain rates achievable in laboratory experiments over practicable time scales.

This study aims to address that problem directly by extending significantly the range of achievable strain rates through much longer-term experiments conducted in a deep-sea laboratory in the Ionian sea. The project takes advantage of a collaboration with the NEMO Group-INFN, a consortium that is developing a large volume (1 km3) deep-sea detector for high-energy (>1019 eV) cosmic neutrinos. A suitable test site has been identified, some 20km north-east of Catania in Sicily, at a depth of 2100m.

Within the CREEP deformation apparatus, confining pressure is provided by the ambient water pressure (>22MPa), and the constant axial stress is provided by an actuator that amplifies this pressure. Measurement transducers and a data acquisition system are sealed internally, with power provided for up to 6 months by an internal battery pack. The great advantage of operating in the deep sea in this way is that the system is essentially passive, has few moving parts, and requires no maintenance. The apparatus is held in place by a disposable cast-iron anchor and supported above the seabed by a deep-sea buoyage system. On completion of each experiment, an acoustic release detaches from the anchor and allows the apparatus to float to the surface to be recovered by the oceanographic research vessel.

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S22A-0426 1330h POSTER

Low Temperature Bulging Recrystallization in Olivine Aggregates: a Mechanism for Strain Weakening and Localization

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Evidence of strain localization in olivine aggregates has been observed in both obducted slices of upper mantle and in high stress experiments (Post, 1977). Most experimental deformation studies of olivine aggregates have been done in gas apparatus at low P (<300 MPa) and thus at low flow stress; both axial compression and shear experiments involving climb-accommodated dislocation creep show steady state flow, with little if any strain weakening. However, experimental studies of quartz and feldspar at high P have shown the existence of a low T, high stress dislocation creep regime in which climb is very limited and creep is accommodated by bulging recrystallization; in this regime extreme strain weakening and localization occur. To explore high stress dislocation creep in olivine, we have deformed natural and synthetic aggregates using a modified molten salt assembly in a Griggs apparatus at a P of 1.5 GPa, T of 950 to 1100°C, and strain rates of 5×10^{-5}/s to 10^{-6}/s, in both axial compression and general shear. For starting materials we used both Balsam Gap dunite (d∼500 μm) and synthetic aggregates hot pressed from San Carlos olivine powders (10-20 and 25-38 μm). Prior to weld sealing in Ni and outer Pt, each sample was dried for 24 hrs at 900°C in a CO/CO_2 atmosphere. The yield stress of the samples ranged from 1300 to 380 MPa and all samples strain weakened. The highest stress sample shows evidence of semi-brittle flow, with high densities of linear dislocations and a few very small recrystallized grains. A sample with an intermediate yield stress (780 MPa) strain weakened to 600 MPa by 16% strain and shows very high densities of tangled dislocations in the porphyroclasts, and small (1-2 μm) dislocation-free recrystallized grains along their boundaries. The sample with the lowest yield stress (380 MPa) strain weakened to a steady state flow stress of 120 MPa at $\gamma = 4.5$. The few remaining porphyroclasts contain subgrains, and the recrystallized grain size is consistent with the recrystallized grain size piezometer for olivine deformed by climb-accommodated dislocation creep. The microstructures and mechanical behavior of these olivine samples are consistent with those previously observed in quartz and feldspar aggregates, and indicate a transition from climb-accommodated dislocation creep at lower stresses to recrystallization-accommodated dislocation creep at higher stresses. It appears that bulging recrystallization in low T, high stress dislocation creep is capable of producing significant strain weakening and strain localization in the upper mantle.

S22A-0427 1330h POSTER

Effect of Dehydration Reaction on Serpentinite Deformation in Torsion

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Dehydration of serpentine to olivine, talc and water during deformation is critical for understanding the possible localization of deformation into shear zones and the generation of earthquakes along subduction zones. In order to investigate the effect of the dehydration reaction on the strength and ductility of serpentinite, torsion experiments were performed using a Paterson high PT torsion rig at constant shear strain rates of 10^{-4} to 10^{-5} s^{-1}, temperatures of 550 to 750 °C and a confining pressure of 300 MPa, to local shear strains up to $\gamma = 3$. We deformed two types of serpentinite: antigorite from Val Malenco, Italy, a high-temperature phase of serpentine (stable at T <500 °C), and lizardite from Elba, Italy, a low-temperature phase of serpentine (stable at T <400 °C). Most of the samples were shaped in dog-bone geometry with a central hole along their axial direction which acted as a fluid conduit, enabling an easy escape for any released fluid during the dehydration reaction. We also deformed solid bone-shaped specimens to compare the mechanical behavior of solid and hollow specimens. In both cases, porous alumina spacers were placed on both end sides of specimen and led to the atmosphere through the pore pressure line. Thus our experiments were performed under drained conditions. Antigorite deformed in the semi-brittle field at the run conditions. Visible faults formed probably due to reaction-induced fracturing, and the stress started to drop just after the initial peak stress (∼350 MPa at 650 to 700 °C and ∼280 MPa at 750 °C). Highly comminuted grains with various sizes along the faults were identified as partially dehydrated antigorite (H_2O ∼6 wt%) at 650 °C and olivine and talc at >700 °C. Mechanical behavior after the peak stress is thought to occur by cataclastic flow, possibly assisted by diffusion mass transfer processes of these fine-grained reactant minerals. We have also investigated the effect of pre-heating on the strength of antigorite. The peak strength of a sample pre-heated at 750 °C for 3 hr and then deformed at 700 °C is 70 MPa lower than a sample deformed directly at 700 °C. This stress reduction occurred due to the presence of a mechanically weaker reaction product (talc) rather than elevated pore pressure because the sample was deformed under completely drained conditions. By contrast, a solid sample was weaker than hollow ones by ∼100 MPa, mainly due to low permeability of the serpentinite. Excess fluid pressure in solid specimens leads to a drop in the effective pressure and appears to have enhanced the dehydration reaction along microfractures. Our data shows that dehydration weakening of serpentinite is caused not as much because of excess pore pressure but more because of the weaker mineral assemblages from the reaction. In contrast to semi-brittle faulting in antigorite, deformation of lizardite at 550 °C to a bulk shear strain of 0.9 was widely distributed, showing typical ductile microstructures such as boudinage and S-C fabric. A well developed secondary foliation (C-plane) and strong lattice preferred orientations of lizardite grains were observed close to the localized shear zones. After the initial peak stress, steady stress values of 250 MPa were measured. We intend to focus on how the localized zones evolve and how the mechanical response changes with increasing shear strain during the reaction.

S22A-0428 1330h POSTER

Water Weakening of Clinopyroxene in the Diffusion Creep Regime

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We investigated water weakening of clinopyroxene aggregates, prepared by hot pressing ground powder of natural Sleaford Bay clinopyroxenite consisting of Fe bearing diopside of composition $Ca_{0.97}Mg_{0.78}Fe_{0.26}Si_{1.99}O_6$. Wet and dry aggregates were deformed at a confining pressure of 300 MPa at temperatures between 1323-1423 K and 1398-1503 K, respectively. Water was added to the sample during the run by dehydration of a talc sleeve. The wet aggregates crept about 15 times faster than the dry aggregates. The stress exponent in both cases was $n = 1$. The activation energies under the water-saturated and under-saturated conditions were 342 ± 27 and 759 ± 23 kJ/mol, respectively. We suggest that under water-saturated conditions, water derived point defects become the majority point defects and the charge neutrality condition changes into $\left[Fe'_{Si}\right] = \left[OH^{\cdot}_{O}\right]$ from $\left[V''_{Fe}\right] = \left[Fe^{\cdot\cdot}_{i}\right]$. Comparison of water weakening of clinopyroxene, olivine and anorthite aggregates deforming in the diffusion creep regime suggests that of these three minerals, water weakening is most significant in clinopyroxene.

S22A-0429 1330h POSTER

Frictional Properties of Feldspar and Quartz at the Temperatures of Seismogenic Zone

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Most of earthquakes in the crust occurred at the depth of 5 to 20km, and temperatures of 100 to 350°C. The physical properties of rocks at around these temperatures were determined by many frictional experiments. These results indicated the velocity dependence of steady state friction $(a-b)$ was switched from velocity weakening (seismic slip) to velocity strengthening (aseismic slip) at around 350°C in the wet condition. In these experimental studies, granites were generally used. On the other hand, it is important to evaluate and to compare the physical properties of each mineral which composed of crustal rocks, for example feldspar and quartz, in order to understand the source processes of earthquakes in detail. In this study, we conducted frictional experiments by using albite, anorthite, and quartz gouges (about 3μm diameter) under high pressure and high temperature in a triaxial apparatus, and compared frictional behaviors of three minerals with elevated temperature under the wet and dry conditions. These experiments were conducted by the velocity-stepping test. Temperature varied from room temperature to 600°C. 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 diameter × 40mm long). The sawcut was oriented at 30° to the loading axis. These were jacketed with thin sleeves of annealed Cu. The values for a-b of quartz and albite were positive under the dry condition from room temperature to 600°C. On the other hand, those values of albite and quartz were negative at the temperature of 200°C and 300°C under the wet condition respectively. Those values of quartz decreased as the temperature increased from 100°C to 300°C and increased as the temperature increased from 300°C to 600°C. Those values of albite were switched from velocity weakening to velocity strengthening between the temperature of 200°C and 300°C, and increased in the temperature range up to 600°C. The frictional coefficient of albite decreased gradually not exponentially after velocity-step from the temperature of 250°C to 350°C. We will discuss these frictional properties with the texture of samples by the SEM observations.

S22A-0430 1330h POSTER

Permeability Changes Of Fault Gouge While Frictional Sliding Under High-Temperature And High-Pressure Conditions

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Recently, measurements of permeability of fault rocks become one of the important test items to understand the fluid flow properties in the vicinity of the faults. Previous studies have clarified general permeability profile of the fault rock. While fault gouge, due to its smaller grain size, shows low permeability and becomes a seal to prohibit fluid flow across the fault, the fault breccia including numerous connecting fractures becomes the high permeable conduit along the fault. However, most of previous studies did not address these transport properties while the faults are moving, becouse they have investigated the permeability of fault rocks under hydrostatic pressure. Here, to reveal the evolution of transport properties of various fault rocks during fault moving, the high-temperature and high-pressure triaxial testing machine was employed to investigate the permeability changes of artificial/natural fault gouge during the fault sliding. Experimental apparatus at AIST is a triaxial gas-rig which can produce high temperature of 800 degree C and high confining pressure of 200 MPa in maximum. Artificial gouge (Na montmorillonite powder) and natural fault gouge sampled from a normal fault with ca. 5 m of fault displacement in sandstone at Katuura, Japan were sandwiched by pre-cut surfaces of sandstone angled 30 degree to the cylindrical axis. We used the pore pressure oscillation method to measure the permeability, which is advantageous to measure the permeability dynamically. We would like to compare the patterns of permeability change with the degree of the deformation localization varied as gouge, cataclasite, breccia and protolith. It will be of particular interests in the estimation of pore pressure increasing/decreasing in the vicinity of the fault, caused by porosity change during fault sliding. This kind of research would be a key to deduce the mechanism of abnormal pore pressure occurrence at faulting, considered as a trigger of seismic event.

S22A-0431 1330h POSTER

Experimental Study of the Failure Procedure of Echelon Fault Structure Using Digital Speckle Correlation Method (DSCM)

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The echelon fault structure is one of the most important structures in the earth's crust because it often initializes earthquakes. Therefore, the mechanism for the failure of this fault structure is of great importance to the understanding of earthquakes. In this study, the failure procedure of echelon fault structures are experimentally studied using digital speckle correlation method (DSCM). The specimen is a marble plate 400 mm x 400 mm x 40 mm in size. In order to simulate the echelon fault structure, 2 parallel slits are cut and then filled with gypsum. The specimens are loaded on a 500 T large scale double-axis test machine. During the experiment, the specimen is loaded laterally with a pressure of 40 MPa first and then compressed axially under the constant displacement rate of 0.02 mm/min. The DSCM system captures speckle images during the test process at 1 frame/sec. About 900 images were captured during the 15 minute compression test for each sample. 4 samples are tested with the same structure and loading in this experiment. The whole failure procedure of echelon fault structure and the field deformation on the surface of the sample was revealed by DSCM system. It is clearly shown by the evolution of the deformation field that the deformation is firstly localized at the fault zones and then the echelon area, where the two faults are interactive with each other. The failure also finally evolved in this echelon area. Based on these experimental results, a detailed failure procedure and the mechanism of failure were analyzed. Moreover, the deformation field during loading is statistically studied and a quantitative Cv-value, which expresses the characteristics of deformation localization, is an indicator for the failure of the echelon fault structure.

S22A-0432 1330h POSTER

Spatial Distribution of Crustal Anisotropy in and around the Atotsugawa Fault, Japan -To Infer the Frictional Coefficient of Active Fault-

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The spatial variation of frictional coefficient along active fault can be inferred from detail observation of stress field around the fault. We infer the spatial variation of maximum compressional stress axis around the active faults from dense observation of crustal anisotropy. The major possible cause of seismic anisotropy in the crust is the preferred orientation of micro cracks directed parallel to the axis of maximum compressional stress. Seismic anisotropy data are integrated effects from hypocenter to observatory, similar to travel time analysis, so we can obtain detailed images of the stress field by a tomographic approach if huge amounts of anisotropy data are available. The resolution of stress field imaged by the observation of anisotropy is expected to be higher than that studied by focal mechanisms or geodetic measurements such as GPS observation. In this study, we analyzed detailed anisotropy structure in and around the Atotsugawa fault, central Japan. The Atotsugawa fault, 60 km in length and N 60°E of strike, is located along the Niigata-Kobe tectonic zone, which is recognized as a deformation zone with a high strain rate. GPS observation indicates that the central part of the Atotsugawa fault is creeping and the other parts of the fault is locked to a depth of 15 km. Therefore, we can expect that the axis of maximum compressional stress is varied along the fault. Our observation indicates that crack orientation in and around the Atotsugawa fault is nearly consistent with the direction of the regional maximum stress in this area (NW-SE). On the western part, at stations 5 km away from the fault, crack orientation almost correspond to the regional maximum compressional direction. However, the direction of maximum compressional stress that inferred from anisotropy seems to have variation. At the western part of the fault, the direction of maximum compressional stress is estimated to be WNW-ESE. At the eastern part of the fault, the angle of maximum compressional axis makes more acute with the fault. This result may imply that frictional coefficient at the eastern part of Atotsugawa fault is higher than that of the western part.

S22A-0433 1330h POSTER

High Temperature Deformation of Stoichiometric Dolomite

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Three stoichiometric dolomite rocks have been shortened in triaxial compression experiments at T = 500° - 800°C, P_c = 300 - 400 MPa, and $\epsilon = 10^{-7}$ - 10^{-5} s^{-1}. Natural dolomite starting materials include 1) Blair dolomite ($Ca_{1.027}$ $Mg_{0.973}$ $(CO_3)_2$) investigated earlier by Handin et al. (1967) and Hugman and Friedman (1979), with a grain size of <10 μm, 2) Kern Mountains dolomite ($Ca_{1.008}$ $Mg_{0.992}$ $(CO_3)_2$) from eastern Nevada, with a grain size of 80 μm, and 3) Madoc dolomite ($Ca_{1.000}$ $Mg_{1.000}$ $(CO_3)_2$ from Ontario, Canada, with a grain size of 240 μm. Blair dolomite contains as much as 10% secondary phases, including quartz and feldspar, while Kern and Madoc dolomites are monomineralic, with only traces of impurity minerals. Microprobe analyses indicate that Fe is below detection limits for all three dolomites. Over all conditions investigated, Blair dolomite is strong, with differential stresses reaching 800 MPa and brittle faulting following soon after yielding, while the coarser Kern and Madoc dolomites exhibit lower strengths (200 - 600 MPa) and finite strains reach 15% without macroscopic failure. Microstructures indicate that strains are accommodated by mechanical twinning on *f*-planes (mostly at the higher differential stresses) and intracrystalline slip. For a given set of conditions, flow strengths of Kern and Madoc dolomites are comparable and they vary systematically with temperature and strain rate, with similar sensitivities to T and ϵ observed by Barber et al. (1994) for Crevola dolomite (grain size ~1 mm).

S22A-0434 1330h POSTER

Enhanced Imaging of an Active Collision Zone: The South Falkland Basin

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The South Falkland Basin is an active foreland basin located at the southern end of the Falkland Plateau. The basin was formed by flexure of the lithosphere of the South American Plate under the load of the Burdwood Bank, a continental fragment of the predominately oceanic Scotia Plate. The entire region is submarine, so the basin can be well imaged. It is therefore an ideal place for a detailed analysis of the geological structures comprising an active collision zone.
2D marine seismic reflection data were acquired by Geco-Prakla in 1993 and have been generously provided for this research project. These data have been reprocessed with modern seismic processing and imaging techniques such as radon, source signature deconvolution and pre-stack time and depth migration. Enhanced images of the deeper structures reveal normal faulting ranging from Mesozoic to Recent times within the flexed plate. Further south, convergent thrust faulting and piggy-back structures of Cenozoic age are present. Previous interpretations based on time-migrated data suggested that the normal faults were listric. On the depth-migrated sections, however, these faults are approximately planar and deeply penetrating (up to 15 km). The depth images also show that the normal faults were active during plate flexure. The presence of these active planar normal faults suggests that the upper crust does not support crustal loads in accordance with simple flexural models.

S22A-0435 1330h POSTER

On the recovery of effective elastic thickness using spectral methods: examples from synthetic data and from the Fennoscandian Shield

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The effective elastic thickness, T_e, represents the response to long-term loading of the lithosphere; it is thus a useful measure of its strength. However, the use of different methods and assumptions to calculate T_e yield different results, leading to controversial interpretations of the relationship of T_e to rheology. We investigate the ability of the Bouguer coherence and free air admittance to recover T_e assuming that surface and subsurface loads exist. We use synthetic data to show that the estimated Te using both functions is similar; the recovery with admittance is somewhat poorer due to leakage problems. When the underlying T_e is constant, the bias and variance of the resulting T_e increases with decreasing analysis window size and increasing underlying T_e value. When T_e varies spatially, T_e estimation using sliding, overlapping windows retrieves a structure that approximates the true spatial variability, but window sizes must be chosen carefully. In light of these results, we analyse T_e in Fennoscandia using both techniques and obtain similar estimates. T_e is 20-40 km in the Caledonides, 40- 60 km in the Swedish Svecofennides, 40-60 km in the Kola peninsula and 70-100 km in southern Karelia and Svecofennian central Finland. These estimates are not biased by unrecovered post-glacial rebound and also potential noise introduced by long-term erosion and sedimentation does not appear to affect T_e. An independent estimate of T_e using rheological modelling, confirms that T_e in central Finland should be high. Because T_e exceeds crustal thickness (~ 60 km), the mantle must contribute significant strength to the total. T_e is also larger than the seismogenic thickness, thus indicating that they represent different physical behaviours. In general, T_e in Fennoscandia increases with tectonic age, seismic lid thickness and decreasing heat flow. T_e is low where seismicity is frequent and high where it is reduced. In Proterozoic and Archean lithosphere, the relationship of T_e to age breaks down, indicating that compositional effects might be more important for the strength of stable continental lithosphere than tectonothermal age.

S22A-0436 1330h POSTER

Mobile Belts, High Lithosphere Temperatures, and Subduction Zone Backarcs

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At many continental plate boundaries, there are mobile orogenic belts or zones of distributed deformation hundreds of kilometres wide. An important characteristic of "mobile belts" is a long geological history of ongoing deformation or of repeated deformation events that suggests long-term lithosphere weakness compared to cratons. Thus, they are "mobile" not just because they are subject to deforming forces, but also because they are weak. In contrast, Precambrian cratons have exhibited very little internal deformation for long geological periods, and are inferred to have long-term strength. We propose that most mobile belts are weak because they are hot, and they are hot because they are in backarcs or geologically recent backarcs. Most continental backarcs are observed to be hot; the temperature at the Moho is 900C compared to 400C for cratons, and the lithosphere thicknesses are 50-60 km compared to more than 250 km for cratons. The high temperatures result in thermal expansion and the common high elevations in backarc mobile belts, even where the crust is not thickened. Backarc mobile belt lithospheres are at least a factor of 10 weaker than those of cratons. Backarcs may be hot and have thin, weak lithospheres because of the water driven upward into the backarc mantle wedge from dehydration of the underlying subducting plate. The water reduces the effective asthenosphere viscosity and allows vigorous free convection. High backarc temperatures appear to decay after subduction stops, with a time constant of 50-100 m.y. Many continental mobile belts are hot enough for there to be a weak lower crust detachment so surface tectonics are decoupled from the upper mantle. For example, foreland thrusting at the craton edge of a mobile belt may be driven by continental margin plate boundary forces 100s of km away, with translation of the crust over a lower crust detachment.

S22A-0437 1330h POSTER

Heat flow, thickness, and strength of the lithosphere in the Canadian Shield

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The effective elastic thickness of the lithosphere (T_e) is estimated from the coherence between Bouguer gravity and topography. The spatial resolution is low (on the order of 1,000km) because of the size of the windows needed to determine the spectra. Within the the Canadian Shield, T_e varies significantly (from < 40 to >100km) over distances on the order of 1,000km. Elastic thickness variations are observed within each of the provinces in the Shield and exhibit no geographic trend.
More than 300 heat flow values are available for the southern part of the Canadian Shield. The mean surface heat flow is the same for all the provinces in the Shield ($41 \pm 10(\sigma)$mW m^{-2}), but there are marked differences between sub-provinces characterized by different rock composition and mean crustal heat production. The heat flow and effective elastic thickness maps of the Shield appear to be negatively correlated with T_e highest (>120km) in the areas where heat flow is lowest ($\approx$ 32mW m^{-2}). From the heat flow and heat production data, we have calculated thermal models and rheological profiles of the crust and lithosphere. The results show that most of the observed variations in T_e in the Canadian Shield can be accounted for by differences in thermal regime.

S22A-0438 1330h POSTER

Mantle heat flow in the Canadian Shield from joint inversion of seismic and heat flow data

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We have used a Monte Carlo inversion of seismic surface wave data to obtain a thermal model of the upper mantle beneath the Canadian Shield in terms of Moho temperature, and mantle heat flow, and the potential temperature of the convecting mantle. The study area (40-60° N, 120-55 °W) includes several Provinces ranging in age from Archean to Paleozoic (the Appalachians). The inversion is constrained by heat flow and surface heat production data wherever they are available. The Monte Carlo inversion gives an ensemble of models that fit the data, providing estimates of uncertainties in model parameters. We also estimate the effect of uncertainties in the interconversion between temperature and seismic velocity. The analysis suggests that the lithosphere is coldest beneath the northernmost part of the study area. Mantle heat flow and lithospheric thickness vary from 11 mW m^{-2} and nearly 400km beneath the PaleoProterozoic Trans Hudson Orogen to the northwest to about 24 mW m^{-2} and less than 150 km beneath the Appalachians to the southeast. Within the Precambrian Shield, variations in shear wave velocity and Moho temperatures appear on a spatial scale of several hundred km. These variations appear not to be correlated with geological provinces tectonic history but they may be related to sub provinces with distinctive petrological characteristics.

S22A-0439 1330h POSTER

Variations in Elastic Thickness in the Canadian Shield

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We have used different spectral methods (Blackman-Tukey, Multitaper, and Maximum Entropy) to determine from the coherence between Bouguer gravity and topography the variations of the effective elastic thickness (T_e) of the lithosphere in the Canadian Shield. These methods differ mostly by their spatial resolution (1,000 to 2,000km) determined by the width of the windows applied to the data sets to obtain the spectral estimates but yield comparable results and the maps of T_e show similar trends. The highest resolution is obtained from the maximum entropy method. The Canadian Shield includes several geological provinces ranging in age from Archean to mid Proterozoic. The effective elastic thickness varies from <30km to > 100km over distances comparable to the width of the moving window. There is no clear relationship between elastic thickness and age as high and low values of T_e are found within each of the geological provinces. The map of T_e does not show a clear geographic pattern with high elastic thickness values found near the edge as well as near the center of the continent.

S22A-0440 1330h POSTER

Relating Seismic Velocities, Permeability and Crack Damage in Interpreting the Mechanics of Active Volcanoes.

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Improvements in volcano monitoring techniques have resulted in interpretative models of the physical and chemical changes associated with the renewal of activity of volcanic systems. However, accurate and meaningful interpretation of the relationship between the build-up of tectonic stress and precursory deformation requires a knowledge of the changing physical and mechanical properties of the relevant rocks. We report simultaneous laboratory measurements of seismic velocities and fluid permeability on basalts from Etna (Italy) and Iceland, and tuffs from Campi Flegrei (Italy).
Measurements were made in a servo controlled steady state flow permeameter at effective pressures from 5 to 80MPa, during both increasing and decreasing pressure cycles. Selected samples were thermally stressed at temperatures up to 900°C to induce thermal crack damage Acoustic emission output was recorded throughout each thermal stressing experiment.
At low pressure, the P-wave velocity for the columnar Icelandic basalt was 5.4 km/s, while for the Etnean lava flow basalt it was only 2.5 km/s. On increasing the pressure to 80 MPa, the velocity of Etnean basalt increased by 80%, whereas that of Icelandic basalt increased by less than 10%. Furthermore, the velocity of Icelandic basalt thermally stressed to 900°C fell by about 2.0 km/s, whereas the decrease for Etnean basalt was negligible. A similar pattern was observed in the permeability data. Permeability of Etnean basalt fell from about 750 microD to about 150 microD over the pressure range 5 to 80 MPa, while that for Icelandic basalt varied little from its initial low value of 9nD. Again, thermal stressing significantly increased the permeability of Icelandic basalt, whilst having a negligible effect on the Etnean basalt. These results clearly show that the Etna basalts contain much more crack damage than the Icelandic material. As a consequence, their seismic velocities are much lower than those generally assumed in tomographic studies of Etna (i.e. 5-6 km/s for the basalt layer).
Campi Flegrei tuff is a strongly heterogeneous pyroclastic flow material, which includes cavities, pumice and crystals. It has an initial porosity of around 45%, and a P wave velocities that increases from around 2 km/s to around 3 km/s over the pressure range 5 to 80 MPa. In marked contrast to both basalts, significant velocity hysteresis was observed in the tuff, with only about 50% of the velocity change recovered during depressurization. Significantly, the overwhelmingly bulk of the reduction in both porosity and permeability occurs over the first 15 MPa of applied effective pressure. This observation, together with the hysteresis, strongly suggests that the main mechanism of deformation is inelastic pore collapse. In a similar manner to the Etna basalt, Campi Flegrei tuff exhibited significant decrease in velocity after thermal stressing. However, in this case, the main decrease occurred over the temperature range 300° to 600°C. This suggests that the most likely mechanism is thermal cracking induced by dehydration of the zeolite phases present.
These results clearly demonstrate the importance of understanding the details of specific rock physical properties, and how they change in response to pressure and temperature, in interpreting models derived from the results of field-scale monitoring of active volcanoes.

S22B MCC: Level 1 Tuesday 1330h

The Fate of Seismic Waves: Measurement and Interpretation of Q of the Earth II Posters *(joint with T, DI)*

Presiding: **L Warren,** University of California, San Diego**; D McNamara,** U.S. Geological Survey

S22B-0441 1330h POSTER

The Reference Frequency of Teleseismic Body Waves

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Anelasticity of the Earth causes physical dispersion of seismic waves. Our question is addressed to how to choose the reference frequency of physical dispersion, f_0, consistent with the extensive data sets of hand-picked body wave arrival times compiled through the long history of seismology. The appropriate choice of reference frequency is also important to determine arrival times of body waves, especially later arrival times, from broadband seismograms by fitting observed to synthetic waveforms. Setting the reference frequency to be the conventional one, 1 Hz, we measured *S-P* differential travel times by waveform fitting. We found a systematic discrepancy between the measured and hand-picked *S-P* times that can be removed by changing f_0 from 1 Hz to 2 Hz. This change of f_0 requires a correction in Q of the *PREM* model: 1) if Q is strictly frequency-independent, we need a 15 % increase in Q value, or 2) if Q is fixed to the value given by *PREM* at a period of 200 s, we need to introduce a small frequency-dependence in Q, where the dependence is expressed by the power law with an exponent of 0.04.

S22B-0442 1330h POSTER

Characterization of Dispersive Rayleigh Waves Using Wavelet Transform.

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This contribution covers various aspect of the characterization of dispersive Rayleigh waves using the Continuous Wavelet Transform (CWT). We particularly show how to use the CWT with multicomponent seismic data to extract time and frequency dependent polarization attributes. In addition, we investigate the