Range Province, the Pacific Northwest, and the Mountain States are all tectonically active regions and have frequency-dependent functions of $Q = 152(\pm 37)\ f^{\,0.72}\ (\pm 0.16)$, $Q = 105(\pm 26)\ f^{\,0.67}\ (\pm 0.16)$, $Q = 200(\pm 40)\ f^{\,0.679}\ (\pm 0.12)$, $Q = 152(\pm 49)\ f^{\,0.76}\ (\pm 0.18)$, and $Q = 166(\pm 37)\ f^{\,0.61}\ (\pm 0.14)$ respectively. The remaining two regions, Central U.S. and Northeastern U.S., fall into the stable tectonic region category and have frequency-dependent functions of $Q = 640(\pm 225)\ f^{\,0.344}\ (\pm 0.22)$ and $Q = 650(\pm 143)\ f^{\,0.36}\ (\pm 0.14)$. Both scattering and intrinsic attenuation mechanisms are likely to play an equal role for the range of frequencies considered in this study.

S22B-0460 1330h POSTER

Factors affecting the evaluation of scattering attenuation

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The scattering of waves is a near ubiquitous phenomenon in the earth and has been widely studied in seismology. Scattering attenuation can be calculated by a formulation based on an approximation allowing for both multiple forward-scattering and a single backscattering process. In this approximation possible interaction between scattering in the forward and backward directions is neglected. In this study we examine the effects of multiple scattering and propagation distance on the evaluation of scattering attenuation through numerical experiments on highly heterogeneous models. A change in propagation distance results in the variation of the radius of the Fresnel zone, which controls the interference volume of scattered waves. We find that primary waves display a characteristic attenuation pattern depending on both the frequency content of the incident waves and the change in propagation distance. On the other hand, the coda energy is determined to be nearly constant for changes in the random model and perturbation level.

S22C MCC: 3009 Tuesday 1340h

Mechanical Strength of the Continental Lithosphere I *(joint with T, V)*

Presiding: **W Chen,** University of Illinois, Urbana-Champaign**; B Evans,** Massachusetts Institute of Technology

S22C-01 1340h INVITED

Metamorphism, Metastability, Mechanical Strength, and the Support of Mountain Belts

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We explore links between geophysical observations related to mechanical strength of the lithosphere and geological observations of metamorphism and metastability in the lower continental crust. Our recent studies of elastic thickness (T_e), determined from gravity measurements, and seismogenic thickness (T_e), determined from teleseismic waveforms, led to the view that everywhere on the continents $T_e < T_s$ and that all significant long-term strength of the continental lithosphere resides in a single seismogenic layer within the crust. We found no significant evidence for teleseismically-recorded earthquakes in the continental mantle, and we suspect their absence is related to small amounts of water in nominally anhydrous mineral phases. The strong, seismically active, lower crust of northern India appears to underthrust much of southern Tibet, where the crust is up to 80 km thick. Several authors have pointed out that the lower crust in this region must consist of granulite, not eclogite. Psuedotachylites that formed in lower continental crust under eclogite conditions in southern Norway are ancient analogues of earthquakes that occur today in the lower crust of southern Tibet at depths of 70-80 km. These psuedotachylites show that the dry granulite host rocks in which they occur were metastable at pressures 10–15 kbar beyond their equilibrium range, and that their partial conversion to eclogite was controlled by water infiltration along fractures. The change from granulite to eclogite was accompanied by a dramatic loss of mechanical strength, and a change in deformation style from localised brittle failure to distributed ductile flow. We suspect the same processes observed in Norway are occurring today beneath S. Tibet. Argument by analogy suggests that: (1) earthquakes at depths of 70-80 km beneath S. Tibet occur in the dry, strong, granulite lower crust of the Indian shield; (2) those earthquakes represent the start of a process that will eventually convert, and possibly remove, the lower crust by eclogitization; (3) the sequence of metamorphic and mechanical changes is driven, and limited by, the supply of water — probably from the underlying mantle of the Indian shield and originating from the breakdown of hydrous mantle phases. In this view, the rheology of the continental lithosphere in S. Tibet is controlled by composition, rather than by temperature, and suggests that the support of the highest mountains on Earth would not be possible without the metastability of dry continental lower crust.

S22C-02 1355h

Earthquake Focal Depths and Crustal Structure of Northern India: Implications for Crustal Rheology

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Most intraplate continental earthquakes occur in the upper ∼15 km of the crust but occasionally earthquakes occur at deeper levels beneath the continents in some regions. This observation coupled with laboratory measurements of rock properties as a function of temperature and pressure, led to a model for the continental crust consisting of a brittle upper layer and a weak lower layer, overlying a brittle uppermost mantle. Key observations leading to this model came from earthquake foci and crustal structure in northern India. We re-examine these observations. We use receiver function and published refraction/reflection results to determine the variation in crustal structure of India. We find that the crust beneath the south Indian shield is relatively uniform with a thickness of $\sim 36 \pm 2$ km, but the north Indian crust thickens to about ∼50 km as a result of the down-bending of the Indian plate as it thrust beneath the Himalaya and southern Tibet. The Moho of the Indian crust beneath southern Tibet is at ∼85 km depth. We redetermine focal depths for earthquakes in northern India using this crustal model. For recent events we determine focal depths using waveform modelling or from the timing of depth phases on broadband waveforms. We correct the foci of published event hypocenters using our crustal velocity model. Earthquakes occur to ∼35 km depth in central India, ∼50 km depth beneath the Himalaya, and ∼80 km depth below southern Tibet. All major earthquakes across northern India and southern Tibet occur in the crust and there is no evidence for significant sub-Moho seismicity beneath northern India and southern Tibet.

S22C-03 1410h

Depths of Earthquakes in the Central Tien Shan

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Using a variety of techniques, we relocated local and regional events recorded by the GHENGIS deployment of Broad Band sensors in the central Tien Shan from 1997-2000 in order to determine the extent to which earthquakes occur within the lower crust in the Tien Shan and surrounding regions. We generated probability density functions using a new spherical coordinate adaptation of the Eikonal Equation solver in combination with refined tomographic images which should provide accurate estimates of travel time in this complicated structure. We also used a new algorithm based on the Progressive Multiple Event Location (PMEL) that associates each event in the catalog with one or more control points in a 3D grid and locates these events with PMEL. The implementation allows us to resolve the traditional bias problem by folding in anomalies computed from a 3D model through a set of matrix projectors. These relocation efforts significantly improve the spatial resolution of the GHENGIS catalog. We find that while hypocenters from some regions where lower crustal earthquakes were previously reported were in fact poorly constrained, there appear to be several well constrained depths in the central Tien Shan south of Lake Issyk-Kul, and a large number near the Jiashi region of western China. A combination of tomographic and receiver function images suggests that these events are clearly located in the lower crust.

S22C-04 1425h

New Evidence for Strong Lithospheric Mantle: Mantle Earthquakes beneath the Himalayan-Tibetan Collision Zone

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The mechanical strength of lithospheric mantle beneath continents has far-reaching implications for understanding continental dynamics. For two decades, one of the key evidence for a strong lithospheric mantle is the occurrence of intra-continental earthquakes in the mantle, originally discovered beneath southern Tibet in 1981 (Chen et al., JGR, p. 2863). To a large extent, recent debate on this issue hinges on whether BOTH focal depths and crustal thickness are well enough determined in the same region to resolve if earthquakes near the Moho occurred in the mantle. We present a significant amount of new data and a comprehensive compilation of focal depths, fault plane solutions, and crustal thickness in and around the Himalayan-Tibetan collision zone to show that there are a number of mantle earthquakes, reaching a body-wave magnitude of 6, beneath the western Himalayan syntaxis, the western Kunlun, and southern Tibet (near Xigaze). Focal depths for some of these earthquakes reach over 100 km, as evidenced by matching broadband (high-resolution) waveforms. Frequent occurrence of intra-continental earthquakes in the mantle is clear, in situ, evidence that the lithospheric mantle is strong enough to accumulate elastic strain under geological strain rates. (Supported by NSF Continental Dynamics Program, Project Hi-CLIMB.)

URL: http://www.uiuc.edu/∼wpchen

S22C-05 1440h

Rheological Consequences of Rapid Erosion in Active Orogens

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It has long been recognized that erosion can influence the geodynamics of an orogen by redistributing mass. However, only recently has it become appreciated that rapid exhumation can locally alter the three-dimensional thermal structure of the crust, profoundly changing its rheology and weakening portions of the crustal profile. This process in turn permits feedbacks between erosion, rheology, and deformation. Specifically, based on geological and geophysical observations at Nanga Parbat in the northwestern Himalaya, we have proposed the "tectonic aneurysm" model, in which significant erosion (at Nanga Parbat, along the large Indus River valley) is sufficient to weaken the crust and divert crustal flow into the region. This in turn facilitates coupled rock uplift and erosion, which further weaken the crust as the shallow thermal gradient steepens, localizing and enhancing deformation. Geological observations at the Nanga Parbat antiform in support of this model include a concentric distribution of metamorphic facies distribution with high-T/low-P granulites at the center, a bulls-eye distribution of very young cooling ages and Neogene decompression melts, and the prevalence of compressional deformation for all young and active structures (which young towards the interior of the antiform). Geophsyical data in the form of dense seismic tomography, distribution of microseismicity, and magnetotelluric measurements document a volume of warm, weak, and resistive crust localized beneath the antiform, none of which appears to be molten to any significant degree. Three-dimensional mechanical models of active incision into a lithosphere with thermally activated lower crust can initialize the aneurysm behavior when fluvial incision occurs along a valley with approximately the same width as the thickness of the frictional upper crust. As the aneurysm grows through positive feedback of advective heating and thermal weakening, the rheological effect becomes dominant over the topographic effect of the incising valley and extreme topography can result. The implications of aneurysm behavior for the integrated strength of a lithosphere with a thermally activated lower crust arise from the sensitivity of integrated strength to the square of the thickness of the upper frictional layer. Aneurysm behavior observed in the Himalayan syntaxes imposes constraints on the rheology of the lower crust as well. In order to concentrate vertical displacement into the thermally weakening region, the lower crust must not be relatively weak, precluding a widespread zone of partial melt within the lower crust upstream of the aneurysm. In general, we hypothesize that the rheology and morphology of convergent plate boundaries will be strongly influenced by any mechanism of localized voracious erosion. In the somewhat different tectonic setting of the eastern Himalayan syntaxis, similar large-magnitude surface processes seem to be producing an antiformal structure localized at Namche Barwa near the dramatic knickpoint on the Tsangpo River. The presence of extreme topography at a plate corner, preliminary field observations, and geochronological measurements suggest development of aneurysm behavior is occurring here as well. The St. Elias Range in southeastern Alaska, developed in the presence of strong coupling between glacial erosion and local uplift related to oblique plate convergence, represents another case where we would predict such behavior.

S22C-06 1455h INVITED

Flexural Strength Of Continental Lithosphere: What? Again? Don't We Know All About This Already?

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A major controversy continues to exist concerning the flexural strength of the continental lithosphere despite 20+ years of active research on the subject. Lithospheric strength is often expressed as an effective elastic thickness (Te), an enginnering concept that relates the flexure of a thin elastic plate overlying a fluid substrate to its thickness. Te is used to represent the flexural strength and mechanical behavior of the lithosphere in a depth-averaged sense. Attempts to constrain Te accurately are commonly thwarted by an inadequate knowledge of load distribution (either surface or subsurface), lateral variations in Te, or appropriate geological and geophysical constraints. Two approaches are used to map the flexural strength of the lithosphere: 1) Inverse gravity admittance and coherence techniques, which exploit the statistical relationship between topography and gravity anomalies; and 2) Forward modeling strategies that attempt to model the architecture of extensional and foreland basins and their respective free-air gravity anomalies. In the latter, load amplitude and distribution are constrained by sediment thickness, stratal relationships, and the geological and tectonic history of the basin. In the former, large 2D and often significantly incomplete data sets are Fourier transformed and used with approximations for surface and subsurface loading ratios to map Te. Forward modeling of simple loading systems (e.g. rift flank topography and foreland basin architecture) and the flexural response to serendipitous surface loads (e.g. Kilimanjaro and Mt. Erebus) is probably the most reliable approach to estimate Te. The long-term temporal behavior of Te is provided by analyses using the wavelength and amplitude of free-air gravity anomalies observed in many cratons (e.g. central Australia and Brazil) and the geometry of Proterozoic foreland basins. The present failure to find a straightforward relationship between Te and the thermal structure of the continental lithosphere is likely a consequence of an incomplete, if not compromised, database of continental Te values. Research needs to concentrate on improving considerably the quality of Te estimates before statements of weak continental mantle, relationships between Te and seismogenic zone thickness, and the rheological zonation of the lithosphere can be assessed reliably.

S22C-07 1510h

The Influence of Loads Without Topographic Expression and Edge Effects on Estimates of the Elastic Thickness of Continents

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The elastic thickness T_e of continental lithosphere is of great importance because it controls the mechanical behaviour of continents. In tectonically active regions there is general agreement that it is small, but estimates for shields still differ by as much as a factor of five. Estimates from Bouguer coherence often exceed 100 km, whereas those from the shape of the flexural gravity anomalies are often less than 20 km. The reason why the Bouguer coherence gives such large values of T_e is because erosion produces loads with no topographic expression, which are therefore incoherent with the topography. However, they do have a coherence of 1 between their surface and internal components. Though such loads are assumed to be absent when estimates of T_e are obtained by the standard methods, they dominate the gravity field over most shields. Though in-plane stresses have an important effect on the stress state of the continental lithosphere, they produce negligible changes in the estimates of T_e. Gravity anomalies due to edge effects at the margins of plateaus also have a minor influence on such estimates when their value exceeds 15-20 km.

S22C-08 1525h

Deep Seismic Imaging of an Active Foreland Basin: Implications for Flexural Models

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The South Falkland basin is a partially filled, active, foreland basin located at the southern edge of the Falkland Plateau. It was formed by flexure of the South American plate as a result of loading by the northern edge of the Scotia plate. Flexure probably started in the Paleogene and continues to the present day. The entire region is submarine and the detailed structure of this basin is clearly imaged on shallow reflection data. Admittance analysis of free-air gravity and bathymetry together with gravity and basement profile modelling suggest that the elastic thickness is 10–20 km. Recently, we have acquired and processed a deep seismic reflection profile which crosses the foreland basin and the zone of active collision. This line was shot to 18 seconds two-way travel time using a 5600 cubic inch airgun array and a 6 km streamer. These new data have yielded spectacular images of the active foreland basin and of the adjacent plateaux. The most striking features are a clearly imaged Moho and a set of highly reflective normal faults which penetrate to about 20 km depth. We can show that these normal faults were active during the process of plate flexure. Their existence, depth of penetration and reflectivity raise important questions about the applicability of elastic models to foreland basin formation. Here we explore alternative models which can account for these new observations without requiring the existence of large elastic stresses.

S22D MCC: 3011 Tuesday 1340h

Earthquake Location: Applications and Developments of New Techniques II *(joint with NG)*

Presiding: **C A Rowe,** Los Alamos National Laboratory; **D R Shelly,** Stanford University

S22D-01 1345h INVITED

Detection of Uncertain Signals

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Relative location of events with highly similar waveforms can be made extremely precise through the use of correlation relative picks. Groups of events susceptible to correlation picking may be identified by cluster analysis using waveform correlation as a clustering metric. Frequently, waveform correlation clustering is used to sift catalogs or lists of STA/LTA detections for events that are correlation picking candidates. An alternative approach is to use correlation detectors to identify groups of related events that are guaranteed to have similar waveforms. Correlation detectors have the additional advantage of greater sensitivity than simple energy detectors, i.e. of much higher probabilities of detection at a fixed false alarm rate under threshold detection conditions. They have the potential to detect smaller correlatable events, and to automate the detection of such events. The similarity of waveforms from related events declines due to variations in source mechanism, source time history and source location. The performance of correlation detectors declines significantly as the uncertainty of the waveform to be detected grows. It is desirable to develop detectors that retain much of the sensitivity of correlation detectors while reducing the loss of performance due to signal uncertainty. Subspace detectors offer one approach to manage this tradeoff. These algorithms detect signals that fall within a subspace of desired signals, represented by a waveform basis. The basis can be chosen to represent the range of uncertainty in the signals to be detected (or conversely, the range of knowledge available about the signals). With this approach it is possible to generate a family of detectors that grade in small steps from a correlation detector, when the signal to be detected is known perfectly, to a simple energy (STA/LTA) detector, when little is known about the signal. This presentation discusses empirical methods for designing subspace detectors, focusing on selecting the order of the subspace representation to maximize the probability of detection at a fixed false alarm rate. The approach is illustrated for the problem of detecting variable mining explosions.

S22D-02 1405h

Calculation of Waveform-based Differential Times with both Cross-correlation and Bispectrum Methods

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Cross-correlation (CC) determined relative time delays, or related differential times, between pairs of seismic events at the same station are often used as input data to improve earthquake relocation results. Researchers generally select those time delays with associated CC coefficients larger than a chosen threshold. When two similar time series are contaminated by correlated noise sources, the relative time delay between them calculated with the CC technique is sometimes not reliable. Noise at a station for different events are expected to be partially correlated due to a combination of constant noise sources with time-varying amplitudes (microseisms, wind or cultural noise) and site response effects. The bispectrum (BS) method performs better with such data by eliminating the effect of correlated Gaussian noise in the third-order spectral domain. In this work, we use both the CC and BS methods to compute the relative time delay between two windowed waveforms of an event pair recorded at the same station. CC is performed only on the bandpass filtered data, while the BS method is applied to both the raw (unfiltered) and filtered waveforms. Because the characteristics of the noise terms in the raw and filtered data are different, the two BS time delay estimates may not always agree with each other. We then use both of them to verify (select or reject) the computed CC time delay, i.e. to check whether the differences between the CC and the two BS estimates are both within a specified limit. The exact verification process for an event pair varies depending on the size of the maximum CC coefficient across all the common stations. This BS verification process can provide quality control over the chosen CC time delays and potentially more differential times for close event pairs. We apply this technique to obtain bispectrum-verified CC differential times for 822 New Zealand earthquakes in the Wellington region. We find that the bispectrum-verified CC time delays provide improved (smaller rms residual and more clustered) earthquake relocation result compared to those selected with the threshold criterion.