

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). Geophysical 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 syntaxis 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 (T_e), an engineering concept that relates the flexure of a thin elastic plate overlying a fluid substrate to its thickness. T_e is used to represent the flexural strength and mechanical behavior of the lithosphere in a depth-averaged sense. Attempts to constrain T_e accurately are commonly thwarted by an inadequate knowledge of load distribution (either surface or subsurface), lateral variations in T_e , 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 T_e . 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. Killimanjaro and Mt. Erebus) is probably the most reliable approach to estimate T_e . The long-term temporal behavior of T_e 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 T_e and the thermal structure of the continental lithosphere is likely a consequence of an incomplete, if not compromised, database of continental T_e values. Research needs to concentrate on improving considerably the quality of T_e estimates before statements of weak continental mantle, relationships between T_e and seismic 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 plateaus. 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,
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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 band-pass 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.

S22D-03 1420h

Kirchhoff Reconstruction for Real-Time Fault Rupture Determination

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We present a method for locating earthquake ruptures in real time using Kirchhoff reconstruction. The method determines not the hypocenter, but the actual shape and dimensions of the earthquake fault rupture. The real time capability to generate a detailed rupture map will provide emergency response teams with information about the region of damage and thereby allow them to optimize the distribution of resources and personnel. In addition, it will allow for rapid deployment of instruments focused on collecting observations of post-seismic activity. Computational time does not scale with event magnitude, so the Kirchhoff reconstruction method can accurately handle earthquakes of any magnitude. The Kirchhoff method uses measurements of ground motion from an array of sensors. A grid is generated covering the area of interest. The ground motion at each grid coordinate is summed based on the measurements at contributing sensor locations and the wave propagation time and distance from these locations. Correlation of the measurements occurs at the grid points that correspond to the trace of the event. Our implementation handles arbitrary grid densities and configurations, allowing high resolution over areas of interest. The method is furthermore independent of any particular sensor geometry. The software is capable of integrating the most detailed rheology or wave velocity model available, in order to achieve greater accuracy. Preliminary results are presented for tests of the method on both simulated and historic data. We demonstrate the robustness of the method with respect to signal noise, and show the level of detail and precision available for example historic events. We intend for the software to be integrated into the TriNet earthquake information system. This will enhance the service TriNet provides to emergency response teams and scientists and researchers assessing the status of seismic activity. The Kirchhoff method can contribute to development of a computerized alert network. The continuous sequence of ground motion images generated by the method provide a rich source of data for further types of science analysis, including the application of various pattern recognition and data mining techniques.

S22D-04 1435h

Locating and Modeling Regional Earthquakes with Broadband Waveform Data

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Retrieving source parameters of small earthquakes ($M_w < 4.5$), including mechanism, depth, location and origin time, relies on local and regional seismic data. Although source characterization for such small events achieves a satisfactory stage in some places with a dense seismic network, such as TriNet, Southern California, a worthy revisit to the historical events in these places or an effective, real-time investigation of small events in many other places, where normally only a few local waveforms plus some short-period recordings are available, is still a problem. To address this issue, we introduce a new type of approach that estimates location, depth, origin time and fault parameters based on 3-component waveform matching in terms of separated Pn1, Rayleigh and Love waves. We show that most local waveforms can be well modeled by a regionalized 1-D model plus different timing corrections for Pn1, Rayleigh and Love waves at relatively long periods, i.e., 4-100 sec for Pn1, and 8-100 sec for surface waves, except for few anomalous paths involving greater structural complexity, meanwhile, these timing corrections reveal similar azimuthal patterns for well-located cluster events, despite their different focal mechanisms. Thus, we can calibrate the paths separately for Pn1, Rayleigh and Love waves with the timing corrections from well-determined events widely recorded by a dense modern seismic network or a temporary PASSCAL experiment. In return, we can locate events and extract

their fault parameters by waveform matching for available waveform data, which could be as less as from two stations, assuming timing corrections from the calibration. The accuracy of the obtained source parameters is subject to the error carried by the events used for the calibration. The detailed method requires a Green's function library constructed from a regionalized 1-D model together with necessary calibration information, and adopts a grid search strategy for both hypercenter and focal mechanism. We show that the whole process can be easily automated and routinely provide reliable source parameter estimates with a couple of broadband stations. Two applications in the Tibet Plateau and Southern California will be presented along with comparisons of results against other methods.

S22D-05 1450h

Constraining hypocentral position by focal mechanism and 3D velocity model

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The quality of earthquake hypocentral position relies on distribution of stations, precision of traveltimes, and quality of the velocity model. In light of recent advance in improved station coverage, cross-correlation time picking, and more detailed 3D velocity models, I will discuss two approaches to further improve the hypocentral determination. The first is a joint determination of hypocenters with first-motion focal mechanisms. While the hypocentral determination suffers from the tradeoff between focal depth and origin time, focal mechanism solution depends on the hypocentral position but not the origin time. Hence a joint determination of both hypocenter and focal mechanism could improve both solutions. Since the first-motion polarity data is now available at many stations, the joint process is very effective, as shown by tests on over 40,000 earthquakes in southern California. The second approach is a thorough evaluation of the impact of 3D velocity model on the hypocentral determination, particularly in some general scenarios where hypocentral position can be systematically biased by the model error. One such scenario is near the edge of a basin, where the wedge-shaped low velocity basin is difficult to be constrained accurately by most tomographic methods. In this case the location of the basement boundary will greatly impact both lateral and depth positions of the earthquakes. I will present a new deformable-layered tomography method that is effective in constraining the basin boundaries. In general, the 3D velocity model shall be determined together with hypocenters and focal mechanisms of most earthquakes.

S22D-06 1505h

Probabilistic earthquake location and 3-D velocity models in routine earthquake location

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Earthquake monitoring agencies, such as local networks or CTBTO, are faced with the dilemma of providing routine earthquake locations in near real-time with high precision and meaningful uncertainty information. Traditionally, routine earthquake locations are obtained from linearized inversion using layered seismic velocity models. This approach is fast and simple. However, uncertainties derived from a linear approximation to a set of non-linear equations can be imprecise, unreliable, or even misleading. In addition, 1-D velocity models are a poor approximation to real Earth structure in tectonically complex regions. In this paper, we discuss the routine location of earthquakes in near real-time with high precision using non-linear, probabilistic location methods and 3-D velocity models. The combination of non-linear, global search algorithms with probabilistic earthquake location provides a fast and reliable tool for earthquake location that can be used with any kind of velocity model. The probabilistic solution to the earthquake location includes a complete description of location uncertainties, which may be irregular and multimodal. We present applications of this approach to determine seismicity in Switzerland and in Yellowstone National Park, WY. Comparing our earthquake locations to earthquake locations obtained using linearized inversion and 1-D velocity models clearly demonstrates the advantages of probabilistic earthquake location and 3-D velocity models. For example, the more complete and reliable uncertainty information of non-linear, probabilistic earthquake location greatly facilitates the identification of poorly constrained hypocenters. Such events

are often not identified in linearized earthquake location, since the location uncertainties are determined with a simplified, localized and approximate Gaussian statistic.

S22D-07 1520h INVITED

Bayesian Location of Seismic Sequences in 3D Media

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We have developed a method for the Bayesian location of seismic sequences in three dimensional heterogeneous velocity models. The method is based on a Bayesian algorithm for single earthquake location. Joint location of seismic sequences is performed by adding together the probability density functions for individual earthquake locations. One of the main features of the method is the possibility to accumulate travel times in the heterogeneous model, as a function of both the seismic stations and of the grid points simulating the seismogenic volume. The possibility to separate the travel time computation, performed just once, from the location process, is an attractive feature for implementing fast location procedures in 3D models, for instance for surveillance purposes. Probabilistic location of seismic sequences, visualised in terms of contours of earthquake density, moment and energy release etc., can be obtained to give much more seismotectonic insight than classical location algorithms displayed with dots on maps. The continuous character of the output quantities is particularly indicated for seismic network testing purposes. It is in fact possible to compute the response of the location procedure, given the seismic network geometry, to various input earthquake distributions. Some applications of the method are also shown in this work, both to the location of synthetic earthquakes end of real sequences, in volcanic and tectonic areas.

S22E MCC: 3009 Tuesday 1600h

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

Presiding: F J Simons, Princeton University; M R Drury, Utrecht University

S22E-01 1600h INVITED

Rheological Stratification of the Continental Lithosphere: Constraints from Space Geodesy

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Postseismic transient deformation, isostatic rebound from removal of pluvial lake loads, and lithospheric deflection due to reservoir impoundment are each converging on consistent rheological models for the crust and upper mantle of actively deforming continental regions. These results imply a strong elastic crust 25-40 km thick overlain by a viscoelastic substrate with an effective viscosity of 10^{18} to 10^{19} Pa-s. The most surprising result of these studies is that the upper mantle is weaker than the lower crust. However, the lower crust in these regions may deform by ductile flow on longer time scales, and the data provide a lower bound of 10^{20} Pa-s for its effective viscosity. This bound on lower crustal viscosity is consistent with spectral admittance studies of the gravity field and its relation to topography in the western U. S. (Lowry et al., 2000). These results indicate effective elastic lithospheric thickness is 5-15 km in the same regions where the post-loading results indicate the entire crust is strong over about 10 to 10,000 years. Recent (and not so recent) relevant results include: (1) Deformation imaged by InSAR and GPS following the 1992 Landers and 1999 Hector Mine, California earthquakes; (2) Leveling surveys following the 1959 $M=7.3$ Hebgen Lake, Montana earthquake; (3) Isostatic rebound of Lake Bonneville, Utah; (4) Leveling surveys following filling of Lake Mead, Arizona in 1935. Postseismic transient deformation observed following several other recent large earthquakes provides potential constraints on bulk rheology of the lithosphere. However, deformation following events at major plate boundaries, including the 1993 Hokkaido-oki ($M=7.8$), 1999 Taiwan