numerical solutions for the slip development. Remarkably, predictions of the simple energy approach are in reasonable quantitative agreement with them and give all qualitative features correctly. Principal results are as follows: If $n > 2/3$, the behavior is qualitatively similar to that for $n = 1$ (linear case). A slipping region develops gradually with increasing loading until it reaches the critical length above which the system becomes unstable. Beyond that critical length, an unstable equilibrium branch commences for which the load must decrease to continue to grow the slip and size of the slipping region. If $n > 1$, there exists a maximum allowable length of the slipping region, terminating the branch of unstable equilibrium states beginning at the critical length. If $n < 2/3$, like suggested by the observations, the analysis indicates that upon initiation of slip the loading must be decreased in order to expand the slipping region. That is, an unstable equilibrium branch initiates at slip $\delta = 0^+$, and hence the results suggest that instability will occur as soon as the peaked value of the loading stress reaches the strength τ_p. This, however, is a prediction based on using the power law starting at $\delta = 0^+$, whereas the observational results underlying it correspond to an amount of slip that is already greater than the sub-mm range of slip at instability inferred in laboratory studies. In this $n < 2/3$ range, the unstable equilibrium branch ultimately stabilizes with increasing length of the slipping zone, in that the loading must start to increase again to grow the slipping region further.

S61E-07 1000h

Frictional Heating of Pore Fluid Produces Complete Stress Drop in Large Earthquakes

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Heat generated in a slip zone during an earthquake can raise fluid pressure and thereby reduce frictional resistance to slip. The amount of fluid pressure rise depends on the associated fluid flow. Heat generated at a given time produces fluid pressure which decreases inversely with the square root of hydraulic diffusivity times elapsed time. If the slip velocity function is crack-like, there is a prompt fluid pressure rise at the onset of slip, followed by a slower increase. The stress drop associated with the prompt fluid pressure rise increases with rupture propagation distance. The threshold propagation distance at which thermally-induced stress drop starts to dominate over frictionally-induced stress drop is proportional to hydraulic diffusivity. If hydraulic diffusivity is 0.02 m2/s, estimated from borehole samples of fault-zone material, the threshold propagation distance is 300 m. The stress wave in an earthquake will induce an unknown amount of dilatancy and will increase hydraulic diffusivity, both of which will lessen the fluid pressure effect. Nevertheless, if hydraulic diffusivity is no more than two orders of magnitude larger than the laboratory value, then stress drop is complete in large earthquakes.

S61E-08 1035h

Insights on Fault Behaviour From the Seismic Nucleation Phase

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Recent attempts have been done to retrieve such constitutive properties as slip weakening critical slip D_c from seismological data. In the framework of a model first proposed by Ionescu and Campillo (1997), we analyze seismograms featuring a nucleation phase and we show how these observations can help to constrain the constitutive parameters of the fault.

The model predicts an exponential growth of the seismic moment during the unstable dynamic nucleation phase: $M_0(t) \propto \exp(s_m t)$. The growth rate s_m is related to the weakening rate of an assumed linear slip weakening friction law or, in a more general context, to the effective weakening rate of the fault and also the effective properties of the surrounding fault zone. This exponential behaviour implies an exponential rise of seismograms allowing to a direct measure of s_m by seismological, remote, means. We first illustrate the measure of s_m from recordings of the Kobe earthquake, finding $s_m \approx 1/150$ Hz. Consistency is checked by using stations at different epicentral distances. Combining this measure with independent estimates of fracture energy and borehole observations of the structure of the Nojima fault zone, we estimate $D_c = 11$ cm for the nucleation of this earthquake and we assess the role of the structure of the fault zone during nucleation.

S61E-09 1050h

A Common Origin for Aftershocks, Foreshocks, and Mutliplets

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It is well known that many earthquakes trigger aftershocks, subsequent (and traditionally smaller) earthquakes which are nearby in time and space. It has been debated whether other phenomena that involve earthquake clustering, such as foreshock-mainshock pairs and earthquake doublets and multiplets simply result from the same process that causes aftershocks, or are a separate type of special phenomena. Using the CNSS, CMT, and MLI catalogs we demonstrate that for earthquakes in California and the Solomon Islands, the rate at which foreshocks trigger mainshocks, and the rate at which multiplets occur, are in agreement with the rate at which mainshocks trigger aftershocks. We also find that this agreement in rate is highly unlikely to result from random chance, and is similarly unlikely to result from any triggering of incidental seismicity by the growing nucleation zone of a large earthquake. Thus our statistical analysis indicates that only a single model of earthquake triggering is required to explain aftershocks, foreshocks, and multiplets.

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S61E-10 1105h

Influence of Fault Bends on the Growth of Dynamic Shear Ruptures

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Earthquake ruptures are modeled as dynamically propagating shear cracks with the aim of gaining insight into the physical mechanisms governing their arrest or, otherwise, the often observed variations in rupture speeds. Fault bends have been proposed as being a major cause for these variations. Following this line of reasoning, the existence of deviations from fault planarity is embraced as the main focus of this study. Asymmetric impact is used to generate shear loading and to propagate dynamic mode-II cracks along the bonded interfaces of two otherwise identical homogeneous constituents. Secondary planes inclined at various angles are also introduced to represent fault bends or kinks. The experiments show that certain fault bend inclinations are favored as alternate paths for rupture continuation, whereas others suppress further motion of the incoming rupture. The asymptotic elastodynamic stress fields at the tip of the growing rupture are used to develop two criteria for rupture propagation or arrest at the kinked interfaces. These criteria correlate very well with the experimental results. Since most field evidence suggests that the average rupture speeds during crustal earthquakes are sub-Rayleigh, this work first focuses on incoming rupture speeds that are just below the Rayleigh wave speed. Reports of intersonic rupture speeds having surfaced recently, experiments and analyses are also performed within that speed regime.

S61E-11 1120h

Nonrandom Clustering of M4+ Seismicity in Northern and Central California

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A catalog of M4+ earthquakes in northern California and northwestern Nevada was declustered of aftershocks, foreshocks and triggered events and then searched for non-Poissonian elements. This catalog covers the region from 37.0 deg N to 44.5 deg N and the years 1910 to 2001. For this time period the Poisson probability of one or more M4+ events in any 10-day period in this region is 35%. A similar pattern is seen in the seismicity before 1967. Since 1968, 40.3% of the M4+ events in northeastern California and northwestern Nevada were followed by another M4+ event within 10 days somewhere in the study region. Similarly, since 1968, 39.3% of the M4+ events in the San Andreas region of northwestern California were followed by another M4+ event within 10 days somewhere in the study region. Thus, for these areas M4+ earthquakes occur more frequently within short time periods than would be expected from temporally random seismicity. A second catalog of M4+ earthquakes in central California was also declustered of aftershocks, foreshocks and triggered events and then analyzed for unusual spatio-temporal patterns. This catalog covers the region from 34.0 deg N to 40.0 deg N and the years 1932 to 2000. Of 39 M4+ independent mainshocks at Long Valley, California since 1932, 23 occurred within 10 days of an M4+ somewhere in the region of the central San Andreas Fault. This suggests that there is a link between the seismicity of the central San Andreas and Long Valley. Curiously, only five M4+ events at Long Valley since 1932 occurred within 10 days of an M4+ event at or near the Coso geothermermal area..

S61E-12 1135h

Clustering of Major Earthquakes on Individual Faults: Characterization Via a Single Non-Dimensional Parameter

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On a single fault segment, geologic and paleoseismic evidence from locations such as the Basin and Range [*Friedrich et al.* JGR, in review] and Dead Sea Transform [*Marco et al.*, JGR, 1996] indicate that occurrence of major earthquakes in time is often extremely heterogeneous and may exhibit temporal clustering. We consider major earthquake clustering as the occurrence of multiple event sequences with intra-cluster inter-event times much shorter than the average time between clusters. Here we investigate the role of time-dependent postseismic stress transfer, in combination with environmental noise in the parameters that govern fault behavior, in controlling major earthquake clustering.

The role of long-term postseismic transients can be investigated using a pseudo-1D spring-dashpot-slider model of time-dependent stress transfer in a 3-layer lithosphere. To simulate a 2D lithosphere, stress is conserved coseismically and is transferred from the elastic crust to underlying Maxwell viscoelastic elements representing the lower crust/upper mantle. Interseismically, lithospheric layers are coupled so that postseismic stress concentrations in the lower crust/upper mantle may be dissipated via stress transfer between layers. Normally distributed random noise is added to the fault failure criteria to simulate environmental noise.

The equations that govern the system behavior can be non-dimensionalized in terms of various rheological parameters, average earthquake stress drop, $\Delta\tau_{eq}$, effective viscosity, η_{eff}, and the characteristic long-term strain rate across the fault, $\dot{\epsilon}_{flt}$. This non-dimensionalization results in a single controlling parameter W, where W is defined as $\Delta\tau_{eq}/\eta_{eff}\dot{\epsilon}_{flt}$. As W increases, earthquake clustering increases. For a reasonable choice of rheologies and input noise with a coefficient of variation (C_v = standard deviation/mean) of 0.20, W = 1, 10, and 100 yields earthquake recurrence intervals with C_v = 0.217, 0.31, and 1.29, respectively. Qualitatively, clustering phenomena dominates the system behavior when recurrence intervals are distributed with $C_v > \sim 0.5$.

S62A MCC: Hall C Saturday 1330h

Challenges of Regional Monitoring Posters *(joint with PA)*

Presiding: **M P Flanagan,** Lawrence Livermore National Laboratory**; M Tolstoy,** Lamont-Doherty Earth Observatory of Columbia University

S62A-1165 1330h POSTER

Theoretical Analysis of Seismic Wave Imaging Using SAR

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Synthetic Aperture Radar interferometry (InSAR) has been used in many instances to observe surface deformation resulting from seismic events. This is done by comparison of images acquired before and after the seismic event. Dr. Paul Vincent of Lawrence Livermore National Laboratory has hypothesized that SAR could additionally be used to image seismic surface waves as they propagate, i.e. in real time during the seismic event. I present a theoretical analysis that substantiates this conjecture in detail and demonstrates to what degree an InSAR image of an earthquake would be invertible, as a function of both the seismic signal and the radar operational parameters. The inversion would be done in two stages, first from InSAR image to surface deformation of the seismic wave, and second back to the source characteristics of the event. This concept, when demonstrated in practice, will be applicable to seismic research and nuclear test-ban treaty monitoring.

S62A-1166 1330h POSTER

Joint Seismic Waveform and InSAR Modeling of Moderate Earthquakes in Iran

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Synthetic aperture radar interferometry (InSAR) can detect centimeter size displacements that are induced by earthquakes. For large earthquakes (e.g. Landers, Izmit) joint InSAR and seismic modeling has been very successful. We are exploring the potential of joint seismic waveform modeling for moderate-sized earthquakes (magnitude 5-6.5) where there may not be any visible surface rupture and basic seismic parameters such as depth and location may be uncertain by tens of kilometers. We perform seismic event relocations and regional seismic waveform modeling to obtain focal mechanism and depth information. We compare the seismic results to simple modeling of deformation determined by InSAR. We test these methods on several moderate earthquakes in Iran. For example the Ms 6.5 earthquake on March 3, 1999 shows very little InSAR based surface deformation, which is consistent with our estimate of its depth at 26 km and its thrust mechanism. In contrast the much smaller mb=5.3 earthquake of April 10, 1998 shows several centimeters of surface deformation centered about 20 km south of the seismic locations determined by the NEIC, ISC and the REB. We show this deformation and the seismic data are consistent with a relatively shallow strike-slip mechanism.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

S62A-1167 1330h POSTER

Seismic Source Inversion As A Multiple-Objective Optimization Problem

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Combining independent seismic observations helps produce better solutions to inverse problems. Successful examples include the combination of teleseismic and strong-motion seismograms with geodetic data to constrain fault rupture processes, and the joint inversion of surface-wave dispersion with receiver-function observations. In practice however, each observation brings a set of modeling assumptions and problems, such as sensitivity to un-modeled aspects of earth structure and/or source geometry, or different averaging properties of the true three-dimensional structure. Difficulties arise when the observations conflict and no single solution fits all data best (often as a consequence of necessary modeling assumptions). In this case a decision must be made as to how to weight different data to construct a single scalar misfit metric. Multiple objective optimization (MOO) approaches offer a set of tools to investigate and to solve joint inversions of complementary, but often conflicting data. Most important in these analyses is a broader definition of optimal using the concept of model dominance in light of multiple misfit norms. I illustrate these ideas with an application to a relatively simple nonlinear inversion of time- and frequency-domain seismic signals for earthquake faulting geometry and depth. Using examples from earthquakes in Asia, I show the value the MOO approach offers for investigating problem stability and solution reliability. For each grid search, an optimal set of solutions is derived and then combined to explore the consequences of data weighting. Such decisions may have important consequences in the modeling of small earthquakes using a collection of sparse regional seismograms. The most important benefit of the approach is a better understanding of the consequences of data weighting on the solution. Although illustrated using a simple source inversion problem, the ideas are general and require little extra computation to apply to other problems approached using grid searches. For nonlinear inversion problems, a MOO approach represents a philosophical change from seeking models that minimize a scalar projection of a multiple-objective misfit function to a view where the goal is to map out non-dominated solutions that can be used to explore the range of solutions to multiple-data-set inverse problems.

S62A-1168 1330h POSTER

Lithospheric Structure Beneath The Middle East, Southern Europe, and North Africa

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We simultaneously invert receiver functions and surface-wave group-velocities to better illuminate crustal and upper mantle structure beneath the Middle East, Southern Europe, and North Africa and to expand the existing geophysical/seismological information in this area. Surface-wave dispersion observations can determine average absolute shear velocity variations with depth; receiver functions provide constraints on the travel-time between velocity contrasts and boundary sharpness. The joint inversion of receiver functions and surface-wave dispersion is a practical tool to estimate lithospheric structure because the combination greatly reduces non-uniqueness of the solution. We examined data recorded by 20 permanent and temporary three-component broadband seismic stations located in the Middle East, Southern Europe and North Africa. We computed over 2100 receiver functions from 9969 earthquakes for the period of 1990-2002. We obtained localized group velocities from tomographic analyses with a 2-degree resolution for both Love and Rayleigh waves in the period range from 10 to 100 seconds. In our initial step of analysis, we stacked the receiver functions using the thickness-Vp/Vs ratio estimation procedure of Zhu and Kanamori [2000]. This initial analysis provides reasonable constraints on thickness and Poissons ratio (which trade-off) for each station and helps identify stations on top of complex structures (where simple plane-layered methods will fail). For most stations crustal thickness and Poissons ratio vary as a function of back azimuth. Values range from a minimum thickness 24-28 km and a relatively low Poissons ratio of 0.23 (all are less than 0.26) from four stations in Western Europe to a maximum thickness 36-44 km and Poissons ratio around 0.26 in the African archean cratons. The majority of our crustal thickness estimates are consistent with previous geophysical/seismological work, but there are a few differences. In this presentation, we summarize the Poissons ratio work and present the results of joint surface-wave dispersion and receiver function inversions for these stations.

S62A-1169 1330h POSTER

A Study of Regional Waveform Calibration in the Eastern Mediterranean Region.

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We modeled Pnl phases from several moderate magnitude events in the eastern Mediterranean to test methods and to develop path calibrations for source determination. The study region spanning from the eastern part of the Hellenic arc to the eastern Anatolian fault is mostly interested by moderate earthquakes, that can produce relevant damages. The selected area consists of several tectonic environment, which produces increased level of difficulty in waveform modeling.

The results of this study are useful for the analysis of regional seismicity and for seismic hazard as well, in particular because very few broadband seismic stations are available in the selected area. The obtained velocity model gives a 30 km crustal tickness and low upper mantle velocities. The applied inversion procedure to determine the source mechanism has been successful, also in terms of discrimination of depth, for the entire range of selected paths. We conclude that using the true calibration of the seismic structure and high quality broadband data, it is possible to determine the seismic source in terms of mechanism, even with a single station.

S62A-1170 1330h POSTER

Crustal Structure Beneath the Tibetan Plateau Using Receiver Functions and Surface Wave Dispersion Observations

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Despite substantial effort, some uncertainty in the bulk crustal geology beneath the Tibetan Plateau remains. Recent experiments have provided a wealth of seismic data for investigating structures within the Tibetan lithosphere. We investigate the subsurface Tibetan geology using receiver functions from the 1991-1992 Passive Source and the 1997-1999 INDEPTH III experiments. We have completed joint inversions of surface-wave dispersion and select receiver functions for the older data and plan to explore and invert receiver functions from select stations from the INDEPTH III experiment. The combination of receiver functions with surface-wave dispersion does much to improve P- and S-velocity structure resolution, but modeling is most appropriate for relatively simple structures. We begin our analyses with the depth-velocity stacking estimation of Zhu and Kanamori [2000] where we attempt to extract thickness, P-velocity, and Vp/Vs ratios compatible with the move-out of the Ps conversion and multiples from velocity contrasts within the lithosphere. Again, the main limitation of the technique is the assumption of a simple structure to insure consistency with a set of straightforward travel-time equations used to compute arrival-time move-out (as a function of incident-wave ray parameter). Poissons ratio values from the 1991-1992 deployment were difficult to extract because of complex structure. The station with simplest response, WNDO, suggests a ratio of 0.28 beneath the north-central Plateau, which is slightly above average for continental crust. These results are lower than some earlier values which suggested that the lower crust beneath central and northern Tibet may contain substantial partial melt. The joint inversion of the simplest available receiver functions, and global long-period and local short-period surface-wave dispersion observations suggests that the crustal thickness for the northern Plateau ranges from 60-70 km (stations ERDO, BUDO, TUNL). Thickness in the southern Tibet is generally the same, although there may exist a thicker crust along the latitude of LHSA. Since we assumed a Poissons ratio equal to 0.28 for these inversions, the results require affirmation or adjustment of that assumption as more analysis proceeds.

S62A-1171 1330h POSTER

Source-Specific Station Corrections in 3-D Earth Models for Seismic Location Calibration in Eastern Asia

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Source-specific station corrections (SSSCs) to travel-time tables have been constructed for International Monitoring System (IMS) stations in Eastern

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Asia by ray tracing in three-dimensional earth structure. Two types of 3-D models have been tested: (1) a model consisting of 22 1-D velocity regions with lateral transition zones between regions and (2) a hybrid model constructed from 7 layer crust model CRUST 2 and Regionalized Upper Mantle (RUM) model. Three-dimensional models were parameterized by tetrahedra, with linear interpolation of velocities between tetrahedron vertices. This parameterization allows analytic integration of ray tracing equations.

The model based 3-D SSSCs were refined by applying a kriging algorithm to travel time residuals for ground truth (GT) events. Validation tests were performed by evaluating travel time residuals and by relocating the GT events, with and without using SSSCs.

S62A-1172 1330h POSTER

Regional Location Calibration in Asia

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This paper presents a spectrum of issues and efforts involved in improving seismic location performance worldwide. Our efforts are largely designed around providing validated, rigorously calibrated travel times, azimuths, and slownesses along with accurate error estimates. To do so entails a significant effort that includes data mining, data integration, database management, developing optimal 1-, 2-, and 3-D Earth models, using the Earth models to predict wave propagation, developing corrections and errors for travel times, azimuths, and slownesses, and validation of all products. Results presented here will focus on Asia. For the region around station MAKZ in north-central Asia we have looked at several tens of published 1-D velocity models. For each model, travel time calculations were performed, predictions for P and S arrivals were established, and the predicted times were compared to the observed. We will present best-fit models for tectonic provinces out to regional distances from MAKZ.

Previous work has shown that Non-stationary Modified Bayesian Kriging of travel time residuals successfully improves regional seismic event location, and this method is being extended to calculate corrections for azimuth and slowness. The ability to krig over 3-D Earth models is also being implemented. In order to produce the most useful corrections, we require accurate ground truth. For this we are continuing efforts to create a location database consisting of the best available seismic event locations and the most accurate and precise travel times. Building this database relies on participation from universities, other NNSA laboratories, and contacts in private industry. Through the kriging procedure we are able to stabilize location algorithms, but the ultimate usefulness of the corrections themselves is directly related to the quality of the ground truth from which the corrections are derived. Indeed, epicentral mislocations from EvLoc using travel time correction surfaces are directly proportional to the location errors of the ground truth used to generate the corrections.

In aseismic regions, corrections for travel time, azimuth, and slowness are predicted from optimal Earth models using one of the following methods, depending on application: TauP, ray bending, reflectivity, or finite difference. We have developed a model-building tool that can incorporate many different types of data, from surfaces (Moho, bathymetry, topography), to local or regional 1-, 2-, and 3-D models, to reflection profiles, to point data. Numbers of layers are defined within prominent sections of the lithosphere, and interpolation between data points is used to create a smooth, self-consistent 3-D Earth model.

S62A-1173 1330h POSTER

Statistical Assessment of Non-stationary Regional Travel-Time Uncertainty

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We develop new methods to assess travel-time prediction uncertainty in aseismic areas. In particular, we assess the ability of 3-D velocity models to better predict regional seismic travel times, relative to 1-D models, as well as quantify the travel time uncertainties. Accurate travel time prediction and uncertainty characterization is essential for properly identifying regional seismic phases and computing seismic event locations with representative error ellipses. To accomplish this we use an *a priori,* 3-D velocity model of Western Eurasia developed at LLNL [*Pasyanos et al.* , 2002] and a dataset of *P* and *Pn* phase picks from a subset of *ISC Bulletin* events that were relocated by *Engdahl et al.* [1998] and have a location accuracy of roughly 15 km. We test the predictive power of the model by computing the median residuals between the observed *P* arrivals and those predicted by 3-D finite difference computations through both our 3-D model and the 1-D *iasp91* model.

Comparing predictions with observations most directly assesses travel-time prediction uncertainty. However, the observations include additional error processes that hamper model error assessment. We develop methods to extract model errors from those errors attributed to calibration-event location uncertainty and phase arrival picking. Model-based approaches are aimed at improving travel-time prediction at regional distance (1.5 to 13 degrees) and at upper-mantle triplication distances (13 to 25 degrees). Prediction accuracy is assessed in a non-stationary framework, and we test both stationary and non-stationary uncertainty models. Although stationary (scalar) uncertainty is most desirable, we find that uncertainty for most models is dependent upon event-station distance. For simple models, uncertainty must be assessed by geographic region. Our 3-D velocity model reduces the overall variance of travel time residuals as well as reducing their non-stationary character. These results demonstrate quantitatively that 3-D velocity models accomplish two goals: improving travel-time prediction, and reducing the non-stationarity of the uncertainties. Such 3-D models and uncertainty characterizations help to achieve location accuracy and computation of representative location error ellipses in a regional monitoring environment, particularly for small events not recorded teleseismically.

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. Contribution UCRL-JC-149858-ABS.

S62A-1174 1330h POSTER

Regional Travel Time Model of Northern Eurasia using Deep Seismic Sounding Data Sets

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First-arrival travel times from a number of Russian Deep Seismic Sounding (DSS) profiles are used to construct a regional travel-time model of Northern Eurasia. We employ a purely empirical method that is a generalization of the existing regionalization techniques and utilizes offset-dependent spatial interpolation of travel times picked from DSS records. The method is based entirely on the observed travel times and allows continuous refinement of the model as additional travel-time data become available. The travel-time field is described as variations of ray parameter in a three dimensional space of geographic coordinates and source-receiver distance. The resulting travel-time model could be applied to travel time calibration performed within the framework of the Comprehensive Test Ban Treaty (CTBT) in two ways: 1) for construction of approximate source-specific station correction surfaces for any location within the region, and 2) as a region-specific reference model that can be used as a background for further calibration effort. By converting the travel times to depth, we also obtain a three-dimensional regional velocity model that provides a description of the general features of the upper mantle in Northern Eurasia.

S62A-1175 1330h POSTER

Surface Scattering as a Source of Teleseismic Arrival Coda

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The seismic coda of short-period arrivals from peaceful nuclear explosions (PNE) is unusually strong and extensive. We model this coda behavior as a result of scattering of seismic waves from near-surface crustal heterogeneities using the Born approximation. Both the source and Green's functions are computed using 1-D reflectivity synthetics in an IASP-91 model. We used different crustal Q parameters in computing sections to compare results with the coda observed in real PNE data. Scattering points of varying scattering strengths were arranged in areal and linear arrays to determine effects of different scattering regions.

We compare the synthetics with the records from PNE profiles Quartz and Craton and derive constraints on the crustal attenuation and scattering potentials. For areal scattering, synthetic records show effective Q values consistent with those specified in the crustal model, while records outside of an areal region exhibit stronger attenuation. Scattering from linear crustal features (e.g., mountain belts) also results in lower coda Q values. Although simplified, this model appears to explain satisfactorily the coda properties of multiple PNE arrivals at regional to teleseismic distances, such as the P-wave, reflections from transition zone discontinuities, and the whispering-gallery mode (the teleseismic Pn).

S62A-1176 1330h POSTER

Teleseismic Pn Coda Modeled as Crustal Scattering

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Teleseismic Pn arrivals with a long, high-amplitude coda are observed to offsets larger than 3000 km along the Peaceful Nuclear Explosion (PNE) seismic profiles Quartz and Ruby, which were recorded in the former Soviet Union. Analysis of the observed data shows that the teleseismic Pn contains significant amounts of energy in the low- (0-2.5 Hz), mid- (2.5-5.0 Hz) and high-frequency (5.0-10 Hz) ranges.

We model the teleseismic Pn arrivals as multiple sub-Moho refractions, which travel over large distances due to a positive vertical upper mantle velocity gradient, which is characteristic for the study area. Crustal scattering is found to fully account for the teleseismic Pn coda. Tests show that it is not necessary to include upper mantle heterogeneity in the seismic models in order to match the key characteristics of the teleseismic Pn.

Our modeling results are based on two-dimensional visco-elastic finite-difference seismic wavefield simulations in 2000 km long and 250 km deep models of the crustal-upper mantle system. The computationally demanding calculations are facilitated by the use of multiprocessor supercomputer systems. Our preferred model of crustal scattering is in agreement with high-resolution wide-angle and normal-incidence seismic data sets collected in other areas, which typically show reflective crustal intervals and an almost transparent uppermost mantle down to about 80-100 km depth.

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Short-Period Surface-Wave Tomography Beneath the Central and Eastern Tibetan Plateau

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Despite significant effort, the mechanism driving the Tibetan Plateau uplift remains controversial because most results are from geophysical studies concentrated on the southern part of Tibet or used data that traverse the Plateau boundary. Data from two PASSCAL experiments, the Tibetan Plateau Passive

Source Seismic Experiment in 1991-1992 and the INDEPTH III experiment in 1997-1999, provide an opportunity to map the subsurface geology and advance our understanding of the Plateaus dynamics and tectonic evolution. We present the results of our efforts to construct least-squares tomographic maps of short-period Love and Rayleigh wave group velocities across the central and eastern Plateau. We only utilize measurements made using stations and events within the Plateau to localize our sensitivity to Plateau structures. Although the short-period dispersion observations cannot not reliably resolve features below the upper crust, they can be combined with other data such as global surface-wave dispersion models and receiver functions to improve resolution throughout the lithosphere. Our inversion is based on observations using a set of 49 shallow events recorded on the 11 stations of the 1991-1992 experiment. We plan to include additional data from INDEPTH III to extend the study area into the central and southern Plateau. For the data for which we have completed the dispersion analysis, event location and origin time appear to cause noticeable scatter in the dispersion curves. This variation is consistent with inconsistency in small-to-moderate size event locations in global earthquake catalogs and in more refined regional locations. We will investigate the potential of an iterative tomographic and epicenter re-location procedure using surface-wave dispersion values to improve the event epicenters. We have made measurements in the period range from 4 to 50 seconds on about 50 events with magnitudes in the 4-to-5 range. As expected, the shortest and longest periods produce a path coverage too sparse for an informative tomographic reconstruction. In the period range from 10 to 40 seconds, the number of measurements for both Rayleigh and Love waves range between 80 and 250, with a spatial distribution sufficient for the tomographic analysis. We plan to experiment with different approaches to improve epicentral locations and to map subsurface geologic variations. Our ultimate goal is localize short-period dispersion measurements that complement other measurements sensitive to Plateau structure such as receiver functions.

S62A-1178 1330h POSTER

Correlation of Lg Waves for Improved Regional Event Location

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Regional event locations often must use only a limited number of phases and stations due to weak signal to noise and sparse station coverage. This is especially true for monitoring work that seeks to locate smaller magnitude seismic events with a handful of regional stations. Because of uncertainties in the Earth's velocity model and the fewer stations used, it becomes important to calibrate these stations with ground truth events to obtain accurate event locations. Lamont is involved in an effort to calibrate 30 International Monitoring System (IMS) stations in eastern Asia. To obtain a set of reference of events, we are employing modern methods of event location using waveform cross correlation and the double-difference technique in China. 74 events have been examined in Xiuyan, China, known for a foreshock sequence enabling prediction of the 1999 M 5.9 mainshock. From a subset of these events, two clusters are observed that have similar Lg waves. Correlation measurements are performed on the seismograms at four openly available, regional CDSN stations archived at IRIS, using long windows on the order of 25 seconds. Internal consistency of the delay measurements is about a tenth of a sample or 7 ms. Filter bands used are from 0.5 to 5 Hz and the stations are from 500 to 1000 km away. A simple double-difference equation is solved only for the epicenter and origin time assuming straight ray paths and a velocity of 3.5 km/sec. Preliminary results indicate that relative locations have better than 1 km precision. The standard deviation of the location residuals is about 0.02 seconds and the major and minor axes of the 95% confidence ellipses are 100 m and 50 m respectively. We compare the locations of these events using only correlations of Lg waves at four regional stations with local network double-difference locations using P-wave picks observed at 100 to 1000 stations. The results are consistent but display considerable improvement using only the waveforms from the sparse network, due to significantly increased measurement precision. Since the absolute position of these events seems to match a fault trace on the surface to within a few kilometers, the locations are considered to be accurate at the 5 km or better level (GT5) and are suitable ground truth events for calibration of IMS stations. Since the Lg wave is the largest amplitude phase on regional seismograms, this procedure may prove useful for improving locations of other small magnitude events using only a few stations.

S62A-1179 1330h POSTER

Improved Location of Earthquake and Nuclear Explosion Clusters Using Teleseismic and Regional Phase Data

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At present most procedures for global seismic bulletin production are reliant upon manual phase pick information, and upon locating events 'one at a time'. We demonstrate considerable improvement in location precision by combining phase picks from global and regional bulletins with accurate travel-time differentials from waveform cross correlation, and by reducing effects of model errors by simultaneously relocating large number of events with the double-difference (DD) method. The residual (or DD) vector is built from travel-time differences of all pair-wise observed phases (including depth phases) at common stations, and is minimized in a weighted iterative least squares procedure by adjusting the vectors connecting nearby events. We are currently applying the global DD algorithm in several areas using the ISC bulletin, the Annual Bulletin of Chinese Earthquakes (ABCE), and digital waveform data from global stations. For the purpose of collecting ground truth information to monitor the nuclear test ban treaty we have relocated 21 underground nuclear explosions at the Lop Nor test site. Relocation results indicate shifts between ISC and DD locations up to a few tens of km, and 90% confidence ellipses in the range of one km where azimuthal data coverage is good and several km where it is sparse. For selected clusters of moderate size earthquakes in China we improve average location precision by more than an order of magnitude compared to the ABCE locations. By correlating these clusters with mapped surface traces from a digitized fault map we obtain the accuracy needed to use many of the new locations to calibrate IMS stations in Eastern Asia. On the science side deep focus earthquakes in the Central Andes are investigated to resolve the detailed structure of seismicity associated with the subducting slab. Preliminary DD locations for a limited set of earthquakes have relative location uncertainties of only a few km, and indicate a sharp, narrow, possibly double-layered Wadati-Benioff zone at around 200 km depth. Similar recent findings in shallow subduction zones indicate that such earthquakes occur in both the oceanic crust and mantle. Earthquakes at around 550 km depth show strong spatial clustering that persists over the 25 year observational period.

S62A-1180 1330h POSTER

Evaluation of the completeness and accuracy of an earthquake catalogue based on hydroacoustic monitoring

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NOAA's Pacific Marine Environment Laboratory (PMEL) produces a catalogue of Pacific Ocean earthquakes based on hydroacoustic monitoring from April 1996. The International Seismological Centre (ISC) worked without referring to the PMEL catalogue for earthquakes through April 2000, so the ISC and PMEL catalogues are independent until then. The PMEL catalogue includes many more intraplate and mid-ocean ridge earthquakes; more than 20 times as many earthquakes as the ISC catalogue in some areas. In some areas ISC earthquakes are nearly a strict subset PMEL earthquakes, but elsewhere many ISC earthquakes are not in the PMEL catalogue. Along the Pacific-Antarctic Plate Boundary (45°-70°S, 110°-180°W), for example, the PMEL catalogue misses out many ISC earthquakes, including a few MW(Harvard)>5 crustal earthquakes. Near the Cocos Ridge (2°-7°N, 81°-88°E) for many of the earthquakes in each catalogue, there is no corresponding earthquake in the other. Among earthquakes that are in both catalogues, location differences may be much greater than the formal location uncertainties. But formal errors are known to underestimate true location errors, so studying the seismic arrival time residuals with respect to the hydroacoucoustic origins and hydroacoustic arrival times residuals with respect to the seismic origins provides a more rigorous evaluation of the intrinsic differences between these two monitoring technologies.

URL: http://www.isc.ac.uk

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Automatic Detection of Secondary Seismic Phases Using Wavelet Transforms

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The accurate location of a seismic event (latitude,longitude, depth) is a key parameter of interest to nuclear monitoring agencies. Accurate, reliable and automatic arrival time determination, specifically for secondary seismic phases (Lg and Pg), is of prime importance for locating seismic events with a mb magnitude range of 2.5 to 4.5. However, because of its complexity, there is no widely accepted method of picking the Lg phase arrival time, either by automated methods or by seismic analysts. A preliminary method of semi-automatic Lg and Pg phase arrival estimation was developed by Tibuleac and Herrin (1999, 2001). We have improved this method and evaluated its performance compared to two other detection algorithms: computation of a cumulative sum of a test statistic (Der and Shumway, 1999) and a detector using autoregressive analysis and the minimum Akaike Information Criterion to estimate the onset time of the signal. For this purpose we have developed a database consisting of well located shallow events, collocated aftershocks and mining explosions, as well as nuclear explosions recorded in a distance range of 100 - 700 km, from three seismic arrays TXAR (Lajitas, Texas), PDAR (Pinedale, Wyoming), NVAR (Mina, Nevada). Preliminary results show that wavelet based methods are a promising and more accurate tool for obtaining reliable estimates of the Lg and Pg arrival times.

S62A-1182 1330h POSTER

Calibrating the International Monitoring System for Moment Tensor Solutions

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We are implementing seismic moment tensor software routinely used at the Berkeley Seismological Laboratory (BSL) on the test bed at the Center for Monitoring Research (CMR) to provide additional information for the discrimination of nuclear explosions from naturally occurring earthquakes, particularly for moderate magnitude events. For selected events which occurred in 1999 we demonstrate the application of the method to data from the very sparse network consisting of primary stations of the International Monitoring System (IMS), as well as the improvement obtained using data from auxiliary stations. We investigate the lower magnitude limits of the method by applying it to aftershocks, in addition to the selected mainshocks. For events in the Mediterranean region, for example, we can achieve good solutions down to moment magnitude 4.8. For events in the Lop Nor region, we compare results for earthquakes and a few of the most recent nuclear explosions.

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