signature of past deformation episodes, whereas below 200 km, active processes related to current plate motion provide the dominant explanation for the observed seismic anisotropy. The alignment of the fast axes in the flow direction is consistent with the deformation of a dry olivine mantle by simple shear. The correspondence between seismic fast axes and plate motion of Australia is best when the latter is expressed in a hot-spot reference frame. Thus, seismic anisotropy can add information on plate motion with respect to the underlying mantle that is independent from geodetic and plate-circuit constraints. Finally, the comparison of our results with mantle convection simulations suggests how seismic and mechanical models of the lithosphere are approaching resolutions at which they can be treated as "data" to refine forward models, thereby strengthening the crucial links between seismology, tectonics, and geodynamics.

S22E-08 1745h

Did Flow of Weak Middle or Lower Crust Accommodate Extension in the Gulf of California and Salton Trough?

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The strength of middle and/or lower crust (MLC) is key to understanding continental deformation and controls whether or not brittle upper crust and mantle lithosphere are coupled: weak MLC may flow and decouple the adjacent layers. We analyze the extent of MLC flow during rifting in the northern Gulf of California and Salton Trough (NGC/ST; in the NSF MARGINS Rupturing of Continental Lithosphere focus site) using area-balance techniques to compare upper crustal extension and MLC extension. Mid-Tertiary extension in SE CA, W AZ and W mainland Mexico thinned the crust before ∼E-W extension localized in the GC/ST at ∼12 Ma. By ∼6 Ma, NW-SE Pacific-N. American plate separation was concentrated in the NGC/ST, which began to subside below sea level. By ∼3.6 Ma, transform faults connected pull apart basins forming ocean crust (S gulf) and proto-oceanic crust in the NGC/ST. The Peninsular Ranges west of the NGC/ST were not extended at the surface. MLC flow into the NGC/ST is suggested by (1) the fact that the Moho dips W under the unextended Peninsular Ranges (W of the rift) to a maximum depth well W of the range crest (Lewis et. al., 2000, 2001), (2) by an apparent surplus of MLC relative to upper crust within the rift (e.g., Couch et al., 1991), and (3) by the magnitude of extension (∼255 km) between initially adjacent areas on either side of the NGC/ST (Oskin et al., 2001). We constrain the extent of MLC flow two ways: by comparing known upper crustal extension (e.g., Lewis and Stock, 1998; Axen and Fletcher, 1998) to (1) whole-crustal and (2) lower-crustal extension. Whole and lower crustal extension are obtained from cross-sectional areas constrained by depth to Moho and/or to the base of the upper crust (references above), by the extent of new proto-oceanic crust (e.g., Fuis et.al., 1984), and by assuming end-member initial crustal thicknesses (e.g., ∼37-40 km maximum thickness of the Peninsular Ranges or ∼25 km minimum from previously extended crust east of the NGC/ST). In general, the data are much better W of the NGC/ST than to the E, and constrain Moho depth much better than depth to the base of the upper crust (which may not equate to the base of the brittle crust in any case). Therefore we focus on comparisons of whole crust to upper crust in the Peninsular Ranges and western NGC/ST. Preliminary calculations of whole-crustal extension typically exceed known upper crustal extension by up to ∼4 times, strongly favoring MLC flow into the rift. However, for the end-member case of minimum initial crustal thickness, the higher estimates of known upper crustal extension are subequal to the calculated whole crustal extension, requiring no MLC flow. In most cases, area balance requires a present-day deficit of MLC material beneath the unextended Peninsular Ranges. This is key, because MLC deficits cannot be explained by magmatic processes, unlike the surpluses inferred below the rift (e.g addition of basaltic lower crust). These conclusions support much previous work that favors flow of weak MLC in extended terrains. Better constraints should be provided once reflection and wide-angle refraction data from MARGINS seismic profiles across conjugate margins of the gulf are fully processed.

S22F MCC: 3011 Tuesday 1600h

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

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

S22F-01 1600h

Investigating the use of Three-dimensional Travel-time Tables for Standard Regional Seismic Event Relocation

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As computer processor speeds continually increase, we are routinely locating larger earthquake data sets with more complex algorithms. Despite the increase in processing speed and capacity, large global seismic catalogs are still produced primarily using one-dimensional (1-D) velocity models. Results using these models can be significantly improved through application of static or source-specific station corrections – for example, the use of two-dimensional (2-D) correction surfaces developed with kriging methods has greatly improved relocation accuracies for regional events. Three-dimensional (3-D) velocity models, however, are improving in both resolution and reliability. Studies have demonstrated their superiority over 1-D models in terms of improved location and reduction in uncertainty. It therefore seems appropriate that routine seismic event location methods should migrate to the 3-D velocity model standard. We must consider, however, the increased processing time to produce 3-D relocations, even using faster computers. Further, it is important to assess the accuracy of 3-D travel-time (TT) tables and the ray tracing algorithms used to create them, to weigh – in combination with the added computational burden – the merits versus costs of such a transition. The objected-oriented relocation software (LocOO) developed by programmers at Sandia National Laboratories permits the use of 3-D TT tables to relocate events. The code is based on the "libloc" algorithms, accesses Oracle databases, and uses the Parametric Grid Library (PGL) for TT tables and station parameters. We plan to generate TT tables based on an a priori 3-D velocity model of the Central Asia region by selecting stations to maximize azimuthal coverage for the western China area. Using the LocOO software, we will test whether using 3-D TT tables improves the accuracy of regional seismic events that have corresponding ground-truth data for comparison. We will also compare these relocations with those produced using 1-D velocity models coupled with 2-D correction surfaces. Others have used 3-D TT tables for relocation but usually for specific event or event-cluster analyses. Our effort will focus on performing relocation tests on a catalog scale (or at least a large subset), and analyzing computational times to determine if using 3-D TT tables for regional location on a routine basis can be justified in an operational setting.

S22F-02 1615h

MULTIPLE-EVENT LOCATION WITH STATION-CORRELATED PATH CORRECTIONS

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Multiple-event location methods solve jointly for the locations of a set of seismic events and travel-time corrections associated with the paths from the events to the observing stations. Many of these methods assume the path corrections for a given station are the same for all events, which effects an important constraint on the event locations but which restricts the method to event clusters of small aperture. A notable exception is the double-differencing method, which allows for de-correlation of path corrections for well separated pairs of events. However, these methods do not typically incorporate a model of complete or partial correlation of path corrections between seismic stations, and thus omit potentially valuable information for many common network geometries. This paper investigates a new approach to multiple-event location that models the correlation of travel-time corrections for each pair of paths as a function of both event and station separation. The approach generates path corrections from a "universal correction function", which is sampled at the event location and station location to produce the correction for a given path. The universal correction function is estimated from observed travel-time residuals using a geo-statistical interpolation technique (kriging), making use of prior covariance information to impose correlations between paths. We have tested this approach on a data set from the Nevada Test Site (NTS) comprising Pn and Pg arrival times from 64 stations and 74 explosions for which precise location parameters are available. In this data set some stations are separated by less than 10 km while the median nearest-neighbor distance is only 70 km. Our tests compare event locations obtained using station-uncorrelated and station-correlated path corrections, each estimated from the observed travel-time residuals relative to the IASP91 earth model. In our initial tests, the path corrections are derived using the known locations of the events and then used in a single-event location algorithm applied to each event. The resulting event mislocations are consistently smaller when station-correlated corrections are used. More realistic tests entail estimating the path corrections jointly with the event locations in a multiple-event location process. Preliminary tests of this type on the NTS data indicate that multiple-event location methods incorporating station-correlated path corrections yield modestly smaller mislocations than the traditional methods.

S22F-03 1630h

Location Calibration in East Asia: Final Results of a Consortium Project, and Lessons Learned

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We have developed and tested Source Specific Station Corrections (SSSCs) for Pn and Sn travel times at 30 International Monitoring System stations in East Asia, and for 127 other stations used for validation testing. We developed a 3D model of the P–wave velocity for East Asia (using 36 different 1D regions), and used 3D ray tracing in the aggregate model to compute SSSCs. These model–based SSSCs were refined empirically by kriging travel–time residuals for ground–truth (GT) events. Off–line validation tests were performed by relocating GT events, with and without using SSSCs. Nuclear explosions dominated our ground–truth datasets in this project for much of Russia and Central Asia, but it was also necessary to develop GT information on significant numbers of earthquakes, for example to calibrate stations in China. Using the double–difference method and detailed fault maps, we obtained 64 GT5 earthquakes by re-analyzing the Annual Bulletin of Chinese Earthquakes for a 15-year period (1985 to 1999). Other reference events were provided by special studies, and in some cases contributed by colleagues. Using Pn and Sn arrival times for our GT data sets, we relocated 525 events recorded by various combinations of 140 regional stations. Mislocations were reduced for 66% of the events using the model–based SSSCs, and for 85% of the events using model–based SSSCs refined by kriging. Median mislocation improved from 16.9 km to 11.4 km and 6.5 km, respectively. Median error ellipse area was reduced

from 2,616 km^2 to 1,633 km^2 and 722 km^2, respectively. Error ellipse coverage (percentage of GT locations within 90% error ellipses) was 89% without using SSSCs, 91% using model–based SSSCs, and 92% using kriged SSSCs. These results were obtained for source–station paths that sample diverse geological provinces throughout much of Asia. The SSSCs are expected to perform, on average, as well as the test results using the model–based SSSCs, and substantially better for areas where GT calibration data were utilized to refine the SSSCs. Our overall method (of first obtaining model travel times and then kriging with empirical data) is well suited to calibration of any stations in East Asia that have a significant archive of reliably measured arrival times. The method potentially has global application, to greatly improve global bulletins of seismicity without having to rely wholly upon a 3D model of Earth's seismic velocity. But an international long–term effort is needed to build the necessary reference events.

S22F-04 1645h

Relative Earthquake Location Techniques: Tests using both Synthetic and Real Data

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Over the years, researchers have developed various techniques for reducing relative errors in earthquake location among nearby events. These techniques rely on the assumption that if the hypocentral separation between two earthquakes is small, travel time differences at a particular station are not biased by the effects of heterogeneity. Here, we compare three different earthquake location techniques: (1) the hypocentroidal decomposition method of Jordan and Sverdrup (1981), (2) the source-specific station term (SSST) method of Richards-Dinger and Shearer (2000), and (3) the modified double difference method (DD) of Waldhauser and Ellsworth (2001). In principle, all these methods should give approximately the same result for a single compact cluster of events, with significant differences appearing only for more distributed seismicity. We test these methods with both a synthetic data set and actual phase picks and waveform cross-correlation data from the M=5.4 Big Bear California aftershock sequence of February 2003. For the synthetic data, we generate a set of quake locations, station locations and arrival time picks in a simple half-space velocity model. We add random time noise to the data by including contributions of varying size from: (1) normally distributed random picking errors, (2) normally distributed station terms, which are constants for all events recorded by each station, and (3) spatially varying station terms computed by summing travel time anomalies along rays in random 3-D velocity models. In addition, each event is recorded by a random subset of the total set of stations. We quantify the performance of each method by characterizing both the absolute and relative errors in the computed locations as compared to the true locations, experimenting with both compact clusters and more distributed seismicity. The algorithms are also tested on real data, and their performances evaluated on a set of 785 events recorded by the Southern California Seismic Network (SCSN) from a region around the 2003 M=5.4 Big Bear earthquake, for which both phase pick and differential times resulting from waveform cross-correlation are available.

S22F-05 1700h

Location of Earthquakes in Three-dimensional Media Using Repeated, Multiple-Event Locations Over Spatial Grids of Control Points

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We describe a new approach to the large-scale relocation of seismic catalogs based on a variation of conventional multiple event location methods. We associate every event in a catalog with one or more points in a 3D grid of control points. Events associated with each point are located together with an implementation of the Progressive Multiple Event Location (PMEL) algorithm. PMEL estimates a set of path corrections from a given control point to each seismic station along with a set of revised locations. In the estimation we use a set of matrix projectors that allow the unresolvable (absolute) location bias to be extracted from a 3D reference model and project only components of information the available data constrain. This allows us to construct empirically derived travel time correction fields in 3D that are highly data adaptive; the density of control points can be very high where seismicity is intense and low where earthquakes are rare. The 3D model is used only to fill in gaps between control points and correct smoothly varying, bias problems. The algorithm is highly parallel and we found major improvements in performance were possible on massively parallel computers. We applied this approach to data from the Anza network and the Tien Shan (Ghengis) experiment catalog. With the Anza data we achieved remarkable improvements in data fit with most relocation residuals smMaller than 0.02 s which is approximately 1/10 of the catalog residuals. In contrast the variance reduction in the Tien Shan data was much smaller (50%) with 1 s scale residuals common. This difference is attributed to measurement precision. The Anza catalog is dominated by impulse, local P and S phases while the Tien Shan catalog is dominated by emergent, regional phases.

S22F-06 1715h

Use of 3-D Velocity Models and Ray Tracing in the Double Difference Earthquake Location Algorithms: Application to a Data set from the Mygdonia Basin (Northern Greece)

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In the past years there has been a growing demand for precise earthquake locations for seismicity, tectonics and seismic hazard studies. Recently this has become possible because of the development of sophisticated location algorithms, as well as hardware resources. This is expected to lead to a better insight of seismicity in the near future. A well-known technique, which has been implemented as a computer program and has been widely used for relocating earthquake data sets, is the double difference algorithm. In its original implementation it makes use of a one-dimensional ray tracing routine to calculate seismic wave travel times and partial temporal derivatives of source parameters. We have modified the implementation of the algorithm by incorporating a three-dimensional velocity model and ray tracing in order to locate a set of earthquakes in the area of the Mygdonia Basin (Northern Greece). This area is covered by a permanent regional network and occasionally by temporary local networks. The velocity structure is very well known, as the Mygdonia Basin has been used as an international test site for seismological studies since 1993, which makes it an appropriate location for evaluating earthquake location algorithms, with the quality of the results depending only on the quality of the data and the algorithm itself. The new earthquake locations reveal details of the area's structure, which are blurred, if not misleading, when resolved by standard (routine) location algorithms.

S22F-07 1730h

Fine-Scale Structure of the San Andreas Fault and Location of the SAFOD Target Earthquakes

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Arrival-time data from about 900 local earthquakes and several dozen shots are inverted for earthquake locations and three-dimensional Vp and Vp/Vs structure of the San Andreas fault (SAF) zone at Parkfield, CA, using several different tomography methods. Data are included from a temporary array of surface seismic stations installed around the SAFOD site, a vertical array of geophones installed in the 2-km-deep SAFOD Pilot Hole drilled in summer 2002, and permanent network stations. The inversion methods applied are conventional ray-tracing tomography, conventional finite-difference tomography, and double-difference tomography. For double-difference tomography, we use both a regular grid and an adaptive grid based on tetrahedra and Voronoi diagrams. The primary features of the different velocity models are generally consistent with each other. A low-Vp zone (about 25% slower) adjacent to the fault trace penetrates to a depth of as much as 10 km. Nearly all the earthquakes occur almost directly beneath the surface trace of the SAF, on the edge of a zone of high horizontal Vp gradient. Regions of anomalously high Vp/Vs (> 2.0) are found at shallow depths along and northeast of the SAF. These high-Vp/Vs anomalies can be associated with features in an existing resistivity model that are interpreted to represent fluid-saturated zones. We locate several magnitude 1 to 2 earthquakes at depths < 3 km and locations that are on the order of 100 meters southwest of the surface fault trace that are potential target events for drilling of the main SAFOD hole. We discuss a range of tests of our absolute and relative location capability for events in the target region, and identify additional steps needed to reduce location uncertainties to < 100 m and ultimately < 10 m.

S22F-08 1745h

High-Resolution Subducting Slab Structure Beneath Northern Honshu, Japan, Revealed by Double-Difference Tomography

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Double seismic zones separated by 30 km exist at intermediate depths of 50- 160 km in northeast Japan. The upper and lower plane of earthquakes occur mainly in oceanic crust and mantle, respectively, and are assumed to be induced by dehydration reactions of various hydrous minerals. We obtain the seismic structure of the subducting slab with unprecedented resolution beneath Northern Honshu, Japan by applying newly developed double-difference tomography to the two planes of seismicity of the double seismic zone, which provides evidence supporting the above hypothesis. The upper plane consists of two distinct regions: one with relatively high Vp/Vs ratio (1.77-1.8) at 60-90 km depth and one with low Vp/Vs ratio (1.7-1.77) at 90-110 km depth. These two regions may correspond to the transformations of metabasalt/metagabbro to blueschist and blueschist to eclogite, respectively. There is a conspicuous anomaly of very low Vp/Vs ratio (1.6-1.7) associated with the lower plane, in sharp contrast with high Vp/Vs ratio (1.8-1.85) in the region between the two planes. The forsterite-enstatite-H_2O system from serpentine dehydration for the lower plane and possible partial hydration of the region between the two planes of earthquakes may explain the observed features.

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S22G MCC: 3007 Tuesday 1600h

Rise of the Machines: Wave Propagation Theory

Presiding: **C J Thomson,** Queen's University**; K T Nihei,** Lawrence Berkeley National Laboratory

S22G-01 1600h

Coherent-state analysis of the seismic head-wave problem: an overcomplete representation and its relationship to rays and beams

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