MULTI-RESOLUTION GLOBAL MODELS FOR TELESEISMIC AND REGIONAL EVENT LOCATION

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ABSTRACT

Reconciliation of structures shown in global models of Earth structure with those shown in detailed, high-resolution regional models has become one of the most important tasks in seismic tomography. Recent studies have shown that combination of regional seismic phases with teleseismic phases can greatly increase location accuracy; however, for this to be the case, the velocity structure has to be well resolved on a fine scale. The most efficient method to accomplish this task is development of multi-resolution models using local (but smooth) basis functions that increase in resolution from regions with sparse data coverage to regions of dense coverage. This paper reports on recent results from an ongoing project designed to bridge the gap between regional and global seismic tomography and achieve correspondingly incremental improvements in event location. We have previously developed a moderately high-resolution global model (equivalent to spherical harmonic degree 18) using local spline functions. This model improves locations using teleseismic phases over other more finely parameterized models (Antolik et al., 2001). Here we extend the same techniques to simultaneous development of more detailed regional models for inclusion within the global model. We describe progress in constructing a new regional model of the Africa/Mediterranean region which makes use of surface wave dispersion data, regional travel times and waveforms, and teleseismic phase arrivals. This model also incorporates shear wave anisotropy and agrees well with other published models for the region. Other regions for which we intend to develop combined regional/global models include the former Soviet Union and North America.

Tomographic models can also be vastly improved through the use of sources with calibrated travel-time data (i.e., reference events with accurately known locations). However, the current database of such events still suffers from sparse coverage (particularly in oceanic regions). A parallel element of the current project includes improvement of event locations on mid-ocean ridges by making use of focal mechanisms and accurate bathymetry. We have developed a database of some 1500 large events and are expanding to smaller events using the Joint Hypocentral Determination technique. We present the results along with experiments designed to test the accuracy of these locations.

KEY WORDS: Event location; seismic tomography; mantle heterogeneity

OBJECTIVE

The aim of this project is to ultimately improve the locations of earthquakes and other seismically recorded events in order to enhance the ability to monitor the Comprehensive Nuclear-Test-Ban-Treaty (CTBT). Our strategy is based on developing new, detailed 3-D models of the mantle, with an emphasis on P wave structure. This involves the construction of global high-resolution models with more detail in certain areas where particularly good data coverage is available. In our approach, 3-D velocity structure is represented in terms of a horizontally layered and laterally varying crust of variable thickness, overlying a mantle whose heterogeneous P- and S-velocity structure is parameterized radially and laterally in terms of cubic B-spline functions of variable density. The spline functions are split radially at the 670-km discontinuity in order to better resolve changes in heterogeneity patterns across this boundary (Gu et al., 2001). The shallow mantle is parameterized as an anisotropic medium in shear velocity. We have previously developed a new joint P and S velocity global velocity model of the mantle parameterized in spherical B-splines (Antolik et al., 2000). This model, with a nominal horizontal resolution equivalent to degree 18 in a spherical harmonic expansion, improves the average mislocation for explosions in Kennett and Engdhahl's (1991) database and the Prototype International Data Centre's Reference Event database by $>$20% over more finely-parameterized models (see Table 1). We are now moving to take advantage of better data coverage obtainable in certain regions of the globe by inverting for multi-resolution models with finer parameterization confined to certain regions. The first half of this paper describes an anisotropic model of shear wave velocity developed for the African/Mediterranean region developed using this technique. This and other similar models will be used to combine both regional and teleseismic travel times for the improvement of event locations.

Model	Explosions	Earthquakes
PREM	12.92	18.83
SP12	7.83	15.37
MK12	9.53	17.40
BDP98	9.80	17.13
VWE97	10.51	17.33
P362-17	6.27	13.75

Table 1: Average mislocation for 112 test events consisting of explosions and earthquakes using PREM (Dziewonski and Anderson, 1981) and five 3-D mantle models. P362-17 is our new global model of P wave velocity described in Antolik et al. (2000). Only teleseismic P wave arrivals were used to calculate the locations. Location errors for the explosions are significantly smaller than for the earthquakes, which may reflect greater errors in the earthquake reference locations. See Antolik et al. (2001) for description of the other 3-D models and the location method used.

A second, subsidiary objective concerns the development of additional techniques used in locating events teleseismically and regionally with sparse datasets, and with assessing the improvement in accuracy afforded by the new techniques and models. To address this, we are attempting to improve the quality of locations for events in remote regions where the number of reference events is currently small. We use a combination constrained inversion/JHD technique to reconsider the locations of earthquakes on mid-ocean ridges and transform faults.

RESEARCH ACCOMPLISHED

As recent tests have shown that compilation of accurate travel times for regional ($\Delta < 20°$) first-arriving phases can significantly improve location accuracy (Chen and Willemann, 2001), we have begun to make rapid progress in the development of regional velocity models of both P and S velocity, including consideration of anisotropy. The North African/Mediterranean region is one where the current data availability is such that velocities in the upper mantle can be resolved with higher precision than that obtainable globally. The Mediterranean Basin is a geophysically complex area, governed by the slow collision between Africa and Eurasia. The boundary between the two plates is not entirely well defined. Although there is clear geodetic and seismic evidence of northward subduction under the Aegean and Calabrian arcs, diffuse seismicity around the Adriatic Sea and Western Mediterranean requires a more complex description of plate interaction, which is the subject of current research. The densely populated Italian peninsula has a long history of destructive earthquakes, and a better understanding of the regional tectonics would have a significant role in the context of seismic hazard mitigation efforts. Tomographic studies are naturally a means to this end (e.g., de Jonge et al., 1994; Faccenna et al., 2001).

In recent years, seismic images of the Mediterranean Basin have been derived by researchers at University of Utrecht (Wortel and Spakman, 2000) and at I.N.G.V. in Italy (Piromallo and Morelli, 1997). Both groups have focused on explaining observations of body-wave (rather than surface-wave) travel times; the Italian group have emphasized regional data, while the Dutch group, with the recent work of Bijwaard (1999), have derived a high resolution regional model within the framework of a variable resolution model encompassing the whole globe.

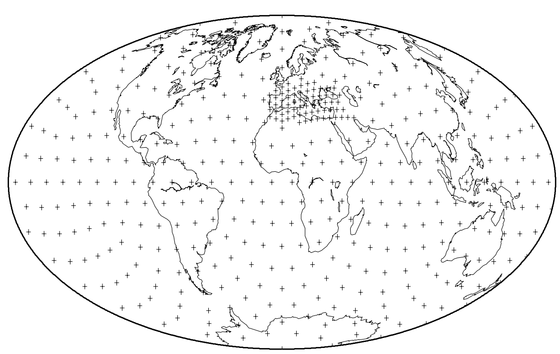

Figure 1: Locations of horizontal spline knots for parameterization of the multi-resolution global model of anisotropic shear velocity.

Free parameters of our least-squares inversions are lateral variations in horizontally and vertically-polarized shear velocities throughout the upper mantle, described as linear combinations of radial and horizontal cubic splines (Boschi, 2001). The basis functions are more densely distributed within the Mediterranean Basin, to achieve a higher nominal resolution. Figure 1 shows the horizontal locations of the spline knots. Globally, the resolution of the inversion approximates a degree 18 spherical harmonic expansion (as in the inversion for joint P and S velocity described above), but becomes more dense within the region of interest. The measured variations in phase delay for Rayleigh and Love waves between periods of 30 and 300 s are defined as

$$\delta\Phi_j(\omega) = \omega \sum_{i=1}^{2} \sum_{k=1}^{K} x_{ik} \int_0^{\Delta_j} \int_0^{a} K_i(r,\omega) f_k(r,\theta,\phi) dr ds, \qquad (1)$$

where the index j represents the individual measurements, the f_k represent the horizontal and radial spline functions, the x_{ik} are the model parameters, and the index i refers to the specific quantities being sought in the inversion, in this case the horizontal and vertical shear velocities. The K_i functions are known as the “sensitivity kernels” (Anderson and Dziewonski, 1982) or partial derivatives. An original feature of this modeling is that the sensitivity kernels are treated as laterally varying, .i.e, the reference model used is not one-dimensional. Instead, we calculate the partial derivatives for model CRUST5.1 (Mooney et al., 1998) overlying a PREM upper mantle. The resulting model shows significant differences in absolute amplitude of the anomalies when compared to models constructed in the conventional manner with a 1-D reference model (Boschi and Ekström, 2001).

Figure 2 shows images at several depths of the global model of vertical shear velocity and the regional Mediterranean model, while Figure 3 shows a cross-section across the western Mediterranean comparing the v_{SV} model to other published velocity models. Among the global features shown in the new model is the high-velocity anomaly in vertical shear velocity in the top of of the upper mantle underneath the central Pacific first reported by Ekström and Dziewonski (1998). Our new Mediterranean model has many features in common with others published for the region. High-velocity anomalies associated with African subduction and the European shield can be readily seen in Figure 2, as well as low-velocity models associated with extension (e.g., Aegean Sea). The cross section shown in Figure 3 indicates that, by accounting for a crust of laterally varying properties in the reference model, we have successfully reproduced the strong slow anomaly (associated with tectonic extension) predicted by de Jonge et al. (1994); in the same region, where the crust is anomalously thin, Spakman et al. (1993) have mapped a fictitious fast anomaly. The thickness of the crust, whose lateral variations Spakman et al. (1993) do not consider, trades off with the imaged shallow upper mantle velocities.

We are currently refining our imaging techniques. While the model described above only accounts for measurements of surface-wave phase velocity, we expect to be able in the near future to derive a single model from the simultaneous inversion of surface-wave phase velocity, surface-wave group velocity (from a local data set assembled and made public by the Lawrence Livermore National Laboratory), body-wave travel times, and mantle waveforms, including joint consideration of P and S velocities. This step should improve the effective resolution of our image in the upper mantle, and provide a reasonable coverage of the lower mantle.

In addition to the construction of more detailed and accurate global velocity models, we have

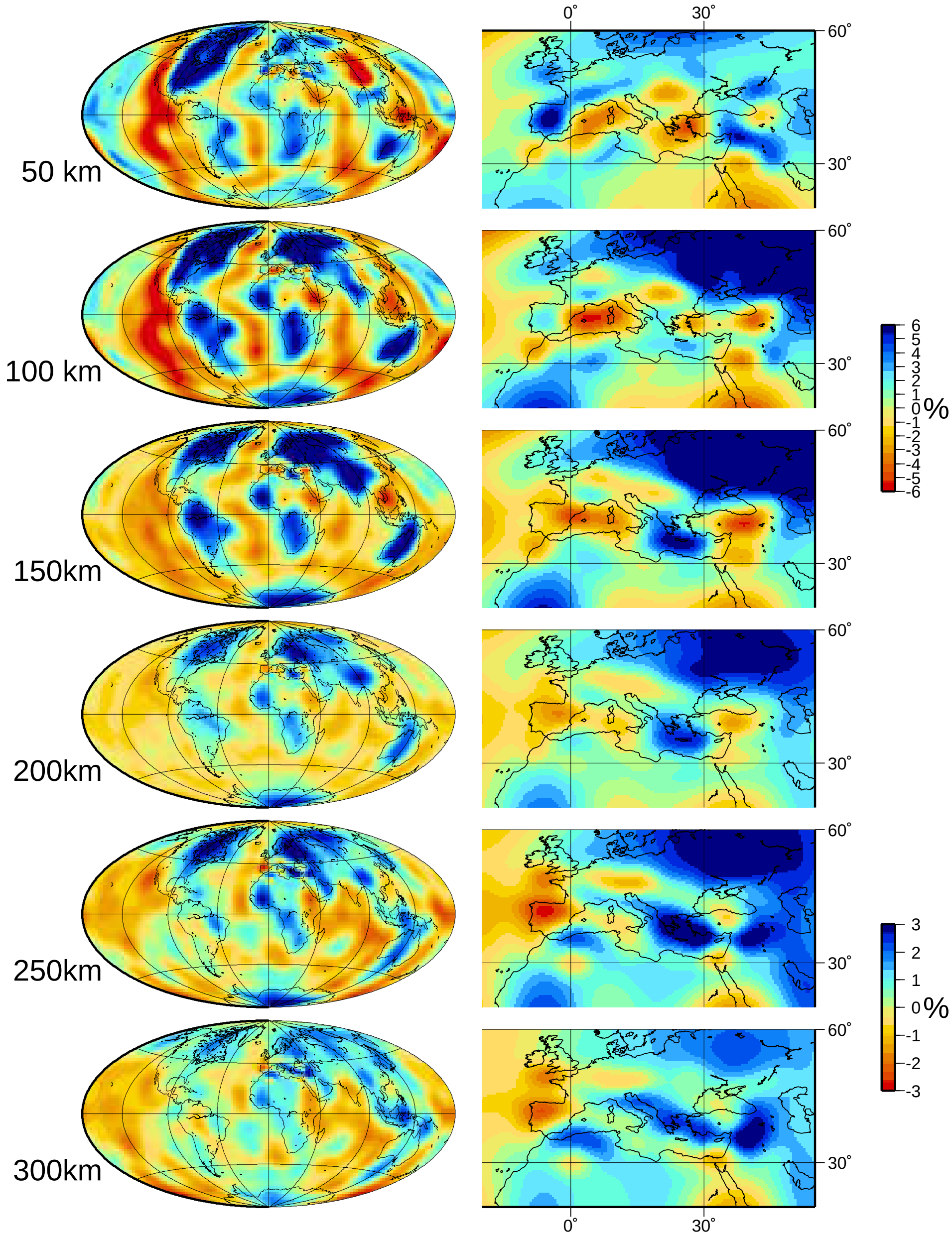

Figure 2: Global (left) and local (right) percent heterogeneity $\delta v_{SV}/v_{SV}$ at six depths in the upper mantle from the variable resolution model of anisotropic shear velocity.

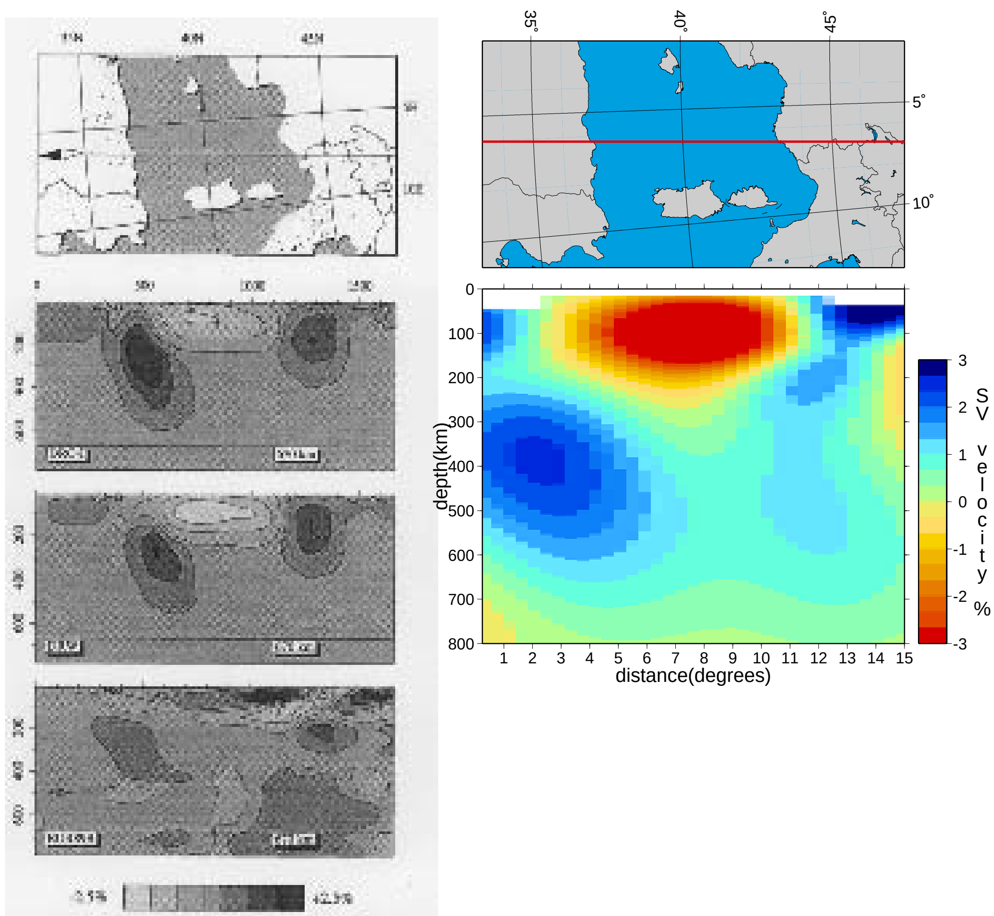

Figure 3: Comparison between four different images of the upper mantle, shown (in cross-section) in the region underlying the Western Mediterranean; the left panels are from de Jonge et al. (1994). DRC-I and DRW are theoretical P-velocity models, computed by de Jonge et al. (1994) on the basis of Dercourt et al.'s (1986) and Dewey et al.'s (1989) tectonic reconstructions, respectively. EUR89B is the tomographic P-model of Spakman et al. (1993), based on regional and teleseismic P-travel time measurements, and including a simplified 1-D reference crustal model. On the right is our own v_{SV} model derived from surface wave phase velocity observations.

focused our efforts on building a larger database of reference or "ground-truth" events to be used for model calibration. So far, the geographical distribution of events with locations known to an accuracy of 5 km or better is extremely limited. Many of these events are nuclear explosions and are concentrated in only a few source regions, making comprehensive testing of velocity models and calibration of new seismic stations very difficult. We have established a catalog of $\sim$1500 large (M $>$ 5.5) earthquakes located along mid-ocean ridge and transform faults using a constrained inversion technique where the event is confined to the nearest appropriate plate boundary feature (ridge or transform fault) based on the CMT focal mechanism. The inversion problem is thus reduced to determination of a single distance. Figure 4 shows the global distribution of these large events. We refer to these events as "master events" in the discussion that follows.

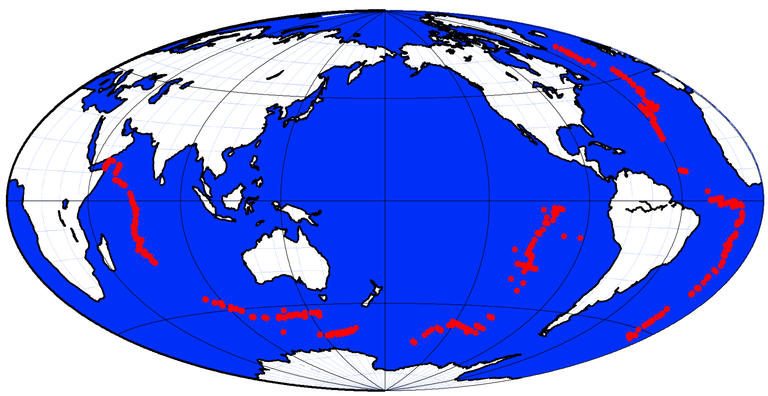

Figure 4: Global locations of relocated master events from the CMT catalog along mid-ocean ridges and transforms.

Improvement in the location of smaller events, for which a focal mechanism has not been determined, might be obtained using the Joint Hypocentral Determination (JHD) technique. To do this, we form clusters of events using those events in the ISC catalog within a circle of radius 100 km about a master events. The differences between our inversion and those of other JHD procedures (e.g., Pavlis and Booker, 1983; Jordan and Sverdrup, 1981) are that we solve for source parameter and station corrections simultaneously, and that the locations of the master events are held fixed during the inversion process. Stations for which there are fewer than 3 observations for a cluster are not included, and we use the LSQR algorithm (Paige and Saunders, 1982) to perform the inversion in order to take advantage of the sparsity of the inner product matrix. The depths of all the events are assumed shallow and are fixed at 10 km. Figure 5 shows the results of one JHD inversion along the Romanche Fracture Zone in the central Atlantic. After inversion the events are drawn toward the fracture zone represented by the low in the bathymetry.

Additionally, we combined the inversion for each master event together to solve for relocation vectors and station corrections for a regional cluster of earthquakes (i.e., JHD with multiple master events). Just as in the single-master-event inversion, each master event influences only those events within a radius of 100 km. In the combined matrices, we apply a smoothing weighting function to the phases of each master event

$$w_j = \sum_K e^{-10\times(\Delta_{jk})^2}, \tag{2}$$

where Δ_{jk} is the distance between the jth and kth master events in the region under study and the sum is over all of the K master events. The phase weights for the smaller non-master events in the inversion are fixed at unity, and all events for which fewer than 30 P phases exist are omitted. We again use an iterative, LSQR algorithm to solve the equations. This process has been applied to approximately 1100 total events within the central Atlantic between 30° S and 30° N.

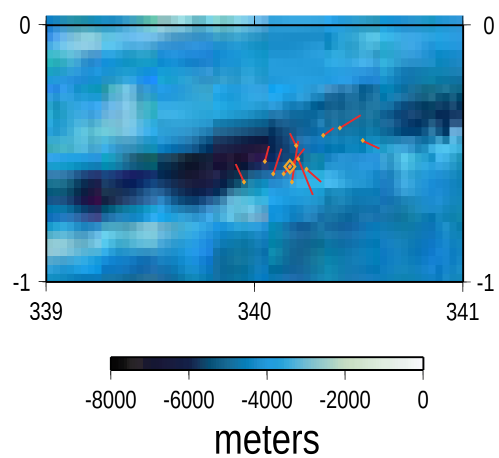

Figure 5: Results of JHD cluster analysis with a single master event (open diamond). Lines show relocation vectors of the smaller events in the cluster, with the new location given by the small diamonds. The vectors have been enlarged by a factor of two in length. The location of the master event was held fixed. Bathymetry is taken from Smith and Sandwell (1997).

Figure 6 shows the regional inversion locations for 148 events along the Romanche Fracture Zone (40 master events). The relocation vectors are shown in the bottom panel, and indicate that most of the epicenters become better aligned along the linear transform fault, except near the eastern edge where there is considerable complexity in the intersection of the transform fault and adjoining ridge. In this region the seismicity shows significant deviation from the great circle defining the plate boundary. The maximum movement obtained for the smaller events in the JHD process (~50 km) is comparable to that observed for the original master events. We find that, after the JHD inversion, the majority of the smaller events show improvement in the residual RMS (w.r.t. the PREM model) over the initial ISC location (the ISC uses the Jeffreys-Bullen travel time tables). After 3 iterations, a reduction in the weighted RMS residual of ~50% is achieved for the Romanche Fracture Zone events. The significant variance reduction achieved for the residuals suggests that the accuracy of the new locations is higher than the original catalog locations. The locations obtained in this step can be compared with those obtained using the single-master-event cluster analysis in order to assess their reliability.

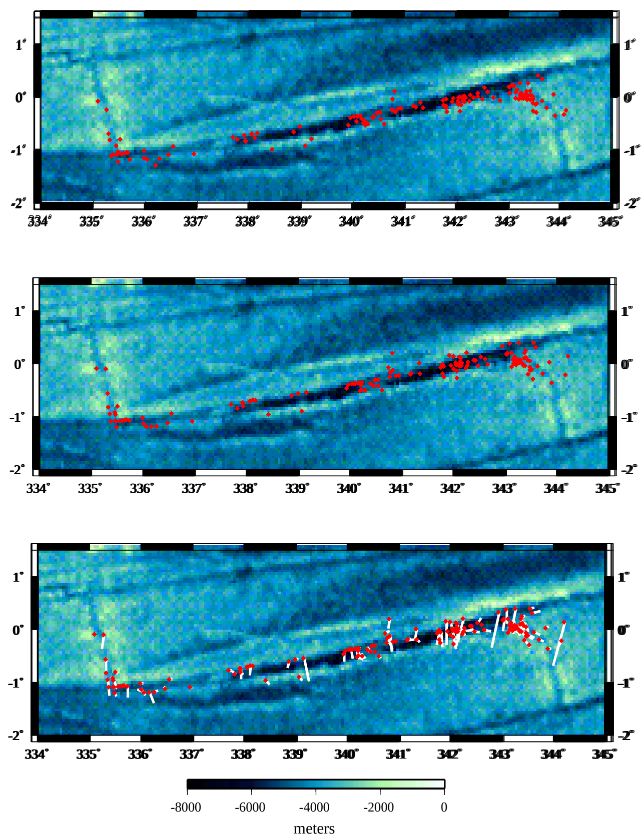

Figure 6: Regional, combined JHD inversion for 148 total events along the Romanche Fracture Zone. Top panel shows the initial ISC locations for the smaller events in the inversion, the middle panel the new locations, and the bottom panel shows the relocation vectors. The 40 master events included (which were fixed) are not shown.

CONCLUSIONS AND RECOMMENDATIONS

Although the current generation of global velocity models provides substantial improvement over 1-D velocity models for teleseismic earthquake location (Smith and Ekström, 1996; Antolik et al., 2001), there is still much room for improvement. The consistent accurate location of small events to within the area specified for on-site inspection under the CTBT (1000 km^2) will likely require the use of regional phases in addition to teleseismic travel times, and also possibly consideration of anisotropy or arrival angle data. To this end, we are developing new global models which combine a local parameterization with the advantages of smoothness over large distances. This will enable straightforward replacement of portions of the global model by a more detailed model covering a particular region. The smooth parameterization will allow simple computation of 3-D raypaths. Our detailed modeling of velocities in the Mediterranean shows the promise of simultaneous consideration of regional and teleseismic data in the tomographic inversion problem.

Testing of new global and regional velocity models, as well as calibration of newer IMS stations, will benefit from the compilation of reference events in remote regions. Our database of relocated events on mid-ocean plate boundaries will also enable construction of more accurate travel time and phase velocity datasets. Since published locations in these regions are known to contain large errors, this database may be of considerable use even if the relocated epicenters are accurate only to within 10 km.

REFERENCES

Anderson, D. L. and A. M. Dziewonski (1982), Upper Mantle Anisotropy: Evidence From Free Oscillations, Geophys. J. R. Astr. Soc., 69, 383-404.

Antolik, M., G. Ekström, and A. M. Dziewonski (2001), Global Event Location With Full and Sparse Datasets Using Three-Dimensional Models of Mantle P Wave Velocity, Pure Appl. Geophys., 158, 291-317.

Antolik, M., G. Ekström, A. M. Dziewonski, Y. J. Gu, J. Pan, and L. Boschi (2000), A new Joint P and S Velocity Model of the Mantle Parameterized in Cubic B-splines, in *Proceedings of the 22nd Annual D0D/DOE Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty*, Vol. 2, 15-23.

Bijwaard, H. (1999), Seismic Travel-time Tomography for Detailed Global Mantle Structure, *Ph.D. thesis*, Utrecht University, Netherlands.

Boschi, L. (2001), Applications of Linear Inverse Theory in Modern Global Seismology, *Ph.D. thesis*, Harvard University, Cambridge, Mass.

Boschi, L. and G. Ekström (2001), New Images of the Earth's Upper Mantle From Measurements of Surface-Wave Phase Velocity Anomalies, J. Geophys. Res., submitted.

Chen, Q. and R. J. Willemann (2001), Global Test of Seismic Event Locations Using Three-dimensional Earth Models, Bull. Seism. Soc. Am., submitted.

Dercourt, J., L. P. Zonenshain, L.-E. Ricou, V. G. Kazmin, X. Le Pichon, A. L. Knipper, C. Grandjacquet, I. M. Sbortshikov, J. Geyssant, C. Lepvrier, D. H. Pechersky, J. Boulin, J.-C. Sibuet, L. A. Savostin, O. Sorokhtin, M. Westphal, M. L. Bazhenov, J. P. Lauer, and B.

Biju-Duval (1986), Geological Evolution of the Tethys Belt From the Atlantic to the Pamirs Since the Lias, Tectonophysics, 123, 241-315.

Dewey, J. F., M. L. Helman, E. Turco, D. H. W. Hutton, and S. D. Knott (1989), Kinematics of the western Mediterranean, in *Alpine Tectonics*, edited by M. P. Coward, D. Dietrich, and R. G. Park, Spec. Publ., Geol. Soc. London, 45, 265-283.

Dziewonski, A. M. and D. L. Anderson, Preliminary Reference Earth Model (PREM) (1981), Phys. Earth Planet. Inter., 25, 289-325.

Ekström, G. and A. M. Dziewonski, The Unique Anisotropy of the Pacific Upper Mantle (1998), Nature, 394, 168-172.

Faccenna,C., T. W. Becker, F. P. Lucente, L. Jolivet, and F. Rossetti (2001), History of Subduction and Back-arc Extension in the Central Mediterranean, Geophys. J. Int., 145, 809-820.

Gu, Y. J., A. M. Dziewonski, W. Su, and G. Ekström (2001), Models of Mantle Shear Velocity and Discontinuities in the Pattern of Lateral Heterogeneities, J. Geophys. Res., 106, 11,169-11,199.

de Jonge, M. R., M. J. R. Wortel, and W. Spakman (1994), Regional Scale Tectonic Evolution and the Seismic Velocity Structure of the Lithosphere and Upper Mantle: The Mediterranean Region, J. Geophys. Res., 99, 12,091-12,108.

Jordan, T. H. and K. A. Sverdrup (1981), Teleseismic Location Techniques and their Application to Earthquake Clusters in the South-central Pacific, Bull. Seism. Soc. Am., 71, 1105-1130.

Kennett, B. L. N. and E. R. Engdahl (1991), Traveltimes for Global Earthquake Location and Phase Identification, Geophys. J. Int., 105, 429-465.

Mooney, W. D., G. Laske, and G. Masters, CRUST5.1: A Global Crustal Model at $5° \times 5°$ (1998), J. Geophys. Res., 103, 727-747.

Paige, C. C. and M. A Saunders (1982), LSQR: An Algorithm for Sparse Linear Equations and Sparse Least Squares, ACM Trans. Math. Soft., Vol. 8 No. 1, 43-71.

Pavlis, G. L. and J. R. Booker (1983), Progressive Multiple Event Location (PMEL), Bull. Seism. Soc. Am., 73, 1753-1777.

Piromallo, C. and A. Morelli (1997), Imaging the Mediterranean Upper Mantle by P-wave Travel Time Tomography, Annali di Geofisica, 40, 963-979.

Smith, G. P. and G. Ekström (1996), Improving Teleseismic Event Locations Using a Three-dimensional Earth Model, Bull. Seism. Soc. Am., 86, 788-796.

Smith, W. H. F. and D. T. Sandwell (1997), Global Sea Floor Topography From Satellite Altimetry and Ship Depth Soundings, Science, 277, 1956-1962.

Spakman, W., S. van der Lee, and R. D. van der Hilst (1993), Travel–time Tomography of the European–Mediterranean Mantle Down to 1400 km, Phys. Earth Planet. Inter., 79, 3-74.

Wortel, M. J. R. and W. Spakman (2000), Subduction and Slab Detachment in the Mediterranean-Carpathian Region, Science, 290, 1910-1917.