UTILIZING THREE-DIMENSIONAL SEISMIC VELOCITY MODELS IN REGIONAL AND TELESEISMIC EVENT LOCATION

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ABSTRACT

The objective of this project is to develop and improve upon three-dimensional (3-D) seismic velocity models of the Earth and to utilize such models for improving the locations of events recorded at regional and teleseismic distances. In previous research it has been shown that 3-D models, even when parameterized in terms of low-order spherical harmonic functions, can provide significant improvement to teleseismic location accuracy over 1-D models. 3-D models of the Earth's mantle continue to evolve, and many P wave models now exist that are parameterized by constant velocity blocks with dimensions of a few hundred km or less, including one developed as part of this project [*Boschi and Dziewonski*, 1998]. In this paper we compare the accuracy of locations obtained for some of the more detailed models to those obtained from longer wavelength models for a set of globally distributed events with known locations. We find that the new, higher-resolution models do not appear to further improve location accuracy. For many source regions the block models do not predict as well the full range of observed residuals. This may be due to a variety of factors. In addition to assessing location accuracy using the full data set of ISC P wave travel times, we examine location accuracy for small to moderate events by performing multiple location iterations using reduced datasets. Use of the 3-D models produces locations within the stated 1000 km ^{2} accuracy goal of the CTBT for ~70% of location trials using 30 phases but less than half of trials using 8 phases. The performance can be improved using either model-based or ground-truth empirical station corrections in addition to the 3-D model corrections.

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. 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 detailed resolution in certain areas where particularly good data coverage is available. 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. In this report we describe recent results concerning this second objective.

RESEARCH ACCOMPLISHED

One stated technical goal for monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) is to locate events of $M \geq 4$ with an estimated uncertainty of 1000 km^2 or less for the purposes of on-site inspection. Because of the lateral heterogeneities present within the real Earth, this goal is usually not achieved using conventional location techniques with standard one-dimensional velocity models. Two general approaches can be used to improve the quality of locations. The first is the application of empirically derived station corrections. While such corrections are calculated only once and then stored, and therefore can be applied extremely quickly in most location algorithms, they are often critically dependent on the source region. Station corrections which are regionally invariant often give little or no improvement in location. Further, the application of source-region dependent corrections depends upon previous sampling of raypaths from all possible source regions. The second approach is the use of a laterally varying Earth model. While this approach does not suffer from the above disadvantage, it requires the calculation of a travel time correction for each ray. In addition, the potential resolution of laterally heterogeneous models is limited by the quality and coverage of the data employed, and also by the computational resources available for their derivation.

Global three-dimensional (3-D) velocity models of the Earth's mantle continue to evolve and become parameterized on an ever finer scale. Models of both compressional and shear wave velocity are now commonly parameterized in terms of constant velocity blocks [e.g., *Vasco and Johnson*, 1998; *Grand et al.*, 1997; *van der Hilst et al.*, 1997] rather than spherical harmonic functions. The model BDP98 [*Boschi and Dziewonski*, 1999a] was developed for an earlier phase of this project. Such "high-resolution" models, using blocks with sizes on the order of a few hundred kilometers, have provided sharper images of coherent smaller scale heterogeneities, in particular fast, sheet-like anomalies presumed to correspond to slabs penetrating into the lower mantle. They should be able to offer a better characterization of P wave residuals for paths through subduction zones or other areas where small-scale lateral heterogeneities are present. However, a number of factors may lead to lower resolution of large-scale, smaller amplitude anomalies in block models. Because of the higher number of unknown parameters, it is still impractical to invert combinations of very large data sets (waveforms and travel times), as is frequently done with spherical harmonic models [*Su and Dziewonski*, 1997; *Li and Romanowicz*, 1996]. This may result in lower resolution in certain areas (particularly the shallow mantle) to which particular data sets are sensitive. In addition, the division into arbitrary, constant velocity blocks may induce an unrealistic shape in long-wavelength anomalies. A lack of correlation between new, high-resolution Earth models and earlier longer wavelength models has previously been noted [*Grand et al.*, 1997]. Another possible factor in this discrepancy may be the use of regularization or damping in the solution of the inverse problem [*Boschi and Dziewonski*, 1999a].

In an earlier phase of this project we have shown that spherical harmonic models of the Earth's mantle are of sufficient quality to be useful in improving the quality of teleseismic locations [*Smith and Ekström*, 1996]. By inverting *P* travel times from a dataset of events with known or very accurately determined "ground-truth" locations, the average mislocation distance was reduced by approximately 40% using the 3-D model S&P12/WM13 (hereafter referred to as SP12) [*Su et al.*, 1993] as compared to PREM or IASP91.

However, only small improvements were obtained for earthquakes occurring in geologically complex areas along plate boundaries, presumably due to the inadequate representation in SP12 of anomalies with wave-lengths of a few hundred kilometers or less. On the other hand, this may be due to the fact that most of these latter events are earthquakes with less accurate ground-truth locations.

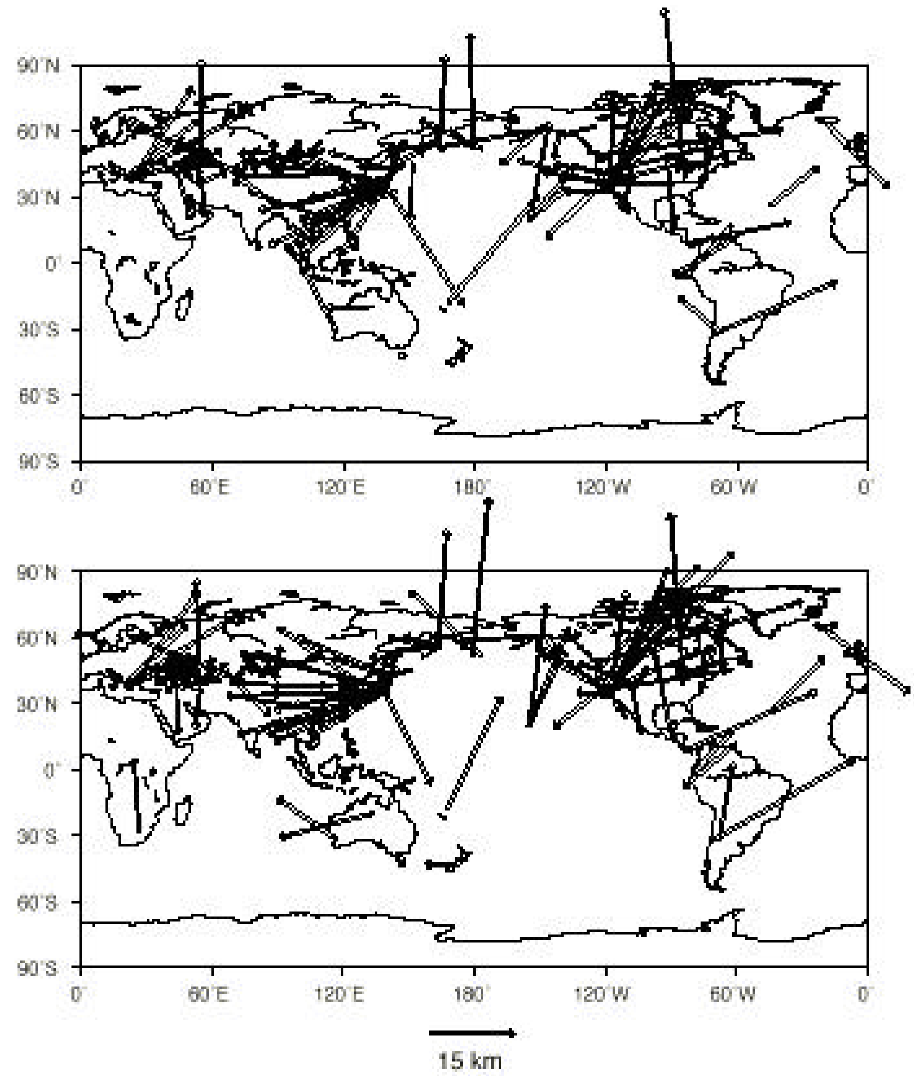

Figure 1: Mislocation vectors for the test events using the complete ISC P wave travel time set, for models SP12 (top) and BDP98 (bottom) without station corrections. Length of the vectors is proportional to the magnitude of the mislocation. The base of each arrow is plotted at the ground truth location and each vector points in the direction of the model-derived location. Explosion events are plotted as the solid vectors and earthquakes as the open vectors. Events located with BDP98 are generally mislocated in the same direction as with SP12, but with a larger error.

Using essentially the same dataset, we tested the improvement which can be obtained in teleseismic event location using the newer block models of mantle P wave velocity compared to model spherical harmonic models and to PREM. In addition to SP12, we also tested a P wave model derived from model MK12WM13 (MK12) [*Su and Dziewonski*, 1997]. *Su and Dziewonski* [1997] obtained a degree-12 spherical harmonic model of bulk sound and shear velocity using a wide variety of direct and differential travel times as well as about 40,000 long-period waveforms. The block models are those of *Boschi and Dziewonski* [1999a] (BDP98) and *van der Hilst et al.* [1997] (HWE97). In addition to the corrections for 3–D mantle structure obtained for the four models, we applied corrections for crustal structure based on model CRUST5.1 from *Mooney et al.* [1998]. We inverted ISC travel times from 25 to 96 epicentral distance for 112 explosions and earthquakes and found that the locations derived from models BDP98 and HWE97 were generally not as good as those obtained from SP12. Figure 1 compares mislocation vectors for model SP12 to those of BDP98. Locations derived from BDP98 are generally displaced from the true location in the same direction as those derived from SP12, although by larger distances. This suggests that the amplitudes of large velocity anomalies are not as well recovered in BDP98, although the lateral positions of the anomalies are similar to SP12. We have noted previously a tendency for anomalies to be smaller in amplitude in the newer block models than in the spherical harmonic models [*Boschi and Dziewonski*, 1999a; *Ekström et al.*, 1998]. Use of the full CRUST5.1 model results in significant improvement in location accuracy over earlier, less detailed corrections for crustal structure.

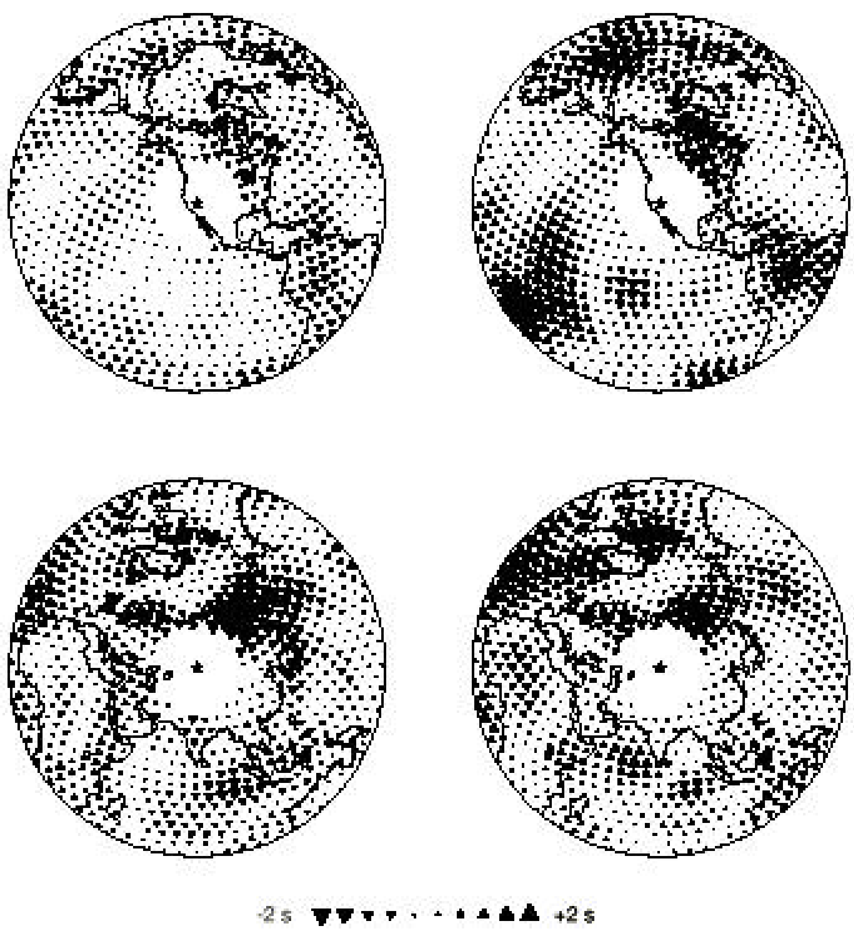

Figure 2: Predicted travel time residuals plotted in 5° x 5° bins for models BDP98 and SP12 for events located at the Nevada and Semipalatinsk nuclear test sites. Each triangle represents the value of the mantle travel time correction in the center of the bin after removal of the mean value over all bins. Top two maps are for an event at the Nevada test site and the bottom two maps are for an event at the Semipalatinsk test site. Maps on the left are for BDP98 and those on the right are for SP12.

One area in which the location difference between BDP98 and SP12 is especially large is in the western United States. It is interesting to compare residuals predicted for these two models for events in this region. Although the areas for which the two models predict particularly large residuals are similar (Figure 2), in general the amplitudes of the residuals predicted by SP12 are larger.

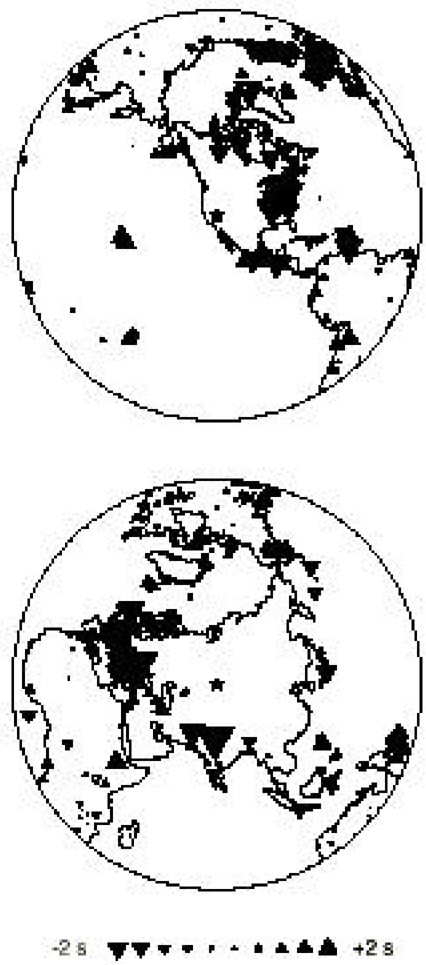

Figure 3: Mean observed P wave travel time residuals for explosions at the Nevada (*top*) and Semipalatinsk (*bottom*) test sites. The value plotted is the difference between the observed travel time and the value predicted for PREM plus all additional corrections except for the mantle correction. The mean of all of the values has been subtracted from each data point. Residuals with a magnitude larger than 5 s have been excluded.

The residual pattern predicted by SP12 much better matches the wide variation in the observed residuals (Figure 3). In contrast, the residuals predicted by both models for events at the Semipalatinsk nuclear test site are much more similar, although some differences (notably in north Africa and Australia) do exist. As a result the locations derived from both models for events in central Asia are quite similar.

Testing 3-D models with sparse datasets

It is important to examine the performance of 3-D models when locating events teleseismically with a limited number of phases. The primary seismic network of the International Monitoring System, for example, is to consist of only 50 3-component stations and arrays worldwide. Station coverage in many areas is therefore sparse.

For each of the test events we randomly selected 30 of the available phases and relocated the event according to the procedure described in *Smith and Ekstr¨ om* [1996]. We repeated this procedure 100 times for each event. No consideration with regard to the aziumth or epicentral distance of the reporting station was made when selecting the phases, except that the distance was restricted to between 25° and 96° as before. A location trial is deemed to be "successful" if it results in a location within the 1000 km^2 area surrounding the actual location specified by the CTBT. We also performed this procedure using 8 phases in each location trial and 250 trials per event.

In addition to relocating the events in this manner using only the model travel time corrections, we computed new empirical station corrections using only the test events. We divided the test events into groups containing three or more events located within 500 km of a central point, and took as the station correction the residual remaining after relocation of the reference event in the 3-D model. These corrections are referred to as "model-based" adjustments. Station corrections were also calculated using the ground-truth location for each event and are referred to as "ground-truth" corrections. Since the stations reporting nearby test events are similar, most of the available stations have a correction for a given event. This allowed computation of station corrections for 69 of the total of 112 test events.

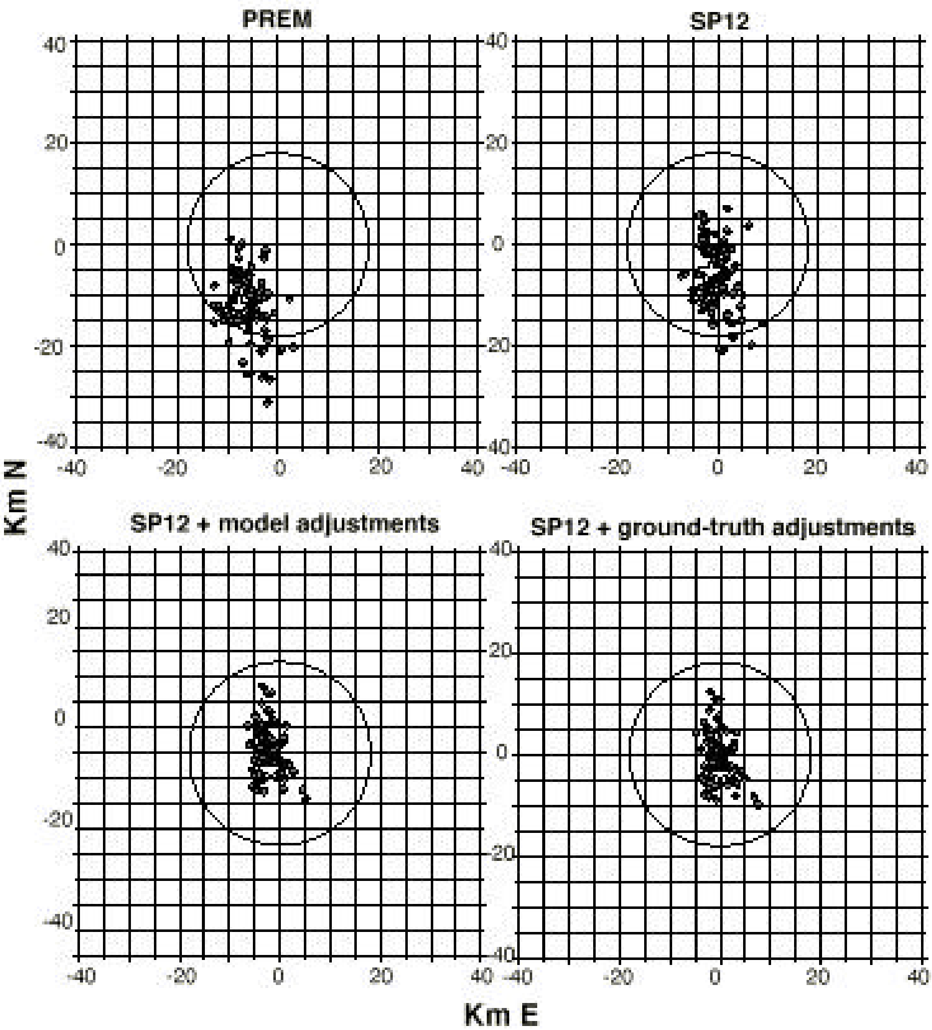

Figure 4: Results of 100 location trials, each using only 30 wave observations, for a single explosion located near the southern Ural mountains. Each grid is a map-view with the ground-truth location denoted by the black cross at the center. The velocity model used for each set of trials is shown at the top of the grid. The grid at top left is for PREM with no station corrections, that at the top right for SP12 with no station corrections, the lower-left grid is for SP12 with model-based station corrections, and the lower-right grid is for SP12 with ground-truth corrections. Each filled circle depicts the location resulting from one of the trials. The white stars indicate the locations obtained from all of the available phases. The black circles delineate an area of 1000 km surrounding the ground-truth location.

Figure 4 shows the results of this process for an explosion in the Ural mountains. Results of location trials using model SP 1 2 are compared with those using PREM. Each level of complexity in the model which is employed results in better locations. For PREM the average location error is about 10 km and about 5 km for SP 1 2. For SP 1 2 nearly all of the location trials lie within the 1000 km^2 objective of the CTBT. The use of station corrections helps to remove both the scatter and the bias in the location trials.

The breakdown of the location trials is summarized by Table 1. When using no station corrections and 30 total phases, the percentage of successful trials is 65-70%, and the average mislocation is only slightly greater than that obtained using all of the phases.

Model	No corrections	Model-based corrections	Ground-truth corrections
SPI2	14.32 (71.5 %)	13.74 (70.8 %)	11.02 (79.1 %)
MKI2	15.24 (67.7 %)	14.30 (68.3 %)	10.97 (78.8 %)
BDP98	14.80 (69.3 %)	14.27 (68.8 %)	10.79 (79.6 %)
VWE97	16.49 (64.9 %)	16.11 (64.2 %)	11.88 (75.8 %)
PREM	17.42 (61.8 %)	-	11.23 (78.8 %)

Table 1: Average mislocation in km for location trials using a random selection of 30 phases. 100 trials were computed for each event. See text for description of station corrections. Numbers in parentheses are the percentage of location trials falling within an area of 1000 km^2 surrounding the ground-truth location.

The model-based station corrections produce some improvement in the average mislocation but not in the number of successful trials. The ground-truth corrections produce significant improvement in both average location and percentage of successful trials. If ground-truth information is available, then an event can be located at a confidence level of 75-80% within the goal of the CTBT. This is even true when using PREM as the location model, which points to the importance of calibration information. The ground-truth corrections reduce the difference between the results for the different models. If only 8 phases are used in the inversion, then less than half of the trials are successful (60% if ground-truth is used) and the average mislocation increases to over 30 km for all of the 3-D models.

Development of new datasets and a regional velocity models

Low magnitude events (below m_b=4.5) are of special importance for the CTBT. Teleseismic detection and location of such events by a sparse IMS network is not usually a simple problem. Hence, regional seismic phases like P_n, P_g, S_n, and L_g are particularly important for CTBT monitoring.

Diversity of regional conditions for seismic wave propagation and associated problems with location are well known. Ground truth data from natural and artificial events throughout of the world make it possible to construct and validate regional velocity models and location procedures. One of goals of the current project is to compile a data set of ground truth events including underground nuclear explosions, chemical explosions conducted for industrial purposes and earthquakes with well constrained location and origin time.

During the period of conduction of underground explosions by the USSR, the Institute for the Dynamics of the Geospheres (IDG) was responsible for data collection from permanent seismic stations in the USSR. Bulletins were compiled for events carried out at Semipalatinsk test site (STS), Novaya Zemlya test site and peaceful nuclear explosions (PNEs). The latter contain the most valuable information for seismological applications since they were conducted in various regions and geological environments. Ground truth data for selected STS explosions and PNEs are now available [e.g., *Sultanov et al*, 1999].

Under the current project, IDG collects ground truth data from the selected events, compiles bulletins for the events, validates various seismic arrivals against IASP91 model, and constructs regional velocity models. The models contribute to the multi-resolution tomography analysis efforts at Harvard University.

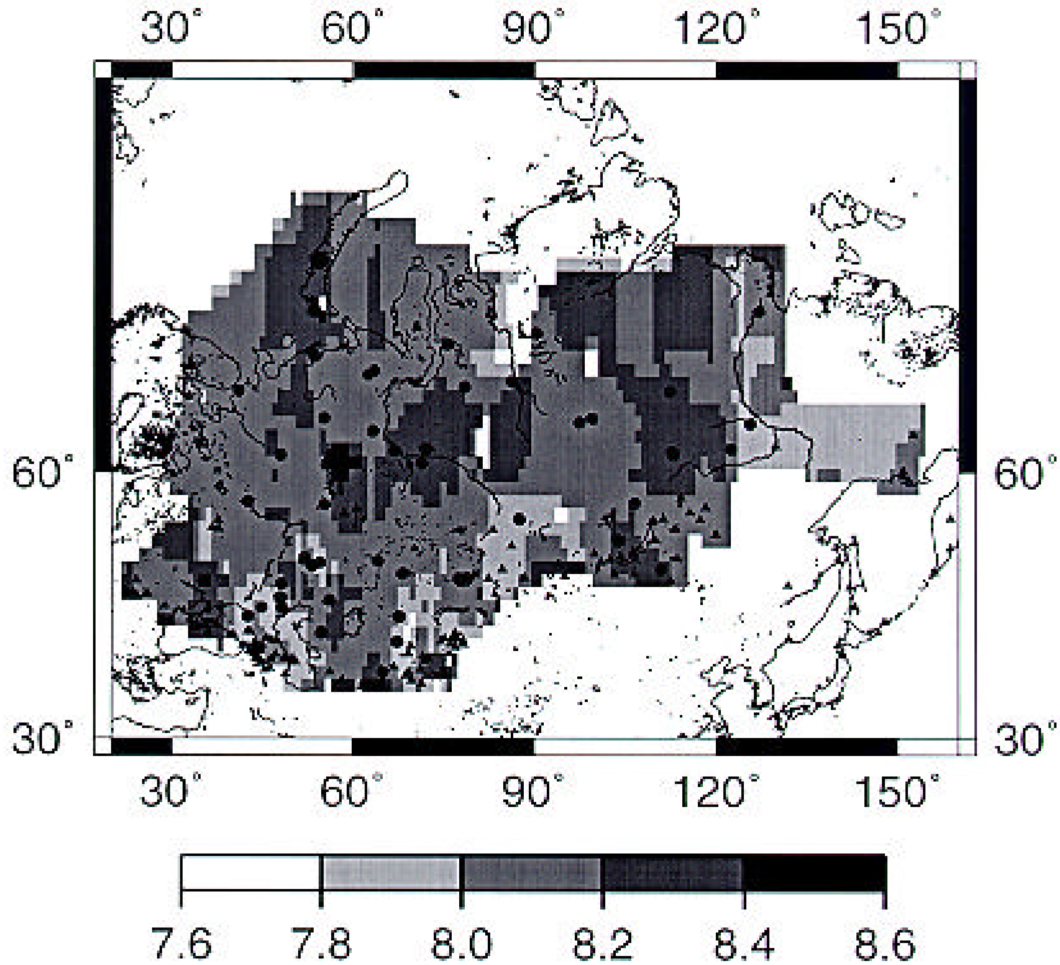

Figure 5: Variations in P_n velocity (v^0_{Pn}) obtained in a preliminary inversion of the ground truth travel time data set compiled under this contract.

The data set is currently under construction and contains travel times of regional phases (P_n, P_g, S_n, and L_g) as well as teleseismic phases (*P, PP, PPP, S, PS, SS,* etc.). Compilation of the data set includes reformatting of the data into electronic form, validation of selected seismic arrivals by analysis of seismic waveforms obtained from seismic stations and against the IASP91 model, analysis of unassociated seismic arrivals, analysis of station statistics and data quality.

The currently available data have been used to construct a 2-D velocity model for P_n-wave propagation across the territory of the former USSR. Common inversion algorithms are used to obtain a best fit model of seismic wave velocity beneath the crust. Since the P_n-wave is not a simple head wave, but a series of diving *P*-waves with increasing apparent velocity along the free surface, an assumption has been made that P_n-wave velocity is a linear function of distance everywhere in the region under investigation, $v_{Pn}(X) = v^0_{Pn} + cX$, where v^0_{Pn} is the P_n velocity just beneath the Moho, X is the distance from the source, and c is a coefficient, that is obtained from the best fit inversion. Figure 5 displays results from a preliminary inversion.

CONCLUSIONS AND RECOMMENDATIONS

Enough data seems to be currently available to conclude that, while all 3-D models of mantle velocity seem to provide substantial improvement over 1-D models in the ability to locate teleseismic events, the degree of improvement does not necessarily increase with the complexity of the model. Since it appears that neither the parameterization chosen for the tomographic inverse problem, nor the particular inversion technique used affect in large degree the solution obtained, some other explanation for this result should be invoked. For example, the type of regularization and damping employed in the inversion for block models with non-uniform data coverage might result in much lower amplitude anomalies in regions where the coverage is relatively low. This might lead to a tendency for block models to underpredict the range of observed residuals for events in some regions, such as we observe in Figure 2. Despite these results, we still believe that block models may be improved by including other types of data in the inversions and also by considering the effects of *P* wave anisotropy [*Boschi and Dziewonski*, 1999b].

To some extent, the results from the location trials with sparse data sets are encouraging in that they show that small to moderate teleseismic events may be located to within the specified 1000 km^2 area for the CTBT about two-thirds of the time. The median mislocation in such circumstances is around 12 km. This is true even if calibration information is not available for any of the stations. Further improvement may be possible if care is taken to ensure that sufficient observations are used from all azimuthal coordinates, which we have not done in this study. The probability of achieving this accuracy is increased to over 75% if calibration information is available. For very small events recorded by only a handful of phases, it will likely be necessary to include regional phases and/or azimuth information when using deterministic model corrections alone.

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