EMPIRICAL ANALYSIS OF A 3−D PAKISTAN REGIONALIZED VELOCITY MODEL FOR IMPROVED SEISMIC EVENT LOCATIONS

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ABSTRACT

The objective of this project is to improve regional event location in Pakistan and the surrounding regions by developing a 3−D velocity model for the crust and upper mantle. The CTBT goal of 1000 km^2 location accuracy for small events is dependent upon the availability of such models, which can be used to compute accurate travel times of regional seismic phases. Our approach is to refine an *a priori* 3−D velocity model through joint nonlinear tomography and multiple event location applied to regional earthquake arrival time data. Previously, we presented our *a priori* model, which is constructed on a 1°−by−1° grid to a depth of approximately 100 km. The preliminary model exhibits complex structural variation in the Pakistan region with crustal thickness ranging from 25 km to 75 km, a clear deviation from 1−D global models such as the IASP91 model (Kennett and Engdahl, 1991).

We have generated 3−D *P*, *Pg* and *Pn* travel time tables at regional distances by applying the finite−difference raytracing method of Podvin and Lecomte (1991) to our *a priori* model. To test our model empirically, we have relocated a suite of 44 Calibration Event Bulletin events using *P* and *Pn* arrival times from 14 stations in the Pakistan region, reported to the International Seismological Centre (ISC). Locations obtained with the IASP91 travel time tables were compared to locations obtained with our 3−D travel time tables. While our 3−D model results in smaller rms residuals for 29 of 44 events, the tests are not definitive since ground−truth locations are not available and the depths of the events are poorly constrained by the regional data.

We are currently expanding our database to include 55,000 phase arrivals from over 4000 events recorded at 77 stations in the study region, which we are expanding to include additional parts of southwest India. The arrival time picks at these and teleseismic stations were reassociated, and the events relocated, by Engdahl *et al.* (1998), leading to high quality location estimates. Approximately ten percent of the event locations are classified as GT5 (5 km location accuracy) or better. Using the reassociated *P* times at the regional stations, we intend to relocate a subset of the events using both the IASP91 and our 3−D travel time tables. A more extensive evaluation of our 3−D model will then be possible by comparing rms residuals, as well as comparing our locations to those obtained by Engdahl *et al.* Furthermore, the residuals resulting with our 3−D tables will comprise the primary data set for tomographic updating of our *a priori* model. We are analyzing the spatial pattern of these residuals and raypath coverage in anticipation of performing the 3−D tomography.

Key Words: seismic, 3−D velocity model, location, Pakistan, tomography

OBJECTIVE

Precise location of seismic events in the context of the Comprehensive Nuclear−Test−Ban Treaty (CTBT) requires accurate velocity models. The purpose of this research is to construct a regional velocity model of the crust and upper mantle structure to improve seismic event locations for the area between 25 and 40 degrees North and 55 and 80 degrees East. This area lies between the eastern border of Iran and the western edge of the Tibetan Plateau. To date we have developed a database of regional seismic events and supplemental information that will be used to construct and refine the velocity model through the application of tomographic techniques. We generate travel times through the region using a finite difference travel time modeling algorithm (Podvin and Lecomte , 1991) and use our grid search algorithm for 3−D hypocenter relocation. We are developing a joint inversion technique that uses multiple event relocation (incorporating input from our database of phase arrivals) to constrain iterative perturbations of the velocity model. This joint inversion will provide the ‘‘best’’ fit, in the least−squares sense, between the observed and predicted arrival times. The end result will be a refined 3−D velocity model and improved multiple hypocenter estimates. In this report we describe the progress we have made towards building a high quality regional model during the second year of this three year project.

RESEARCH ACCOMPLISHED

Phase Arrival Database and 3−D Velocity Model Development and Testing

Two primary objectives during the first two years of this project have been to collect and refine a high quality database of phase arrivals and to develop a good 3−D preliminary velocity model over the region. Both the database and the 3−D velocity model can be used in tomographic studies as well as other related projects. During this reporting period we have addressed gaps in the ray−coverage over Pakistan by expanding our study area boundaries to the West (covering areas of Iran), North (including areas of Uzbekistan, Kyrgyzstan and Kazahkstan) and East (China and portions of northern India) where additional data were readily available. We are also expanding our region to the South to include areas of northwestern India. Below we detail some of the development and testing of the phase arrival database and 3−D velocity model that has occurred during the previous year.

Travel Time Database Improvements

Our initial effort to establish a database of regional phase arrivals began with the acquisition of bulletin data for approximately 700 seismic events. These phase arrivals were obtained from three online sources, including the Prototype International Data Center (pIDC), the International Seismological Centre (ISC), and the Incorporated Research Institutes for Seismology (IRIS). During the early stages of our research, we used these data to identify a set of test events that would contribute the "observables" portion of our input data and also provide a set of validation events. Because these events have been located by multiple organizations, the redundancy of hypocenter estimates and the availability of depth phase data provided a measure of the accuracy of the combined event catalog. Upon comparison of different estimates, it became apparent that the relative quality of the location estimates exhibited significant variation, particularly in depth. The pIDC reported very few ground truth (GT) events with location accuracies better than 25km (GT25). This lack of validation events presents a significant challenge in establishing a demonstrable advantage in using a 3−D model over the standard 1−D models currently used. In this performance period, we have investigated methods of addressing these concerns, and give details of some of these procedures later in the paper.

We have expanded our in−house database of phase arrivals by incorporating the results of very recent hypocenter relocation studies. In particular, we compared the relative hypocenter accuracies of the ISC catalog with those reported by Engdahl *et al.* (1998). In that study, the authors reassociated the ISC arrivals and then relocated the events using the AK135 velocity model. Our original database reflected the hypocentral estimates as reported only by the three locating agencies previously noted. For instance, the pIDC’s Ground Truth Database for the Pakistan region identified only 60 GT events during its period of data availability. Of those, only 7 are reported as being located with hypocenter accuracies better than GT 25 (one event, the 1974 Indian nuclear test, is listed as a GT0, while six events are classified as GT1, including the 1998 India and Pakistan nuclear tests). By comparison, the Engdahl *et al*. (1998) results report 2,181 events qualifying as GT10 or better (including 8 explosions), of which there are 426 events qualifying as GT 5 or better. The availability of these additional well located events improves our ability to verify the quality of our tomographically derived velocity model. In addition, the Engdahl *et al*. (1998) database offers an additional advantage, because P waves were reclassified as Pn when appropriate. This provides an important data distinction that we take advantage of, since in our method we invert for these secondary arrivals using independently derived travel time calculations.

In summary, our database has expanded from 7,599 phase arrivals to 54,770 P, P*n*, and P*g* arrivals. These events are distributed in depth, with the predominant proportion (76.5 percent) being located within the top 100 km of the Earth's surface. The magnitudes of these events range from a high of 6.5 (m_b) to a minimum of 3.0. More than 80 percent of these events have at least 10 regional stations reporting phase arrivals A total of 77 regional stations contributed arrivals to the expanded database. We are currently in the process of evaluating the azimuthal gaps for these events. We will continue our effort to identify, evaluate and incorporate phase data from events with high quality location estimates . To ensure an independent test of our tomographic model, we will establish a set of our highest quality events to be used solely for verification purposes.. The remainder will be used in the tomographic inversion.

Velocity Model Improvements

High density, well distributed ray coverage is crucial to the success of a tomographic inversion, because it constrains the possible velocities for large portions of the model grid. We have increased the size of our study area to incorporate rays that travel significant distances within our contractual region but are not contained entirely within it. This increase in sudy size has required the collection of additional geologic and geophysical information to expand the model to the South into sections of India. There are a number of stations in this region that will provide travel times through the southeastern quadrant where the southwestern portion of the Indus Suture defines the convergence of the Indian plate with the Eurasian plate. Incorporating rays that cross this region is especially important for the purposes of CTBT monitoring because seismic events that occur near test sites would propagate rays through this region. Accurate hypocenter location estimates would rely heavily on the quality of the velocity model available for this region. In the following sections we cover some of the procedures we have implemented to test the validity of our input 3−D regional velocity model.

Velocity Model Testing Using Reciprocity

On 14 Feb 1977, a magnitude 5.2 earthquake (Table 1) occurred in the region near Nilore, Pakistan. The event forms an interesting test of reciprocity for the velocity model near station NIL. We collected arrival time data from 24 stations within our model region that recorded the event, and then compared the observed travel time residuals at these stations, with respect to the Jeffreys−Bullen (JB) global model, to the predicted travel time residuals computed using our preliminary 3−D model (Figure 1). The results show that our 3−D model predicts the regionally observed travel times better than the JB model by a factor of 1.5. We expect that the largest residuals between the predicted and observed travel times (Figure 2) will decrease following a full tomographic inversion of our dataset.

Date	***OT***	***Lat***	***Long***	***Depth (km)***	***Mag***
14 Feb 1977	00:22:38	33.5967	73.2669	27	5.2

Table 1. ISC Origin data for an earthquake that occurred beneath station NIL. The ISC listed the depth as 27 km; however, detailed aftershock studies in the epicentral region suggest the 14 Feb 1977 main shock occurred at a depth of 12−20 km (Seeber and Armbruster, 1979). To accommodate this depth range, we computed the SSSC for station NIL at 15 km.

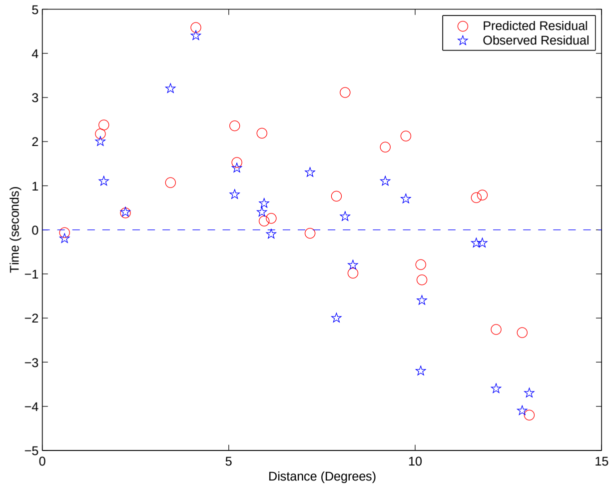

Figure 1. Observed P*g* and P*n* travel times at 24 regional stations that recorded the 14 Feb 1977 event underneath NIL. The predicted travel times were calculated using the Weston 3−D velocity model for Pakistan and were found to model the observed data by a factor of 1.5 times better than the fit provided by the Jeffreys−Bullen model.

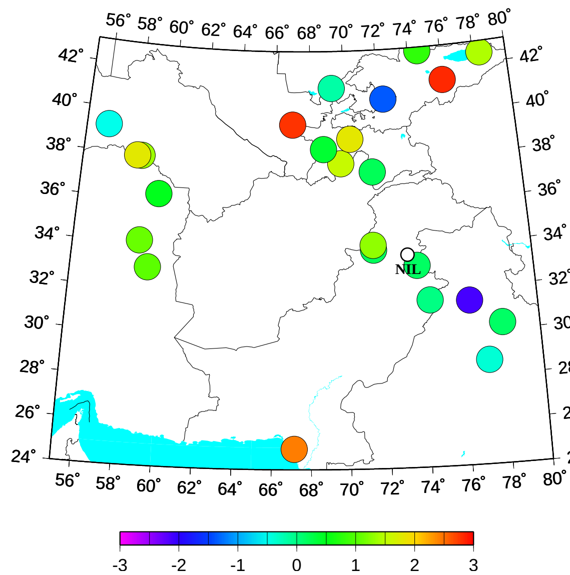

Figure 2 Difference between observed and predicted travel times as plotted at the stations that recorded the Nilore (NIL) earthquake.

Velocity Model Testing Using Jackknifing

We are interested in establishing a baseline understanding of how our preliminary input model performs in comparison to the 1−D IASP91 model. Comparing rms travel time residuals from event locations using the two different models has shown inconsistent results. The jackknife method of estimating error (Efron and Gong, 1983) provides another comparison of location performance between our 3−D model and IASP91. In this method, we relocate each event multiple times (as many times as there are observed phase arrivals in the inversion), and for each relocation, we exclude one phase arrival. Inspecting the spatial distribution of all of the relocation estimates provides a measure of how each data point affects the inversion. Large changes in the hypocenter introduced by a particular datum can indicate either poor quality phase picking or it can indicate a poor model along that ray path. A good model and well picked data would produce a full set of relocation estimates that are tightly clustered.

We applied the jackknife method to four events from the Engdahl *et al.*(1998) database. These 4 events are a subset of 200 that we used for a pre−tomographic analysis test case discussed later in this paper. The results of the 4−event jackknife study are shown in Figure 3. Events 1 and 2 have 24 and 22 arrivals, respectively, and show smaller hypocenter changes relative to events 3 and 4 which have only 10 arrivals. The rms residuals for events 1 and 3 were smaller for our 3−D model (0.923 s and 1.196 s, respectively) than for the IASP91 model (1.071 s and 1.594 s). For event 2, the residuals were similar (0.844 versus 0.883). The residual for event 4 is larger in the 3−D model case (1.572 s) than in the IASP91 case (1.414 s). The results of the jackknife tests indicate that, in all cases, our 3−D model produces smaller relocation scatter than does the IASP91 model (See Table 2 for scatter values). This indicates that even our initial 3−D model produces a more robust fit to the observed data than does the 1−D model, and a 3−D model improved by tomographic inversion should perform even better.

EVENT ID	***3−D*** ***Epicenter Scatter (KM)***	***IASP91*** ***Epicenter Scatter (km)***	***3−D*** ***Depth scatter (km)***	***IASP91*** ***Depth scatter (km)***	***Number of Data***
1	0.6750	0.7375	1.6083	1.9542	24
2	0.5636	0.6227	1.2772	1.2864	22
3	8.2600	12.610	27.810	48.790	10
4	4.3600	4.7500	5.7000	7.9900	10

Table 2. Results of the jackknife study of four events from the Engdahl et al. (1998) database. The values indicate average scatter.

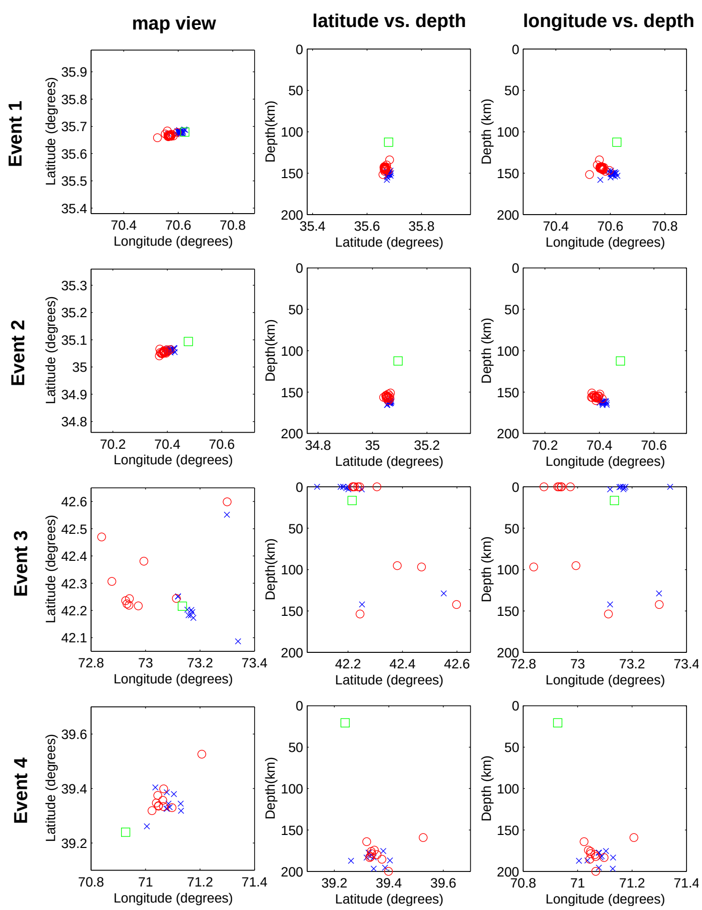

Figure 3. Jackknife test results for four events. "X"s represent 3−D model hypocenters, "o"s represent 1−D IASP91 model hypocenters. Singular squares represent the hypocenters calculated by Engdahl *et al.* (1998) using the AK135 model.

Preliminary Tomographic Analysis

Figure 4 illustrates the five main components in our tomographic inversion method that have either been completed or are in development. The "Condition Model" function transforms input velocity models into the proper format for the inversion. Converting from spherical to Cartesian coordinates produces a station−centered sub−grid which, in part, reduces errors introduced by the coordinate transformation. This module reparameterizes the velocity model to reduce the size of the tomographic inversion and constrain the inversion to geologically realistic solutions. The "Predict travel time" function produces travel time tables for each station. Using a finite difference implementation of Huygen's principle (Podvin and Lecomte, 1991; Lomax, 1999), we

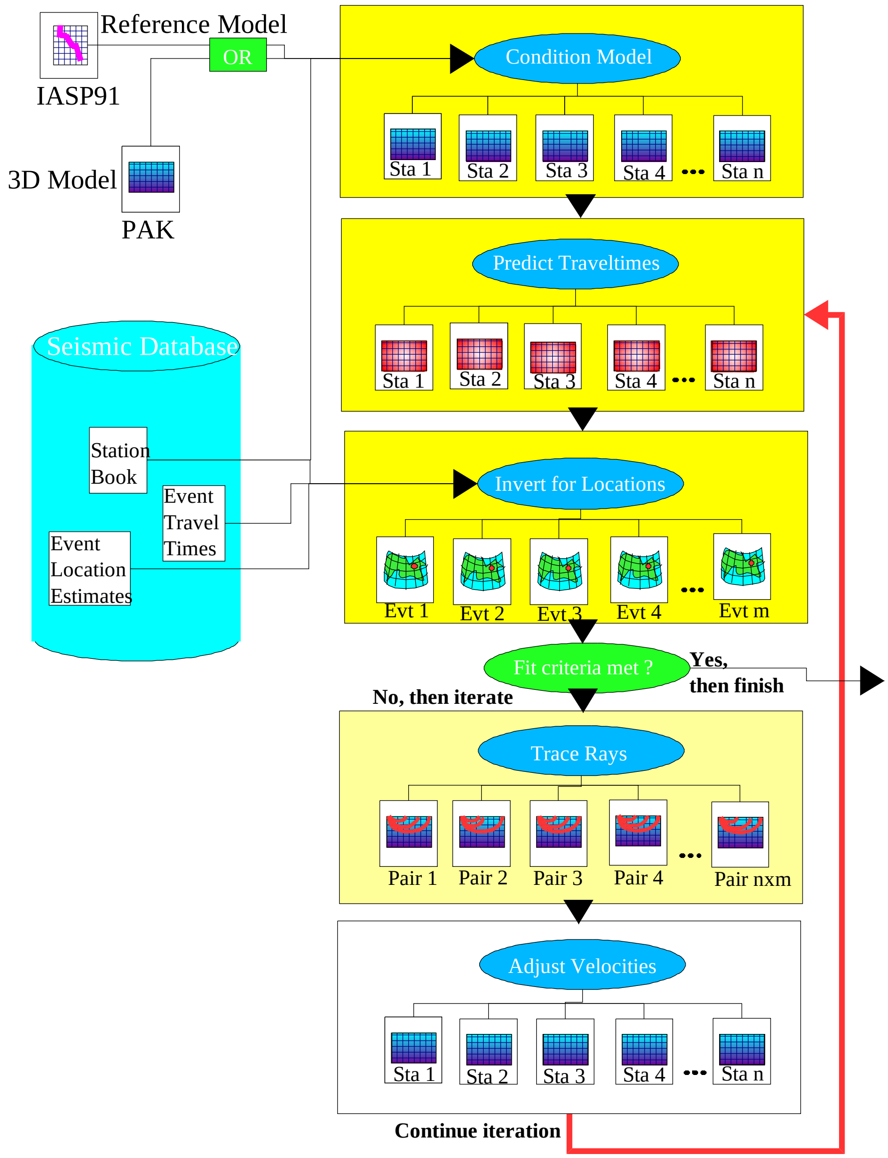

Figure 4: Schematic overview of joint tomographic inversion for a 3−D velocity model and improved seismic event hypocenters. The degree of completion of a particular function is indicated by the shading of the block, where lighter shades indicate modules which require further development.

Our 3−D grid search algorithm ("Invert for location") produces hypocenters for each event in the tomographic inversion. More specifically, it obtains the maximum likelihood estimate (MLE) of the hypocentral parameters and the probability density function scale factor by searching a grid of solution hypocenters through subsets of increasing fineness. The final MLE of the hypocenter is taken as the solution achieving the largest likelihood among all the points of the grids searched. We used this algorithm to generate the estimates shown in the jackknife test discussed previously.

In order to use the Podvin and Lecomte (1991) travel time estimation method as the forward modeling core of the tomographic inversion, we are expanding its functionality to include the generation of accurate spatial coordinates of the rays as they travel from the source to the receiver. The lack of accurate ray coordinates is a deficiency in the original version of the original that must be remedied prior to performing tomographic inversion. The improved ray tracing module will produce ray coordinates for each input station/event phase arrival time, which will be recalculated after every update of the velocity model until the fit to the data falls below a predetermined threshold criteria.

In any inversion, a reasonable guess of the velocity structure in the starting model is very important . To test the appropriateness of our 3−D *a priori* model, we relocated a set of 44 Calibration Event Bulletin events using arrival times form 14 regional stations. In this analysis, our 3−D model resulted in smaller rms residuals for 66 percent of the events. Since ground truth locations are not available for these events and the depths are poorly constrained by the regional data, further analysis was performed on a larger data set. In an extension of this study, we relocated 200 events from the Engdahl *et al.* (1998) database using our current 3−D model (Fiugre 5).

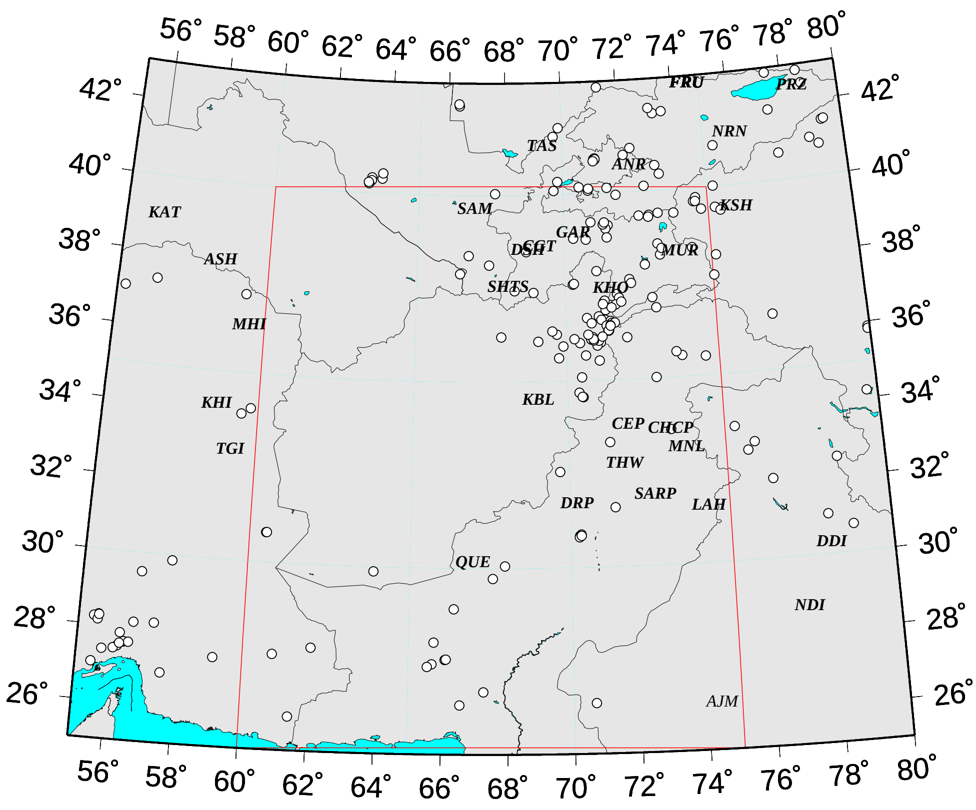

Figure 5. A set of 200 events from the Engdahl *et al.* (1998) database used in an preliminary test of our tomographic inversion plan.

We chose events that were reported in the catalog to have standard error in position of less than or equal to 5 km, as determined from the diagonal elements of the covariance matrix (Engdahl *et al.*, 1998). The event list was further narrowed to optimize spatial distribution and to exclude deep events (maximum depth was 163 km). A subset of thirty regional stations, also selected for optimal spatial distribution as well as for quantity of data reported in the bulletin for each station, was used to locate each event. We relocated each event with the Weston

3−D velocity model of Pakistan and then with the 1−D IASP91 model. This test was performed for three different cases relative to the Engdahl *et al.* (1998) hypocenter solution: (1) constrained to a 10 km radius in X−Y space and +/− 20 km in Z, (2) a fixed depth constrained to +/− 5 km, but free in X−Y space, and (3) a free solution in all directions.

The hypocenter solution for the 3−D model has a smaller rms residual for approximately 75% of the events in both variations of the constrained cases (1 and 2) and it has smaller residuals for just over 60% of the events in the free solution (3) (see Table 3). Average standard error reductions for the set of events are also shown to be 130−170% greater than average standard error increases for the 3−D hypocenter solutions compared with the 1−D solutions. These results show that the 3−D model is generally fitting the data better than the 1−D model. A smaller rms error can be an indication of a better location; however, 3−D structures may introduce biases that lead to smaller rms errors. Therefore, small rms residuals are not an absolute indicator of a better location. Other tests (such as jackknifing, as discussed in the previous section) are required to demonstrate that locations calculated using the 3−D model are more accurate than the 1−D solutions.

Location Constraints	**No. of 3−D Events with smaller rms residuals than 1−D**	**No. of 3−D Events with larger rms residuals than 1−D**	**Average Standard Error Reduction**	**Average Standard Error Increase**
Case 1: XYZ*	148	51	0.4042	0.2098
Case 2: Z	148	52	0.3920	0.2298
Case 3: None	121	79	0.2766	0.2118

**One best hypocenter solution was found outside our model region and was removed from this evaluation*

Table 3. Comparison of rms residuals for preliminary tomographic analysis of 200 events from the Engdahl, et al. (1998) database. These events were relocated using both the 3−D regional model and the 1−D reference IASP91 model. Three different hypocenter contraint conditions were imposed on the inversion.

To obtain a preview of the magnitude and spatial distribution of travel time residuals over the model space, we plotted the residuals for each station−event pair at the great−circle midpoint of the ray. This is only an informal spatial approximation, as the residuals are distributed over the entire raypath. Therefore, interpretations and conclusions drawn from this representation of the results are limited and must take the nature of the midpoint approximation into consideration. We can see from Figures 6 and 7 that locations determined using the 3−D model result in overall smaller residuals than those determined by the IASP91 model. In both cases, the magnitudes and sign of the residuals appear to exhibit a spatial correlation across some regions. For most regions, it appears that the 3−D model already does a better job of approximating the true velocity structure than IASP91, as expected. However, we anticipate that full implementation of the tomographic inversion, which will update the *a priori* model along the full raypath between each station and event, will improve the regions that are less well constrained in the preliminary model. This initial test demonstrates the functionality of the majority of components required for tomographic inversion. It also produces a "preview" of the spatial distribution of travel time residuals over the model space.

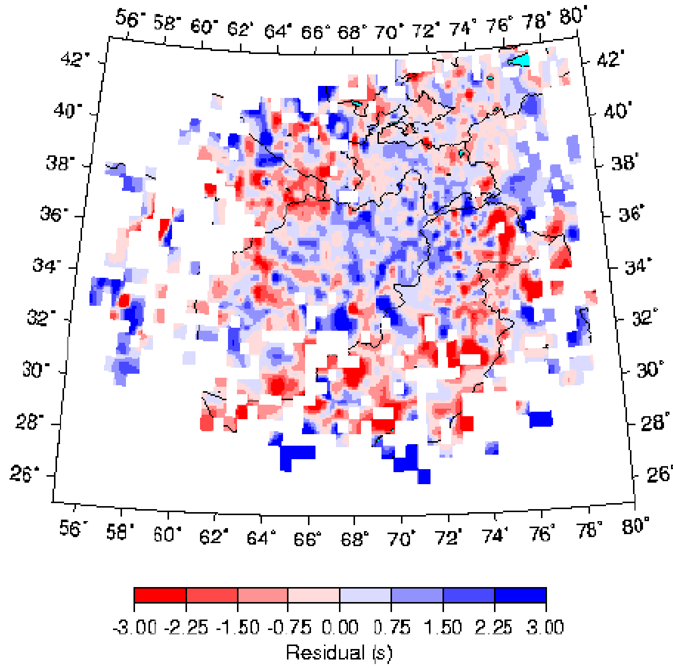

Figure 6. Residuals of 200 events relocated using the Weston 3−D velocity model of Pakistan. The solutions were constrained to within a 10 km radius in XY space and to +/− 20 km in depth of the Engdahl *et al.* (1998) solutions. Residuals are plotted at the great circle midpoint of the raypath and are averaged for points located within a 9 km grid spacing. Areas not resolved from this small set of the data are white. Large residuals (either positive or negative) are indicated in dark shades, whereas light shades indicate residuals approaching zero. Highs and lows are indicated by either a"+" or "−" sign..

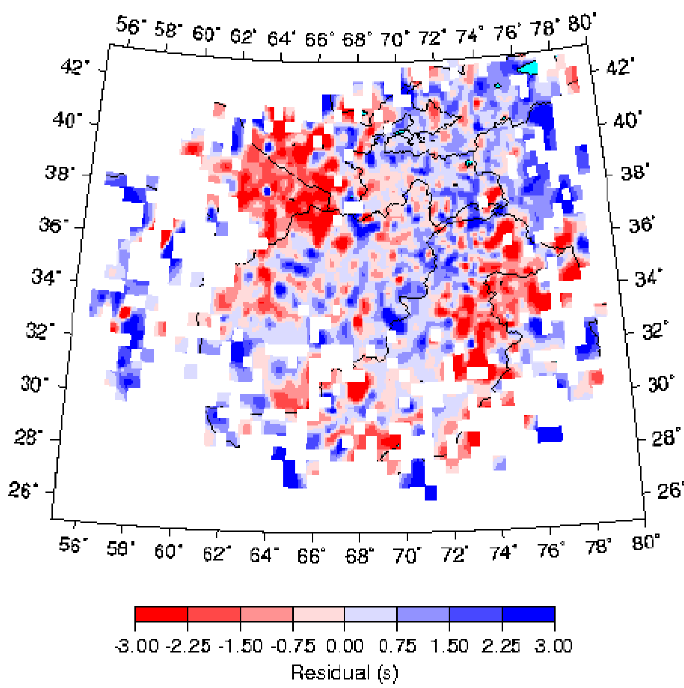

Figure 7. Residuals from the same set of events shown in Figure 6 relocated using the IASP91 1−D travel time tables.

CONCLUSIONS AND RECOMMENDATIONS

During the past year we have made significant progress towards producing a fully 3−D tomographic velocity model of the Pakistan region and surrounding areas. We have completed the development and testing of a 3−D starting velocity model and have established a database of seismic events that we are using as the input travel times to the inversion. We continue to evaluate the quality of each of our input data sets to ensure the highest quality data is available for our inversion. In this paper we have described the functionality and demonstrated the application of key computational modules necessary to support the final tomographic inversion. In each case, we have completed various performance tests on the computational accuracy.

Work to be completed during the final year of this contract includes the final development and implementation of the joint inversion technique and establishment of appropriate convergence criteria. Once these modules are completed and tested, we will perform a full tomographic inversion to produce an accurate regional 3−D velocity model for the Pakistan region and the consequent improved hypocenter estimates.

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