DEVELOPMENT OF A 3-D MODEL FOR IMPROVED SEISMIC EVENT LOCATION IN THE PAKISTAN/INDIA REGION

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ABSTRACT

The ability to accurately perform location calibration in regions of monitoring concern depends heavily on an understanding of the crust and upper mantle velocity structure in the region. Our project is focused on developing a 3-D model of Pakistan and surrounding regions for the purpose of improving seismic event location. During the initial portion of the study, we have developed a preliminary 3-D model of the region and a regional seismic event database as a foundation for performing tomographic inversion and event location.

We constructed the preliminary velocity model by synthesizing data from references that contained both direct and indirect information about the velocity structure, geology, and tectonics throughout the region. The sources of data for the velocity model vary in spatial coverage, resolution, and the number of constraints; consequently, the model varies in a similar manner. Developing a unified 3-D model has allowed us to obtain constraints on the large-scale variations in the depth to the crust-mantle interface (Moho discontinuity) across the region. For example, the Moho is approximately 25 km deep near the coast in the Makran region of southwestern Pakistan where the Afghan plate is being subducted beneath the Eurasian plate (Byrne *et al.*, 1992). In contrast, the Moho reaches great depths beneath the Pamir region in northern Pakistan, where it dives to 70 km depth at the interpreted meeting point of subducted Asian continental lithosphere with the under-thrusting Indian lithosphere (e.g. Fan *et al.*, 1994). Our composite 3-D velocity model illustrates the large range of crustal thickness in the Pakistan region, a factor that could result in significant error in travel-time calculations based upon models (such as IASPEI91) with a constant 35-km thick crust.

In addition to developing the preliminary velocity model, we have also constructed a partial database of phase arrival times and waveforms for local, regional, and near teleseismic events. The principal objective of the event database is to provide as much ray coverage through our 3-D model as possible. We have identified permanent and temporary seismographic stations for the time period between 1989-1998, and have found that at least 12 organizations have operated as many as 159 regional and local seismographic stations in the region. We referred to multiple data collection sources to construct our database, including the prototype International Data Centre's (pIDC) reviewed event bulletin (REB) archives, the International Seismological Center (ISC), National Earthquake Information Center (NEIC), and the Incorporated Institutes for Research in Seismology (IRIS). From these online sources, we were able to obtain phase arrivals from 61 of 159 of the potential stations. Additional offline efforts will be required to obtain times from the remaining 98 stations. Nevertheless, the acquired data provides 6096 phases including P, Pn, P*, pP, PP, PcP, S, Sn, SS, and exhibit an azimuthal coverage which approaches that estimated for the full complement of 159 stations.

We have completed the development of both the preliminary velocity model and a partial database of seismic phases and are currently beginning the tomographic inversion effort. Two initial tasks prior to performing a full tomographic inversion include comparing travel times calculated using the IASPEI91 or other regional 1-D models versus those computed using our model, and performing event relocations with the preliminary 3-D model and a grid-search location method.

Key Words: seismic, 3-D velocity model, location, Pakistan

OBJECTIVE

Seismic calibration of regions of monitoring concern requires the development and validation of 3-D models of regional seismic velocity that improve the location of events. We are working on a multi-year project to develop such a model, along with improved event locations, for a region centered on Pakistan that extends into eastern Iran, southern states of the Former Soviet Union, and western India. The first year of the project has focused on the development of a preliminary 3-D model and the foundations of a seismic event database. We have also begun the development of our joint tomography and location technique, with the ultimate purpose of providing validated source station specific corrections (SSSCs) to the pIDC for International Monitoring System (IMS) stations in the Pakistan/India region.

RESEARCH ACCOMPLISHED

Preliminary 3-D Regional Velocity Model

There are several preliminary steps that must be completed prior to performing tomographic inversion and relocation of events in the Pakistan region. As a first step, we have developed a preliminary 3-D regional velocity model (see Figures 1 and 2) to serve as a starting point for the tomographic inversion. Our model is bounded by 55-80° east longitude and 25-45° north latitude. This is an expansion of our originally proposed model boundaries (60°-75°E, 25°-40°N) to allow for adequate data coverage of the region. This enlarged area includes portions of India, Pakistan, Afghanistan, China, Tajikistan, Kyrgystan, Uzbekistan and Turkmenistan. We defined the preliminary velocity model on a grid of one-degree latitude by one-degree longitude blocks and 5 km depth intervals from 0 to 75 km. We constructed the velocity model by synthesizing data from 27 published references that contained information about the velocity structure throughout the region. To derive a reasonable estimate of the gross velocity structure in regions where direct velocity measurements were lacking, we compiled information indirectly related to velocity from over 50 sources pertaining to the geology and tectonics of the Pakistan area. The sources of data for the velocity model vary in spatial coverage, resolution

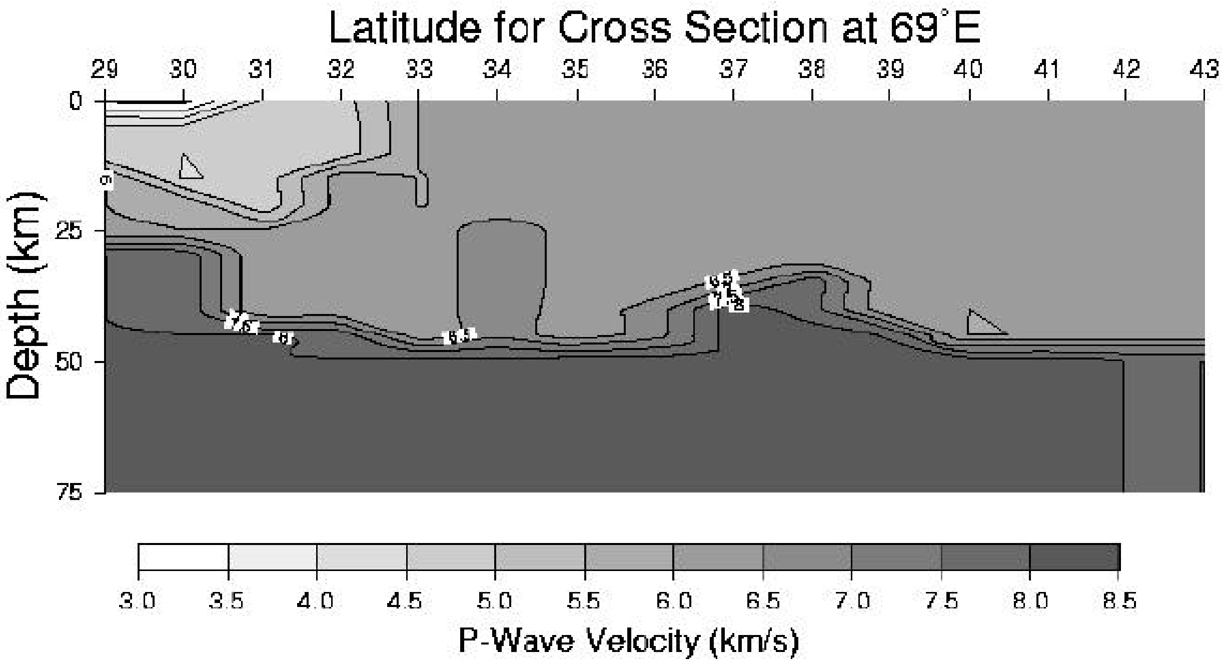

Figure 1. Latitudinal cross section of the preliminary velocity model at 69°E. This cross section cuts through part of the Sulaiman Lobe and continues north across the Tadjik Depression. Note the presence of thick low velocity material in the Sulaiman region (~15 km of sediments) overlying a shallow Moho. The Moho deepens quickly to the north, and then shallows once again beneath the Tadjik Basin (~37°N). This figure demonstrates the effects of merging the results of many studies that have varying resolution on different depth intervals. For example, there have been numerous research studies on the shallow structures in the Sulaiman region as opposed to other areas where more detailed data for shallow structures are lacking. These attributes are subsequently reflected in the velocity model.

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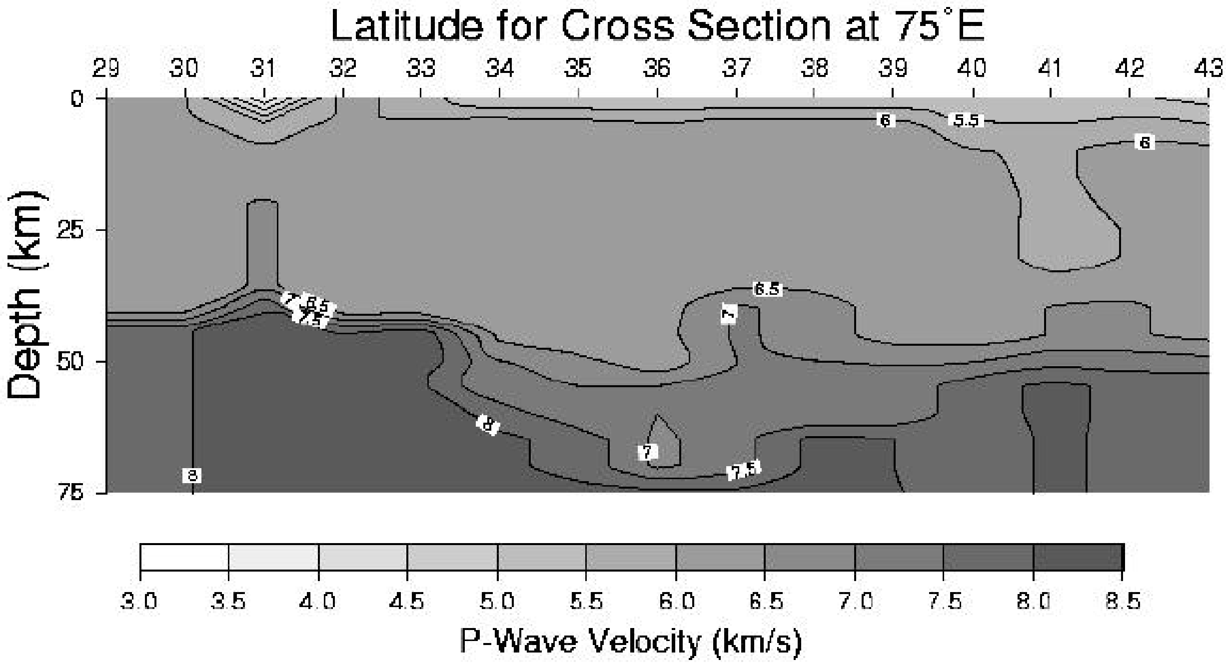

Figure 2. Latitudinal cross section of the preliminary velocity model at 75°E. This cross section is further to the east where the southern part of Indian sub-continent has near-average crustal thickness. Note how the Moho deepens considerably and then shallows again (near 36° N, observing the 7.5-8.0 km/s contour interval) as the cross section passes through the Karakoram and the Pamir regions to the north (e.g. Fan *et al.*, 1994). Other smaller features must be carefully interpreted, because the blending of data from studies of varying resolution scales may lead to certain artifacts in the model.

in a similar manner. We have appended the IASPEI91 model (Kennett and Engdahl, 1991) to the base of the preliminary velocity model, beginning at 80 km depth and extending to 400 km depth, since raypaths of certain event-station pairs within our region travel into the upper mantle. If the need arises, we will compile information on the mantle velocity structure between 80-400 km depth, so that we can replace the IASPEI91 model with one more appropriate to the Pakistan region.

Compiling past and current research into a unified 3-D model has resulted in constraints on the large-scale variations in the depth to the crust-mantle interface (Moho discontinuity) across the region. Due to the complexity of crustal deformation across the region, variations in depth to the Moho are significant (see Figure 3). Any understanding of the nature of these variations is a great improvement from the currently used IASPEI91 model that assumes a constant crustal thickness of 35 km. For example, the Moho is approximately 25 km deep near the coast in the Makran region of southwestern Pakistan where the Afghan plate is being subducted beneath the Eurasian plate (Byrne *et al.*, 1992). In contrast, the Moho reaches great depths beneath the Pamir region in northern Pakistan, where it dives to 70 km depth at the interpreted meeting point of subducted Asian continental lithosphere with the underthrusting Indian lithosphere (e.g. Fan *et al.*, 1994). Travel time calculations based on a constant 35-km thick crust will produce significant error in the Pakistan region, where there is a large range of crustal thickness.

Other large-scale features of note in the Moho surface include the following:

- A slight rise in the Moho beneath the Sulaiman (~32 km depth) before the Moho dips sharply to the northwest at the Chaman fault. At this point the Moho becomes considerably deeper (~57 km depth) beneath the Afghan block (Jadoon and Khurshid, 1996).

- A rise in the Moho beneath the south Caspian Sea (~33 km depth) in the northwest part of our study region (Mangino and Priestley, 1998; Priestley, 1997). Moho depth increases to ~47 km away from this shallow section.
- Shallow Moho (~35 km depth), compared with surrounding regions, beneath the Tadjik Depression located in the region surrounding 37°N, 68°E (e.g. Mellors *et al.*, 1995).

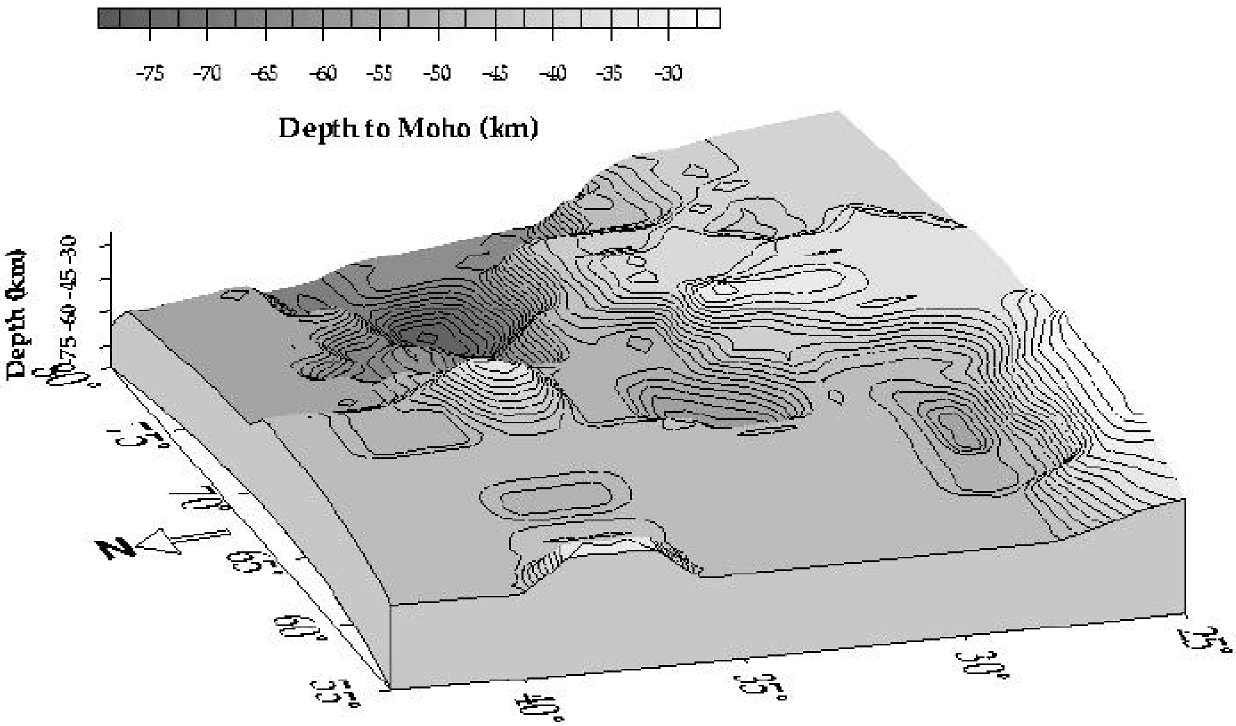

Figure 3. Contoured and smoothed surface plot depicting variations in depth to the Moho boundary determined by data synthesis of approximately 27 published references

Seismic Event Database

Another important step in building a 3-D velocity model of the Pakistan region is to collect a large seismic event database. The information stored in our database is intended to serve multiple purposes. The principal and initial purpose for the database is to provide the arrival time data used to develop our 3-D tomographic model. The database must contain regional phase arrival times for ray paths with enough azimuthal and depth coverage to adequately sample the modeled volume. Additionally, the arrival times must be reliable enough to support the highest quality tomographic results. We are attempting to include only quality arrival times, and so we have started compiling the database by incorporating data from major seismological data-serving organizations. These include the pIDC, the ISC, IRIS, and the NEIC. As our database expands, we intend to increase our list of information sources so that we may improve the available ray coverage for tomography purposes and expand the suite of phase types in our holdings.

A secondary purpose for compiling an event database is to provide useful seismological information for future studies of the India/Pakistan region. We are investigating which seismological data, beyond just the arrival times, will be most useful for CTBT projects, and how this data should best be organized, stored, accessed and shared with outside interested parties.

We are developing the database in three phases, an initial assessment and design phase (already completed), a data collection phase (in progress), and a quality assessment and control phase (upcoming).

Phase One: Geographic Coverage, Station Lists and Event Bulletins

To provide adequate coverage at the edges of our originally proposed model (60°-75°E, 25°-40°N), we populated our database using an expanded grid (Figure 4). We included stations and events from an area 5 degrees larger on the west, north, and east sides of our modeling area and 10 degrees on the southern edge bringing our expanded grid boundaries to 55-80 ^{o} E longitude and 15-45 ^{o} N latitude.

Due to the interesting and complex tectonics of the region, our area of study encompasses a region in which at least 12 seismographic networks have operated more than 159 seismographic stations since the early 1960's (see Figure 4). The temporal availability of data from this set of stations is, of course, variable and we are

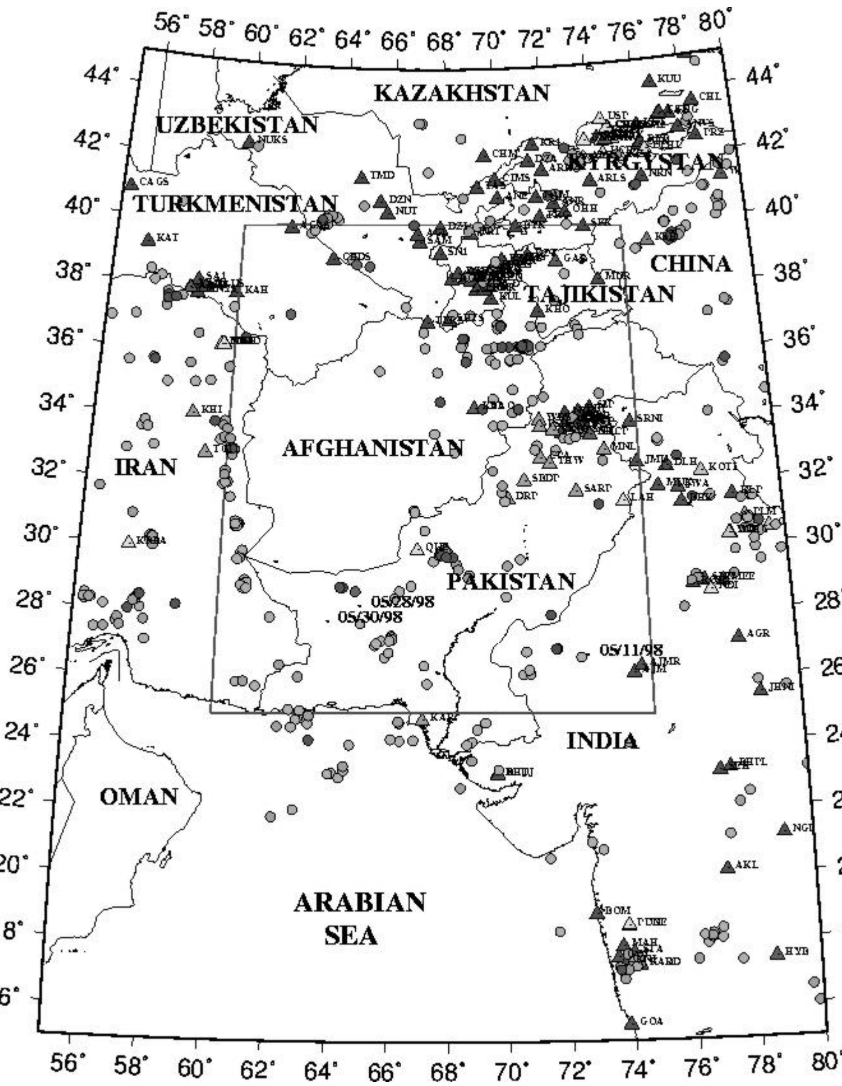

Figure 4. Map of study area showing location of all known seismographic stations and hypocenters for 441 seismic events.

conducting an ongoing investigation to identify additional networks and stations. Our current list of organizations that have operated networks in the area includes: Institute of Physics Moscow (MOS) and

Institute of Physics Moscow Regional Networks (MOSR), the Pakistan Institute of Nuclear Science and Technology (PINS), the Pakistan Meteorological Department Quetta Network (QUE), the India Meteorological Department (NDI), the Wadia Institute of Himalayan Geology, Dehra Dun, India (WHIG), the Institute of Geophysics, Beijing (BJI), Ferdowski University, Iran (MUI), the University of Tehran (THE), the National Institute of Earthquake and Seismology, Tehran, Iran (THR), Lamont Doherty Network(s) (PAL), and Cambridge University.

Currently, our database contains arrival time data from 61 of the 159 known stations. Stations that contribute phase arrivals for the 441 events currently held in our database include: AAA, AAK, ABKT, AGL, AJM, AKL, ANR, ASH, BHJ, BHK, BOM, BZN, CEP, CGT, CHCP, CPA, DDI, DRP, DSH, DZE, DZI, DZT, FRG, FRU, GAR, GOA, HYB, JHNI, JMU, KAD, KAT, KHO, KRU, KSH, KUL, LNA, MAIO, MHI, MUR, NAM, NDI, NIL, NRN, NUT, OBG, POO, PRZ, PTH, QUE, RGR, SAM, SARP, SBDP, SEH, SHTS, SRNI, TAS, THW, TLG, URT, and VAN (see Figure 4). We have identified over 3600 events in our target region for which data is available from the major online sources. Currently, our holdings include 441 of the “best” events. We defined “best” as any event with a relatively higher magnitude than the other available events in the same hypocentral region and a hypocenter location that optimizes the spatial distribution of ray coverage.

The events in our current catalog were recorded during the decade 1989—1999. This time span was chosen to allow more rapid online data retrieval. It is our intent, however, to supplement this catalog with additional data from events recorded prior to this period, provided that the data can be efficiently and accurately incorporated. This effort will include data collection from offline sources and may require selective digitization of waveforms from paper record archives, if particular rays are needed to enhance the tomographic modeling results.

Phase Two: Data Collection

Our database currently contains all of the phase arrivals reported by the source organizations for each of the 441 events mentioned above. We have extracted a subset of these arrivals for further study and possible inclusion in our tomographic inversion. Figure 5 presents the ray coverage available given one possible subset of 6096 regional phase arrivals. The phases represented include P, Pn, P*, pP, PP, PcP, S, Sn, and SS. The rays included in this subset of arrivals provide excellent azimuthal coverage of the area to be modeled. Incorporation of both near and far regional phases and arrivals from events at various depths will provide maximum ray coverage as a function of depth.

We are currently populating our database with both arrival time data and digital waveform data. Our initial priority has been to collect the phase arrival travel times that are needed for the 3-D modeling and tomography. Waveform data collection, while important, is linked primarily with the process of quality assessment and control of the arrival time data. As our phase arrival time database volume increases, we will obtain digital waveform data for each of the events contributing arrival times to our modeling effort. These waveforms will be used to confirm the arrivals incorporated into the modeling and will also be important for future assessment of regional phase characteristics.

Phase Three: Quality Assessment and Control

The events currently held in our database have had hypocentral parameters estimated by all of the agencies from which we obtained our data records. The accuracy of the estimates generated for these events varies according to the number of arrivals used by the particular agency, the quality of those arrivals, the station distribution, the algorithm and the input velocity model. We have attempted to include events with the best hypocentral estimates available, incorporating many events from the pIDC's ground truth databases (GT0,GT1,GT2,etc.) and the Calibration Event Bulletin (CEB). We have reviewed the events listed in the Ground Truth and Calibration event databases and determined that one GT0 event is located in our region, along with an additional five GT1 events (Yang *et al.*, 1999). There are no GT2 or GT5 events, and we are currently conducting a cross-reference of our database holdings with the GT10 and higher database listings. Forty-nine of our events are pIDC CEB events (many of which are anticipated to also be included in the GT10 database event list), 112 are pIDC REB listed events, 211 were obtained from the ISC bulletins and the remaining 64 were obtained from the IRIS and other online sources.

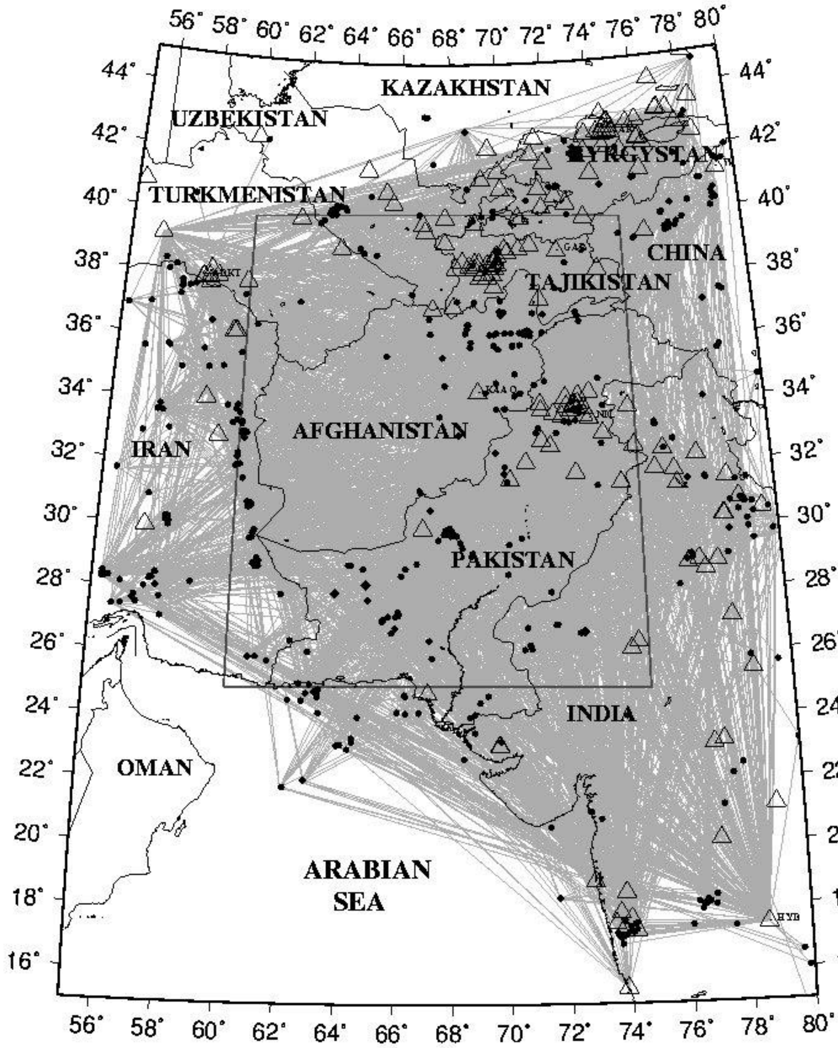

Figure 5. Map of study area showing azimuthal ray coverage for a subset of regional phase arrivals from 441 events recorded at 61 seismographic stations.

3-D Grid Travel-Time Calculations and Event Location

We have completed the development of both the preliminary velocity model and a partial database of seismic phases in preparation for the tomographic inversion effort. During the next phase of the study we will begin to invert the travel time data for updates to the preliminary model and locations of events. One initial task prior to performing a full tomographic inversion includes comparing travel times calculated using the IASPEI91 or other regional 1-D models versus those computed using our model. Presently we are using a 3-D travel time eikonal equation method to calculate travel times through the preliminary model (Podvin and Lecomte, 1991). This method relies on a finite difference approximation of Huygen's principle, which explicitly takes into account the existence of different propagation modes (e.g. transmitted and diffracted body waves, head waves). A great advantage the method has over traditional ray-tracing methods is that it is designed to compute the travel time from a source to every point on a 3-D grid. Further, the method does not require the model to have only smooth velocity variations; it can deal with discontinuities and high velocity contrasts.

The eikonal finite-difference algorithm requires our velocity model to be discretized onto a square, 3-D grid. To maintain reasonable file sizes, we have modified the grid of our model to cover 10 km intervals in latitude, longitude and depth. This required losing some resolution with depth and producing finer grid spacing laterally through linear interpolation. We have calculated travel times to every point in a grid of our preliminary velocity model from the location of the station at Nilore, Pakistan (NIL). We also created a similar pair of velocity and travel time grids using the IASPEI91 model, which we adapted into the correct format for the 3-D travel time algorithm. By subtracting the resultant grid of travel times for the IASPEI91 model from the grid of travel times for our preliminary velocity model, we predict travel time residuals that are consistent with other observations for this region (e.g. Murphy *et al.*, 1998). These results for the surface layer of the grid are shown in Figure 6, where the residuals are on the order of 4 to 6 seconds for shallow events in regions where the Moho is quite deep (the Hindu-Kush, Pamir, and the Karakoram). This residual shrinks to near zero for deep events, which is to be expected since our model currently merges with the IASPEI91 model below 80 km. These

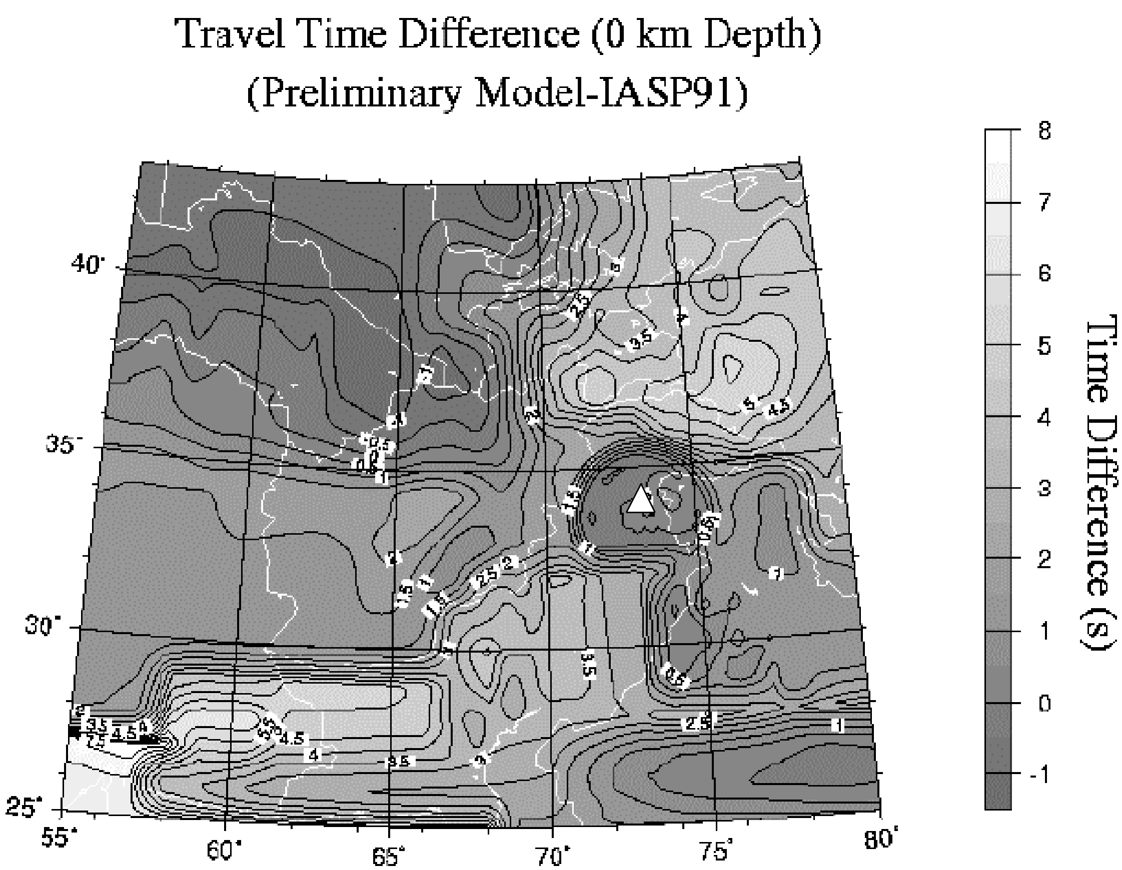

Figure 6. Travel-time differences calculated for station NIL between our preliminary velocity model and the IASPEI91 model at 0km depth. The triangle at 33.65 ^{o} E, 73.25 ^{o} N represents the location of station NIL.

results are encouraging, as they indicate our preliminary model is reasonable. The travel time grid also represents a rudimentary, though unvalidated, form of source station specific corrections (SSSCs) surrounding station NIL. As a subsequent task, we have begun performing event relocations with the preliminary 3-D model and a grid-search location method. This will allow us to estimate the reduction in travel time residuals and determine the tomographic signal we will use to update the velocity model.

CONCLUSIONS

During the first nine months of this study, we have completed the development of a preliminary velocity model of the Pakistan region and a partial database of seismic phases. We are currently beginning the joint tomographic inversion and relocation effort using 3-D, eikonal finite difference methods and a grid-search location method. The first phase of that work will involve identifying the tomographic signal that will be used to update our velocity model from our current database of seismic phase arrival times. We are encouraged by the spatial distribution of ray coverage provided by our preliminary database of seismic phases, and feel we will be able to improve on our preliminary velocity model significantly. Development of our India/Pakistan database will continue as an ongoing effort, and we anticipate including as many of the current catalog of 3600 events as possible. The data collection will be tailored to optimize available ray coverage and arrival time quality, and we hope that the database will serve as an excellent source of data for both current and future investigations in the region.

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