3-D EARTH MODELS AT REGIONAL AND GLOBAL SCALES

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ABSTRACT

We are developing a simple and efficient MATLAB tool for creating improved 3-D lithospheric models for nuclear explosion monitoring. The goal of the model maker is to provide a means for producing 1-D, 2-D and 3-D gridded or layered velocity and attenuation models for travel-time and full waveform synthetic seismic estimates. In the implementation of this code, we include the capability to produce multiple models based on the same *a priori* information by allowing for multiple construction rules. *A priori* rock property information can take the form of surface discontinuities (such as the crust-mantle interface, topography, and basins) or any kind of 1-D, 2-D, or 3-D regional information. Because of the flexibility of the tool, models may be readily updated as new information becomes available. Our current model includes regions of North Africa, Europe, and Asia and is based on the previous Los Alamos National Laboratory model for China, the Maxwell (SAIC) global surface wave model and the Lawrence Livermore National Laboratory Middle East/North Africa/Former Soviet Union model. Models are validated by comparing model-based and empirically derived correction surfaces for important stations in Western China. Waveforms from these stations for events of special interest are also used to test the accuracy of the model using a full waveform finite difference algorithm. We also test the sensitivity of the model predictions to different types of *a priori* data (e.g. structural interfaces like the Moho and 1-D velocity models for geophysical provinces).

KEY WORDS: lithosphere model, Western China, finite difference, travel time, propagation effects, MATLAB

OBJECTIVE

Introduction

Many regions of particular importance for nuclear explosion monitoring are either aseismic or contain few ground truth events. As a result, calculation of correction surfaces or estimation of the propagation effects through these regions is hampered by the large uncertainties associated with sparse data. One solution for mitigating the effects of these uncertainties is to estimate accurate lithosphere models in poorly controlled regions from well known geologic models and rules.

To address this need, we have developed a geophysical model tool that can incorporate various types of geologic/geophysical information and create an estimate of the lithosphere based on various geologic rules.

The primary motivations for developing this modeling tool are to:
1. improve the location of events that fall outside regions where ground truth events exist, and
2. provide insight into the physical basis for propagation effects on discrimination in the regions of interest (e.g. the effects of attenuation, crustal thickness, scattering into anomalous phases).

The purpose of this paper is to present the basic properties of the model tool and to show the initial composite models generated to help in locating, identifying and characterizing events in Asia, parts of the

Former Soviet Union, North Africa, and the Middle East. Our goal is to provide an integrated, validated, and easily implemented set of products to assist the user in location of events where empirical corrections surfaces are poorly defined and give insight into the crustal propagation effects for near-regional, regional and near-teleseismic events. We present some of the work we have completed for Asia.

RESEARCH ACCOMPLISHED

The Modeling Tool: China-East Asia

The purpose of this MATLAB tool is to easily create and manipulate regional models, to aid the discrimination and location of earthquakes and explosions. Previous lithosphere models were created using Stratamodel, a computational toolbox for modeling heterogeneous structural models in 3-D. Certain limitations of Stratamodel have been overcome with our new tool.

The base of the building technique of this code is to include and weight appropriately the available geophysical information for interpolation/extrapolation of a 3-D model based on the fewest non data-based hypotheses. The *a priori* information can be of the type:

- **hard surfaces**: local topography, sedimentary basins, crust mantle interface, any other hard surface imposing a discontinuity (e.g. Conrad Discontinuity, bathymetry) of some sort or very high gradients normal to the surface (in very local models this could include faults and erosional surfaces);
- **any 1-D/2-D/3-D regional information** such as P-wave velocity Vp(x,y,z), density ρ(x,y,z), geophysical province boundary, etc.

The dimensions and grid samples of these input files are not required to be the same. Volumes, layers and point data are re-sampled to output a uniform model. Our 3-D model is a layered model (curved surfaces in 3-D space) constructed in between hard surfaces. Gradients can exist, either implied by the velocities above and below these interfaces or as absolute grids whose attributes reflect the spatially changing properties.

The model building process can be broken down into a number of steps. The simplified steps in building a model are:

- **Building the geometrical framework or skeleton of the model**. This is based on the number of hard surfaces and on the number of conformal (or non-conformal) layers between the hard surfaces. The number of layers in between hard surfaces is chosen by users to match their conception of the complexity of the crust. First, all hard surfaces are reduced to a common grid. Second, the vertical distance between two consecutive hard surfaces at each (longitude, latitude or kilometer or sub-kilometer) grid point is calculated and divided by the number of layers the user had chosen. These intersection points are used to build the layers.

- **Extrapolating/interpolating available information in a form of 1-D/2-D/3-D profiles**. First, all profiles (even 2-D/3-D), are reduced to a set of (longitude, latitude, z, attribute) or pseudo-1-D profiles. Second, the intersection of the data points (longitude, latitude, z, attribute) with the layers is computed and used to evaluate the modeled variable at each layer using an appropriate interpolation scheme ('nearest-neighbor', 'linear', 'cubic', 'spline', etc.). Note that each region in between hard surfaces is interpolated independently. This preserves the discontinuity marked by each hard surface. Third, a 2-D interpolation is done at each layer (parallel to the layer's surface) independently of one another. At this stage a 3-D model is already built but the data are still in a non-uniform vertical grid. Fourth (optional), a final extrapolated 3-D model can be obtained for a uniform 3-D grid to satisfy the requirements of any travel-time code, waveform code, etc.

The conformal layering is one of the geologic "rules" that can be enforced or relaxed to varying degree. Hard boundaries are interpreted as "geologic sequence" boundaries. If, for example, the sequence bounding surfaces are topography and basin depth, then the basins will be subdivided by layers that conform gradually from the topography to the bottom of the sedimentary basins. This is conceptually how these layers were deposited in nature. Non-conformal boundaries (e.g. faults) can be created by introducing additional hard surfaces.

Case Study: Western China

Hard Surfaces

Below, we present one possible model for Western China. The model extends from 22 to 54 degrees North latitude and 65 to 130 degrees East longitude. The model was built from the three hard surfaces or gridded horizons. The gridded horizons we have chosen are the topography, basin and Moho surfaces accessible via the Cornell database (http://www.atlas.geo.cornell.edu/ima.html). Figure 1 shows the topography, basin and Moho relief from the IPE Cornell data set. Previous modeling studies of path effects through western China (e.g., Jones et. al, 1998; Bradley and Jones, 1998), have used these surfaces as a framework around which individual crustal models (e.g. Romanowitz, 1982; Kosarev et al., 1993; Curtis and Woodhouse, 1997; Jih, 1998; Mahdi and Pavlis, 1998, Mooney, 2000) have been used to improve upon the model.

These data surfaces divide the lithosphere into sequences that have undergone distinct geophysical processes in time, pressure and temperature, and logically should be treated differently by the model creation process. These surfaces are the reference for the lithospheric model. and subdivide the model into geophysically independent sequences. These sequences are the basin (and topography) structure, crustal structure, and Moho or lower lithosphere structure. The 1-D/2-D/3-D regional information controls layering within each of these sequences.

1-D/2-D/3-D regional information

In an oil reservoir there may typically be well data to enhance the information on the geostratigraphy. In a similar vein, there are many detailed studies of regions of interest in western China, some encompassing extensive regions (Jih, 1998; Li and Mooney, 1998; Mooney, 2000; Stevens and Adams, 1999). These individual studies provide 1-D and 2-D information about specific geophysical provinces. Figure 1 shows the geophysical provinces we have chosen for the initial model of western China. There are 33 distinct provinces, each of which has a 1-D structural model associated with it. The preliminary velocity models were derived from Jih, 1998, and Li and Mooney, 1998. Currently there are 15 1-D models for the 33 provinces so there is some redundancy, but we have allowed for expansion.

The 1-D structural models are treated like wells in the model tool. They provide the detailed information for the sub-layering within each sequence. This information is called the “attribute” model.

Once the stratigraphic framework is built to describe structure and stratigraphy and well models are in place for the correlation of individual provinces, the attribute model must be defined. The attribute model describes how the geophysical rock parameters are distributed throughout the model grid. This distribution can be based on simple mathematical relations or higher order geostatistical parameters.

Within each model cell, the search radius, the mathematical bias relative to the “well” data and the interpolation scheme determine the attributes associated with it. For our current model, we are calculating Vp, Vs, density, and the intrinsic attenuation coefficients for P-waves, Qp, and S-waves, Qs (Figure 1).

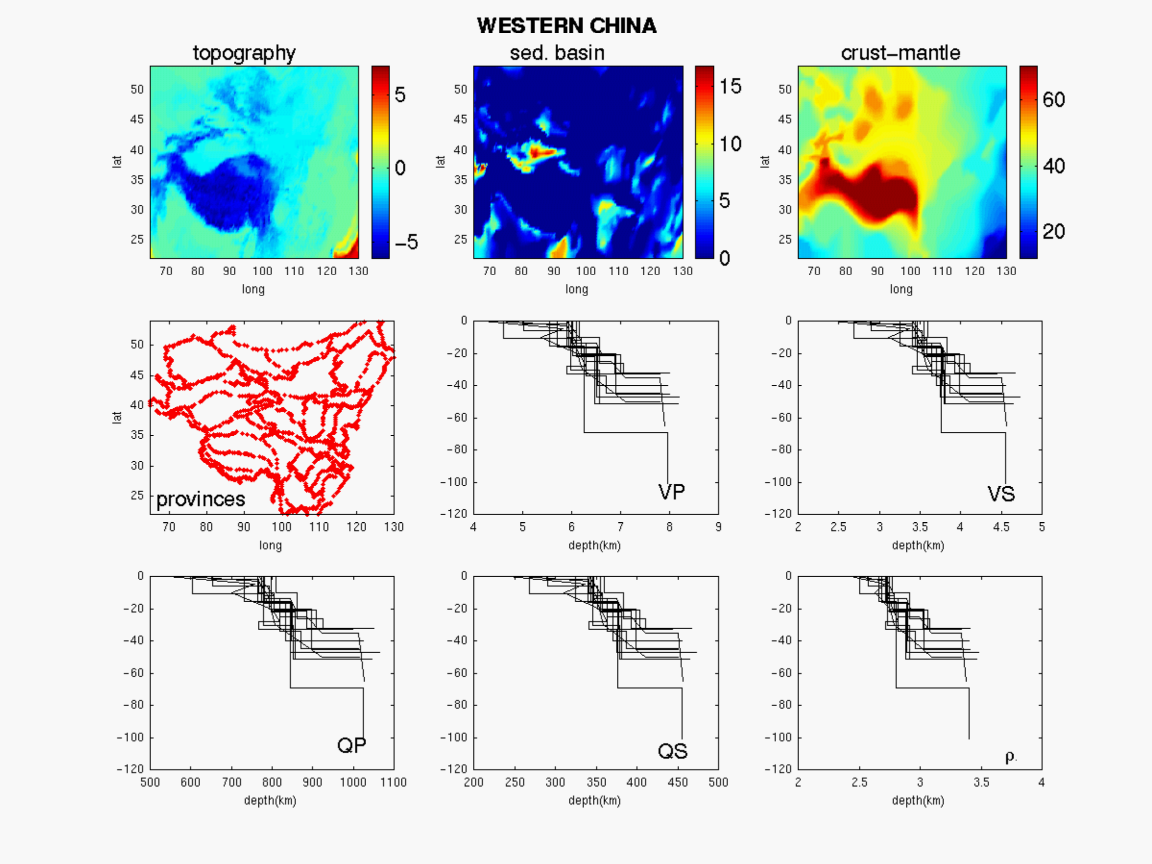


Figure 1. *A priori* information to build a model for Western China. Upper panels: hard surfaces, topography, sedimentary basin's depths, crust-mantle interface. The color bar indicates depth in km. Left middle panel: 1-D profiles are available for 33 provinces in Western China, this is a map showing these provinces. Rest of panels: 5 panels showing each the 33 superimposed 1-D profiles for P-wave velocity, S-wave velocity, Qp, Qs, and density

These are the basic building blocks for this model. Additional data sets that are used to improve on the model include Crust 5.1 (Mooney et al., 1998) and Moho and crustal P- and S-wave velocity/structure maps provided by Mooney, 2000.

An example of the model created from this data set is presented below. In Figure 2, we show the 3-D perspective of the provinces and the 1-D "wells" at their center. The calculation of the velocities within each province is enforced as a function of distance from the center of gravity of the province. In this example we have chosen 3 basin layers and 6 crustal layers. The velocities at layer 5 (a crustal layer) are plotted in the lower right panel (Figure 2-D). The province boundaries are strictly enforced in this example by forcing the 1-D velocity model to be unchanged over 80% of the province. This requirement can be relaxed if a smoother merging of province boundaries is desired.

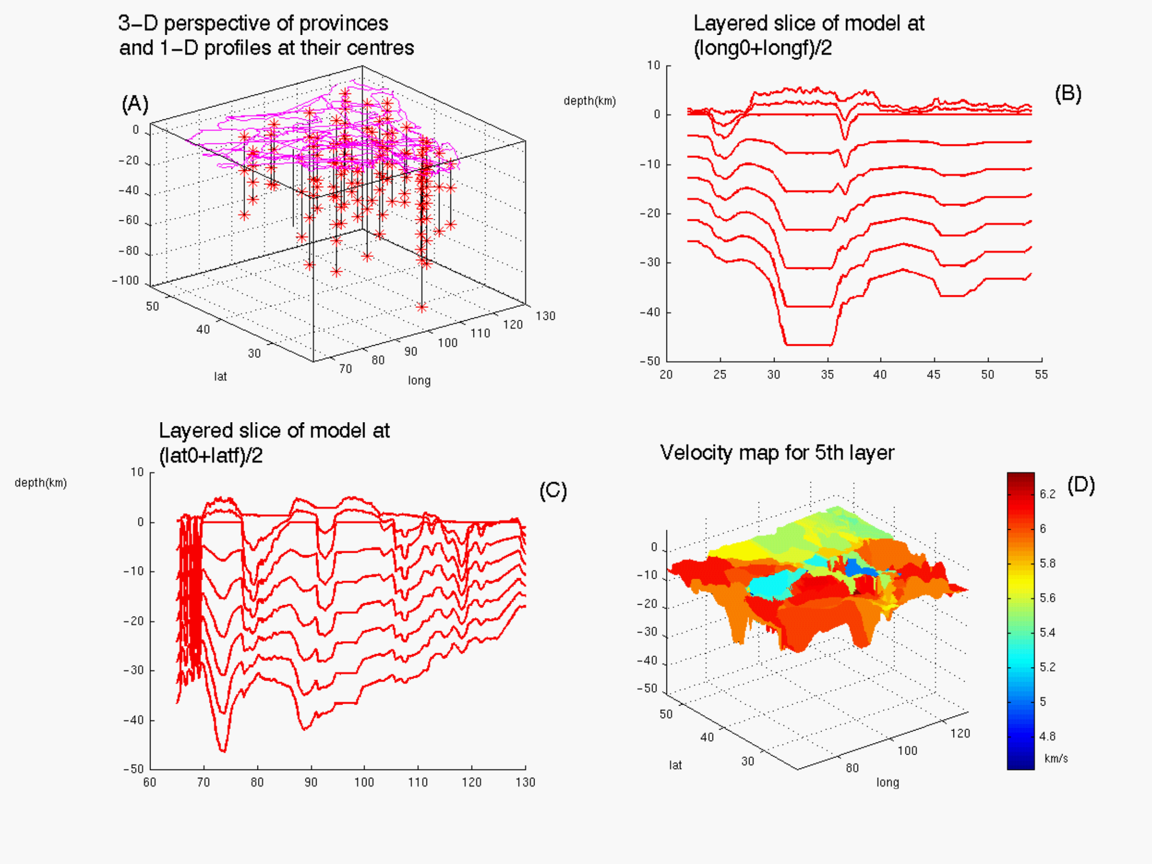


Figure 2. (A) a 3-D visualization of the 33 Chinese provinces (purple lines) and the vertical grid (red stars) for the 1-D profiles, located at the center of the provinces only for reference.(B) The 3-D model is composed by a number of layers, here a 2-D slice at the mid longitude showing a detail of the skeleton of the model; and (C) the same at the mid latitude of the model. (D) example of the fifth layer for a 3-D model of Vp.

Validation and Testing

The above model can be validated in two important ways. First, model-based correction surfaces for stations of importance to nuclear explosion monitoring can be created and compared to those empirically derived. An example of this is shown in Figure 3a for station LSA in Tibet. The models will also be validated by reserving a portion of the travel-time picks used to create the correction surfaces to test and estimate the accuracy of the model in a given geophysical province. The correction surface was generated by first calculating all the travel times to the free surface from a synthetic event at station LSA. This result was then subtracted from those times predicted by IASPI91. In general, the times are in good agreement up to approximately 1000 km. Improvements to the model can be made to increase the accuracy of the surface out to greater distance. Once we have reasonable assurance that the model is accurate, corrections surfaces for future stations can be used to help calibrate them. Calibration experiments can also be planned based in part on the geophysical model.

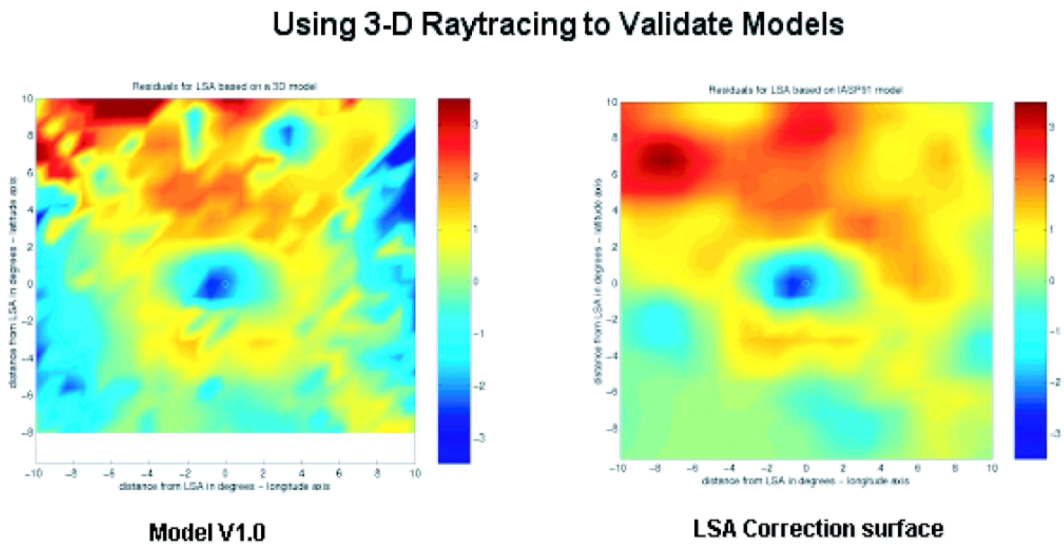


Figure 3a. A comparison of model-based and empirically derived correction surfaces for station LSA. Travel-time residuals for the model are calculated using a 3-D ray-tracing algorithm.

In addition to the travel-time calculations, full waveform finite-difference calculations are made along paths of limited range (<1500 km) with a limited bandwidth (0-1.0 Hz) and compared with ground truth data. Figure 3 shows the initial model from an event near Lop Nor to Station MAK. Figure 4 shows an example of several synthetics created with a 2-D finite-difference forward wave propagation code using several different source mechanisms.

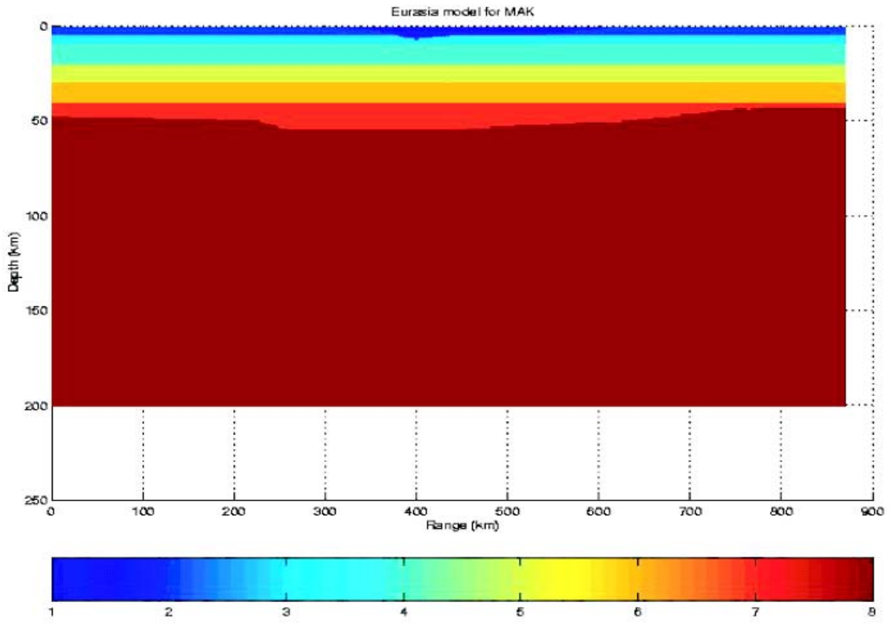
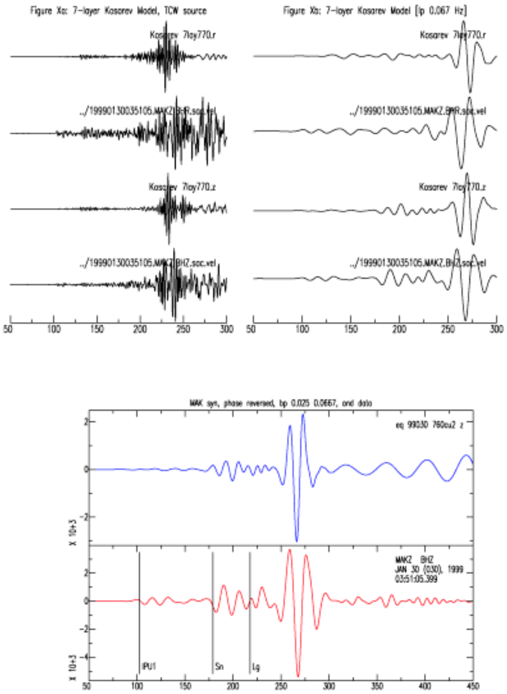


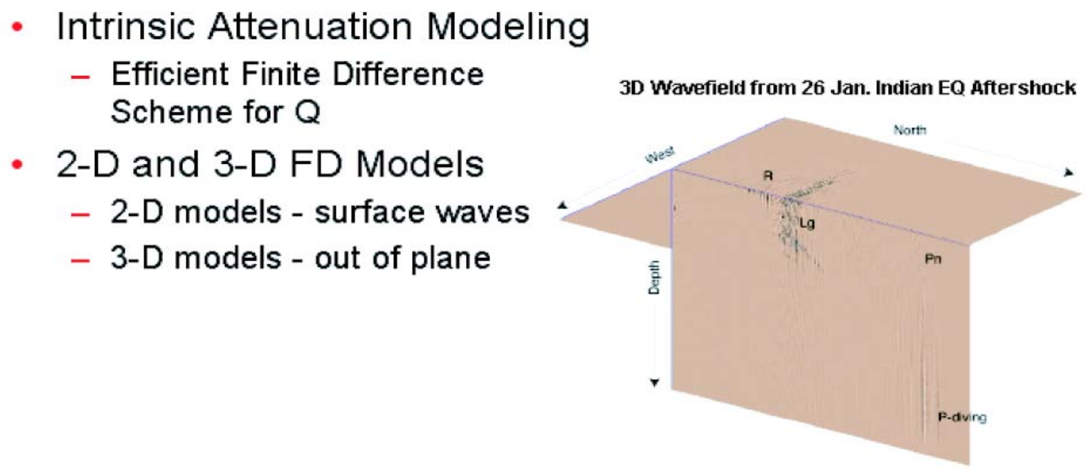
Figure 3b: Initial model of the path from the event to station MAKZ. Layercake stratigraphy is created by modifying the Kosarev model to match body wave travel times.



Results of 2D finite difference runs to match body and surface wave phases. Polarization differences between the model and data show up in the surface wave phases. Timing and waveform of the primary Pg, Sn, and Lg phases are well modeled.

Figure 4: Results of 2-D finite-difference synthetics for an event near Lop Nor to Station MAK. Low-frequency features are well modeled.

Full 3-D wave propagation including intrinsic attenuation has been used to validate specific paths of interest. Areas of particular interest for the validation are the overlap zone and near test sites. In Figure 5 we show the 3-D wavefield for the 26 January 2001 earthquake. This calculation was done using a 4 order staggered-grid finite-difference code. The code employs a new memory-efficient algorithm for calculation of the full 3-D anelastic wavefield (Day and Bradley, 2001). Memory-efficient schemes like this increase the practicality of 3-D full waveform simulation.



- Intrinsic Attenuation Modeling
  - Efficient Finite Difference Scheme for Q
- 2-D and 3-D FD Models
  - 2-D models - surface waves
  - 3-D models - out of plane

3D Wavefield from 26 Jan. Indian EQ Aftershock

Figure 5. 3-D wavefield from simulating the 26 January 2001 Indian Earthquake. The distance to the station is approximately 20 degrees. Primary discrimination phases are indicated on the orthogonal planes.

CONCLUSIONS AND RECOMMENDATIONS

There is a need for improved models in regions of interest and particularly where there are few ground truth events. This model tool provides a method for updating and improving models. Intrinsic Q and topography will play a greater and greater role in amplitude and travel-time tomography. Having a versatile tool for incorporating the effects of these two attributes will benefit both location and discrimination efforts in nuclear explosion monitoring.

The initial models have performed well in generating model-based correction surfaces but are not yet accurate enough to model high-frequency (> 1-Hz) features in the waveform data. Both Q and topography play a role in these misfits as well as the uncertainty in the model. Models should be primarily validated using the travel-time correction surfaces. Though the discretization of the model is a user-defined function within the model tool, the accuracy of the model is a function of the input surfaces and 1-D models. Users may need to define a greater number of interfaces for their modeling efforts.

In the future, Q tomography and stochastic model extrapolation should be used to create models accurate enough to simulate the full 3-D analastic wavefield. For low-frequency simulations, 2-D models perform well; however, for higher frequency simulations, estimating the effects of the full 3-D lithosphere is necessary.

REFERENCES

Aprea, C., C. Bradley and L. Steck (2001), Calibration of 3-D Earth Models at Regional and Global Scales, LA-UR-01-XXXX.

Bradley, C. R. and L. E. Jones (1999), Full Waveform Modeling of the Effects of Q and Structure Over Subregional Paths in Western China, 21st Annual Research Symposium on Monitoring a CTBT.

Bradley, C. and E. Jones (1998), Modeling propagation effects from explosions in western China and India, Proceedings of the 20th Annual Seismic Research Symposium on Monitoring a CTBT, Santa Fe, NM.

Curtis, A. and J. H. Woodhouse (1997), Crust and upper mantle shear velocity structure beneath the Tibetan plateau and surrounding regions from interevent surface wave phase velocity inversions, *J. Geophys. Res.,* 102(B6), 11,789-11,813.

Day, S. and C. Bradley (2001), Memory-efficient simulation of anelastic wave propagation. Bull. Seis. Soc. Am., 91, 520-531.

Jih, R.-S. (1998), Location calibration efforts in China, in Proceedings for the 20th Annual Seismic Research Symposium, 12pp.

Jones, E., C. Bradley, F. App, R. Bos, and H. Patton, (1998), Modeling seismic propagation from large scale structural features in western China. LANL Memorandum, LA-UR-97-4186.

Kosarev, G.L., N.V. Petersen, L.P. Vinnik, and S.W. Roecker 1993), Receiver functions for the Tien Shan analog network: Contrasts in the evolution of structure across Talasso-Fergana fault, J. Geophys. Res., 98, 4437-4448.

Li, S. and W. D. Mooney (1998), Crustal structure of China from deep seismic sounding profiles, Tectonophysics, 288, 105-113.

Mahdi, H., and G. Pavlis (1998), Velocity variations in the crust and upper mantle beneath the Tien Shan inferred from Rayleigh wave dispersion: Implications for tectonic and dynamic processes. *J.. Geophys. Res., 103(B2*) , 2693-2703.

Mooney, W. D. (2000), Crustal and upper mantle structure of China and adjacent areas. Interim Report (9/28/99-9/29/00): Data compilation and results, DOE IA (ID): DE-A104-98AL79758.

Mooney, W. D., G. Laske, and T. G. Masters (1998), CRUST 5.1: A global crustal model at 5° X 5°: Journal of Geophysical Research, 103, 727-747.

Romanowitz, B. (1982), Constraints on the structure of the Tibet Plateau from pure path phase velocities of Love and Rayleigh waves. *J. Geophys. Res*., 87(B8), 6865-6883.

Smith, W. H. F. and P. Wessell (1990), Gridding with continuous curvature splines under tension, Geophysics, 55, 293-305.

Steck, L. K., A. A. Velasco, A. H. Cogbill, and H. J. Patton (2000), Improving regional seismic event location in China, accepted at Pageoph, March.

Stevens, J. L. and D. A. Adams (1999), Improved methods for regionalized surface wave analysis, Annual report Submitted to DTRA, November.