IMPROVED VELOCITY MODELS IN WESTERN CHINA FOR TWO- AND THREE-DIMENSIONAL FINITE DIFFERENCE MODELING

L. K. Steck, C. R. Bradley, and L. E. Jones
Los Alamos National Laboratory

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ABSTRACT

In order to improve our understanding of the tectonics of western China, we are developing methods for creating improved three-dimensional (3-D) lithospheric structural models for the region. Stratamodel®, a computational toolbox for modeling fully heterogeneous rock properties in 3-D and ArcInfo, a widely accepted surface mapping routine, form the framework within which we build our models. To explore the accuracy of our new velocity structures, we compare synthetic seismograms from a full-waveform finite difference algorithm with regional data available from the IRIS-DMC for seismic events in western China. In this paper, we present seismogram modeling results from an earthquake in the Xinjiang province of western China, demonstrate improvements to previous velocity models, and describe the scheme we are using to create 2-- and 3-D velocity models for western China.

On January 30, 1999, at 03:51:07 GMT an earthquake occurred at 41.67 W, 88.46 N near the Lop Nor test site in western China. Using an anelastic finite difference code, we model the records from this event at the stations AAK, MAKZ and WMQ. Preliminary two-dimensional models were obtained for each source-receiver path from the Cornell Database, and these are fused with appropriate one-dimensional velocity models from published receiver function work or our own surface wave inversions. For each source-receiver path, the Cornell Database provides a topography profile, a depth-to-basement (or basin) profile, and a Moho profile. To date we have not included topography effects in our modeling.

The Cornell Database contains two surfaces that define the interfaces between the basin and crust, and the crust and Moho. These interfaces form the primary structural divisions in the Arc-Info data set. The structural model is then improved with the addition of geophysical province models. The specific path from source to receiver is then forward modeled and the velocity model refined. The ultimate goal of the model maker is to provide a tool for building 2-D and 3-D gridded velocity models for travel-time and full waveform seismic estimates.

Given that any particular source receiver combination may cross several geophysical provinces, full waveform modeling is incorporated to model the specific path effects on the waveform. We have modeled both elastic and anelastic realizations of the crust for several events, and present a memory-efficient scheme for modeling the effects of Q in three dimensions.

Key Words: velocity model, tectonics, finite difference, wave propagation

OBJECTIVES

One of the fundamental problems facing discrimination and location of earthquakes and explosions is creating accurate structural models for the lithosphere. Path effects on the seismic waveform can obscure spectral and time domain discrimination indices and poor velocity models generate ambiguity in event depth and location.

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It has been our objective over the last year to generate a methodology for providing improved velocity models for western China and to test this methodology via the method of finite difference waveform modeling. Our specific objectives are:

1) Provide a method for generating improved velocity models by incorporation of 1-D and 2-D velocity models into an algorithm to merge these models into a 3-D structure.
2) Generate an interface for extracting these models into a useful form for either ray tracing or full waveform modeling.
3) Test the accuracy of the models via finite difference and travel time calculations for known earthquake and explosion paths.
4) Perfect a memory-efficient method for simulating intrinsic attenuation (Q) in the lithosphere for full waveform simulation.

To date, we have addressed items (1) and (2) through two commercial software systems: Stratamodel®, a software package designed to incorporate several types of structural information for the creation of a global 3-D lithospheric model, and ArcInfo®, a data base algorithm we are using to pass lithologic surfaces to the waveform or travel-time modeler.

We have selected an event from January 30, 1999, that occurred near Lop Nor in western China to test our wave propagation algorithms and the accuracy of the velocity model maker. The results of our analysis follow.

RESEARCH ACCOMPLISHED

Finite difference modeling of the 1999 January 30 earthquake near Xinjiang Province, western China

On January 30, 1999, at 03:51:07 GMT, an earthquake occurred at 41.67 W, 88.46 N. Using an anelastic finite difference code, we model the records from this event at stations AAK, MAKZ, and WMQ. Preliminary 2-D models were obtained for each source-receiver profile from the Cornell Database, and these are fused with appropriate 1-D velocity models from published receiver function work or our own surface wave inversions. The Cornell Database contains two 3-D structures from which 2-D profiles can be obtained: a "Eurasia" model (EU) and the University of Colorado (CUB) dataset. The latter is derived from inversion of surface wave data and is thus appropriate for modeling longer period energy. Both the EU and CUB models are comprised of 3-D "topography", "depth to basement" and "depth to Moho" information. To date we have not included topography effects in our modeling. We compare results from 2-D profiles obtained from the EU and CUB to synthetics from purely one-dimensional models. For each source-receiver path presented here, our synthetics comprise a bandwidth from roughly 0.02 Hz to 1.0 Hz.

Station WMQ

Station WMQ, at roughly 247-km epicentral distance, is located on the northern edge of the Tarim basin (Figure 1). Seismograms at WMQ were modeled using the CUB and the EU basement and Moho profiles, along with several simple 1-D models. The primary velocity structure used for this source-receiver profile is based on a 7-layer modified Tien-Shan model (Kosarev et al., 1993) over a mantle half-space. Velocities for a 1-D, 3-layer average Tien-Shan model were, in turn, a simplification of this primary velocity model. Both velocity models are given in Table I. Several alterations to the 7-layer model were made, including removing the crustal low-velocity zones and thinning the crust by about 10 km. None of the source/velocity model combinations tried were able to fit both the body and surface waves simultaneously. The TW and GER2a models fit the body wave arrival times and polarities well, particularly for the prominent depth phase and Lg. The surface waves are not well matched with this source model. In contrast, the CMT and GER1 models fit the surface waves well, but did not match the polarities of the body waves. The GER1, GER2, and CMT depths appear to be too deep by about 5 km, based on depth phase arrival time and waveform matching. The depth phase arrival time and polarity are consistent with it being an sP. Figure 2 compares several of our models for WMQ.

Station MAKZ

We model station MAKZ, at 770-km epicentral distance, with a similar modified Kosarev structure since its source-receiver path passes primarily through the Tien Shan fold and thrust belt (Figure 1). Crustal thickness along the profile varies from about 42 km to nearly 50 km and Moho depth increases gently from the source end of the profile to the receiver end, of whether the complex **EU** or simpler **CUB** basement and Moho are used. A seven-layer structure based on the Kosarev model (reference above), a simplified average three-layer (*basin, basement*, and *mantle*) structure, and a model based on phase velocity inversion work by Curtis and Woodhouse (1997) were tested.

The 7-layer Kosarev model (Table I) was fused with depth to basement and Moho information from the EU and CUB datasets, while the 3-layer 'average' model was tested for the CUB profile only. Results for the Kosarev model and CMT solution show reasonably good fits to the body wave data, but, as we observed at station WMQ, surface waves appear phase shifted. The 3-layer average Tien Shan model, coupled with the CU basement and Moho structures, produced similar results.

The modified Curtis and Woodhouse model produced surface waves that were obviously fast by more than 10 seconds for both the TCW and GER source mechanisms. Note that the TCW source produces body waves of incorrect polarity and unusual complexity on the radial component. The GER source produces correct polarities for the body waves, and a more distinct 'beating' on both the vertical and radial component; a feature observed in the data.

All velocity models produce, with varying degrees of success, a waveform feature in the Lg phase that resembles 'beating'. The presence of this feature in the synthetics may be due to the 2-dimensional nature of the modeled Moho structure.

Table I: Velocity Structures

(Modified) Kosarev Model Kosarev et al., 1993	depth	Pvel	Svel	density
	0.0	**4.19**	**2.42**	**2.44**
	5.0	**5.83**	**3.37**	**2.72**
	10.0	**5.60**	**3.11**	**2.72 LVZ**
	20.0	**6.12**	**3.54**	**2.78**
	30.0	**6.21**	**3.59**	**2.82**
	40.0	**7.09**	**4.10**	**2.97**
	Mantle	**7.80**	**4.51**	**3.37**
Average Tienshan Model				
	0 – 5	**4.19**	**2.42**	**2.44**
	5 – 50	**6.205**	**3.587**	**2.82**
	Mantle	**7.61**	**4.40**	**3.28**
(Modified) Curtis and Woodhouse Model Curtis and Woodhouse, 1998				
	0 - 5	**5.93**	**3.43**	**2.768**
	5 – 50	**6.17**	**3.57**	**2.88**
	Mantle	**8.11**	**4.69**	**3.65**

Modeling the Lithosphere of Western China

Discrimination and location of earthquakes and explosions depend on the source model but also depend on the effects to the seismic waveform as it propagates through the crust. The problem of creating accurate structural models for the crust is difficult in regions where data are sparse or non-existent. We have chosen to use Stratamodel, a toolbox created by Landmark Graphics Corporation, to model the 3-D lithospheric properties. The algorithm incorporates known published data and interpolates or extrapolates properties based on a set of arithmetic or geostatistical rules.

It has been our objective over the last year to generate a methodology for providing improved velocity models for western China and to test this methodology via the method of finite difference waveform modeling. Below we discuss the data sets we are using and the method for their incorporation into Stratamodel to create better models of the lithosphere.

Stratamodel

Stratamodel, which models heterogeneous rock and fluid properties in three dimensions for geological analysis and visualization, was originally designed to model oil and gas reservoirs. We have reformatted our data sets for western China to mimic Stratamodel's required format.

There are three types of models required by Stratamodel in order to create a full 3-D model of the lithosphere: 1) the Stratigraphic Framework Model, 2) the Well Model and 3) the Attribute Model.

Stratigraphic Framework Model
Gridded horizons, layer boundaries, and detailed reservoir characterizations (typically well data) form the basis for Stratamodel's 3-D modeling. The gridded horizons we have chosen are to the topography, basin and Moho surfaces accessible via the Cornell database (http://www.atlas.geo.cornell.edu/ima.html). Figure 3 shows the 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) have been inserted in a "layercake" manner for the particular region of interest.

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 stratigraphic framework in the lithospheric model. These surfaces dictate the cell resolution of the initial 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 "well" model controls layering within each of these sequences.

Well Model
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, 1999). These individual studies provide 1-D and 2-D information about specific geophysical provinces. Figure 4 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 fifteen 1-D models for the 33 provinces so there is some redundancy, but we have allowed for expansion when our knowledge of the crust improves.

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

Attribute Model
Once the stratigraphic framework is built to describe structure and stratigraphy and well models is 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, determines 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.

The Model

The stratigraphic framework defined by the Cornell surfaces and the well data defined within each geophysical province have given an initial lithospheric model for China. Each sequence defined by the topography, basin and Moho surfaces has been subdivided by four layers (Figure 5). The number of layers in the crustal sequence was chosen to match the models presented in Mooney, 1999. The basin and lower lithosphere layering will be improved as more data are incorporated into the model. In Figure 5 the topography and two orthogonal cross sections through the model are displayed. In the basins, the layering is assumed to be proportional. This forces the layers within the basin to pinch out as the basins shallow. Within the crust and lower crust, the layers follow the top of the sequences that define them. The resulting model follows structural trends more closely than simple "layercake" models.

The well data are shown in Figure 6 for the 33 provinces used in this model. The effect of the wells is to bias the nearby model cells with information from the physical province. Each sequence is independent of the others. This forces the cells that lie within a sequence to use only well data lying between the surfaces that define that sequence. Currently, the weighting scheme for the cell attribute is a simple inverse distance weighted average of the well data and a search radius from each cell equal to half the total model size.

Future models will refine the weighting scheme and well density to more strictly enforce the transition from province to province in the geophysical model. With the current model we are performing full waveform modeling and travel-time tests to determine the accuracy of the model.

CONCLUSIONS AND RECOMMENDATIONS

We have performed 2-D modeling of an event near Xinjiang, China at stations AAK, MAK and WMQ. Depending on our choice of focal mechanism, we have achieved a good fit for the body wave phases, event depth and surface waves. No single mechanism fits all of these features simultaneously. We conclude that path effects on the recorded waveform are not yet being fully simulated and that better crustal models need to be developed. These are our recommendations.

1) A robust model-making method is critical to address the need for 2-D and 3-D structure in the simulation of path effects on the recorded waveform.

2) Validation through modeling of the velocity structure should include full 3-D simulation, and there may be a need for intrinsic attenuation in the simulations.

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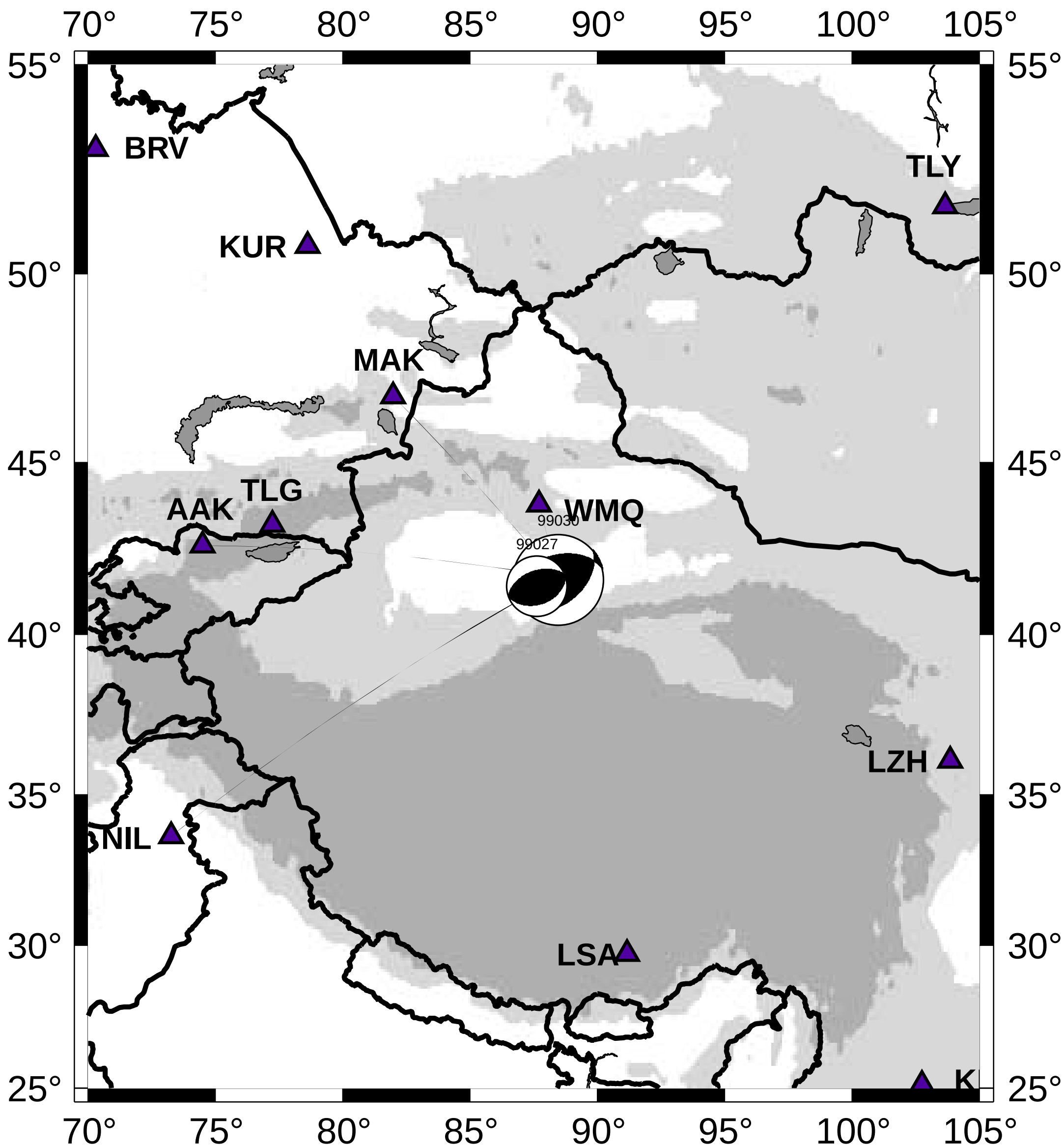

Figure 1: Map of source region for the 30 January 1999 event. Focal mechanisms are shown as predominantly thrust component. Stations modeled are indicated by the back azimuth lines shown.

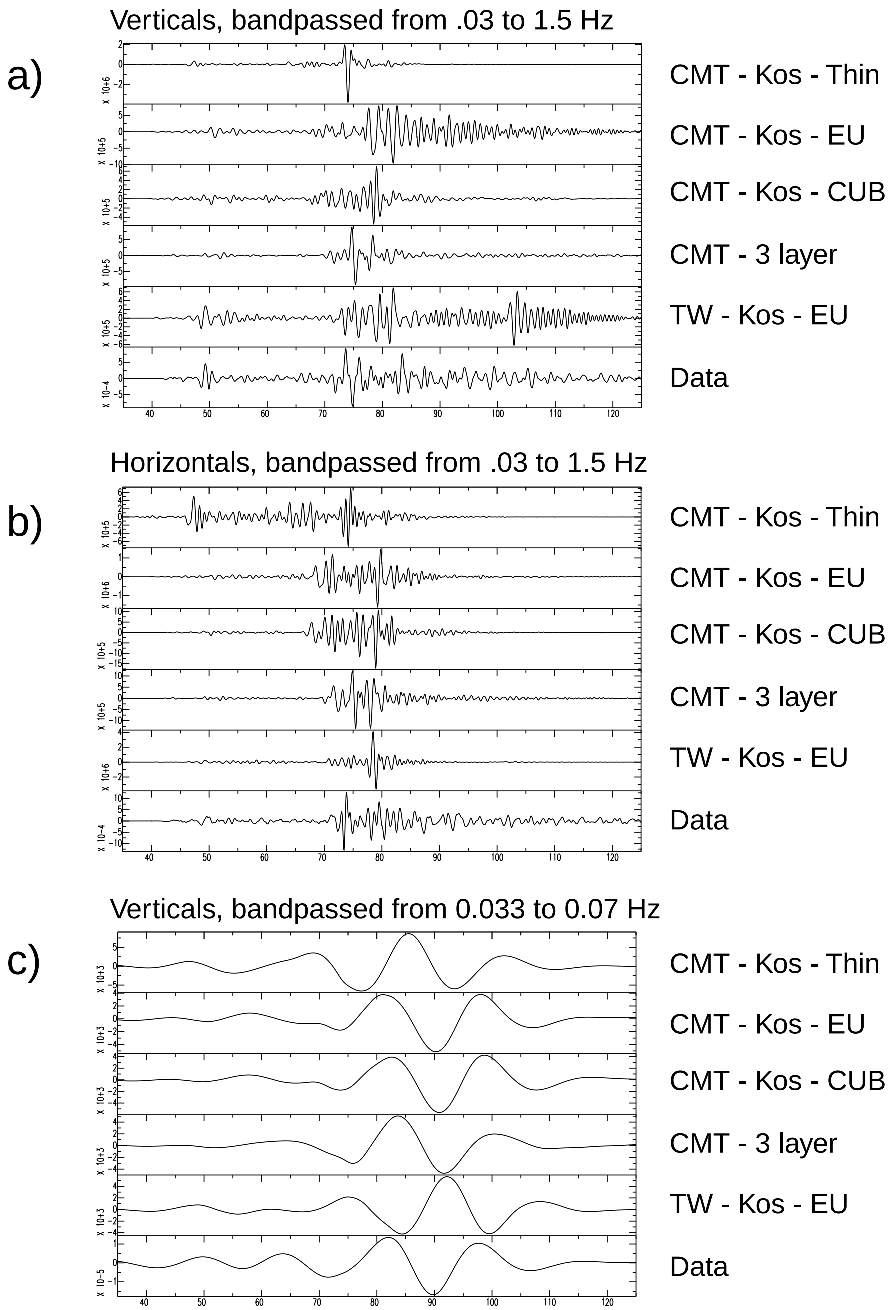

Figure 2. This shows (a) vertical, (b) radial, and (c) long-period vertical synthetic waveforms for several source/velocity model combinations. Instrument-corrected velocity data are shown with the synthetics. The source model and velocity model are indicated, along with the type (if any) of depth-to-basement and depth-to-moho information. The 'Thin' velocity model is an abbreviated flat-layer Kosarev model with a 40-km-thick crust (no EU or CUB information used). The '3-layer' model is an average Kosarev model with 3 flat layers.

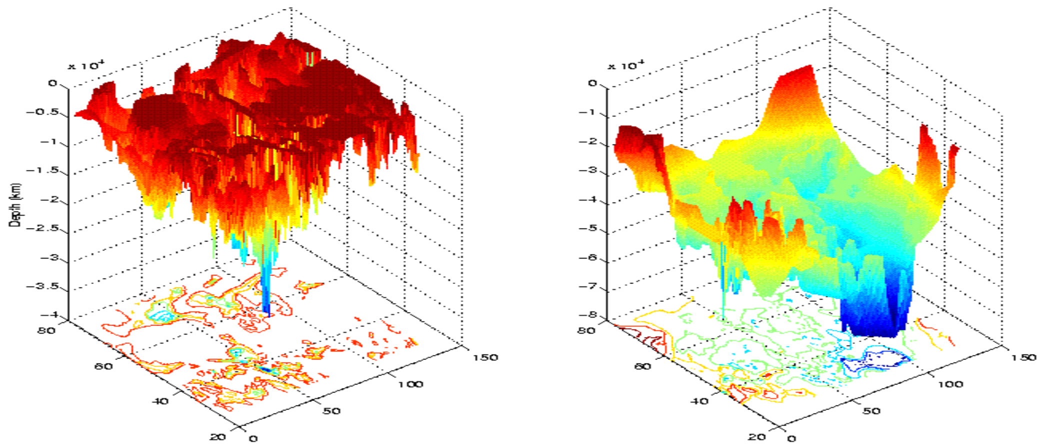

Figure 3. The IPE basement and Moho surfaces from Cornell. These surfaces are used to define the initial lithospheric sequences. Layering within the sequences is dictated by 1-D models describing distinct geophysical provinces.

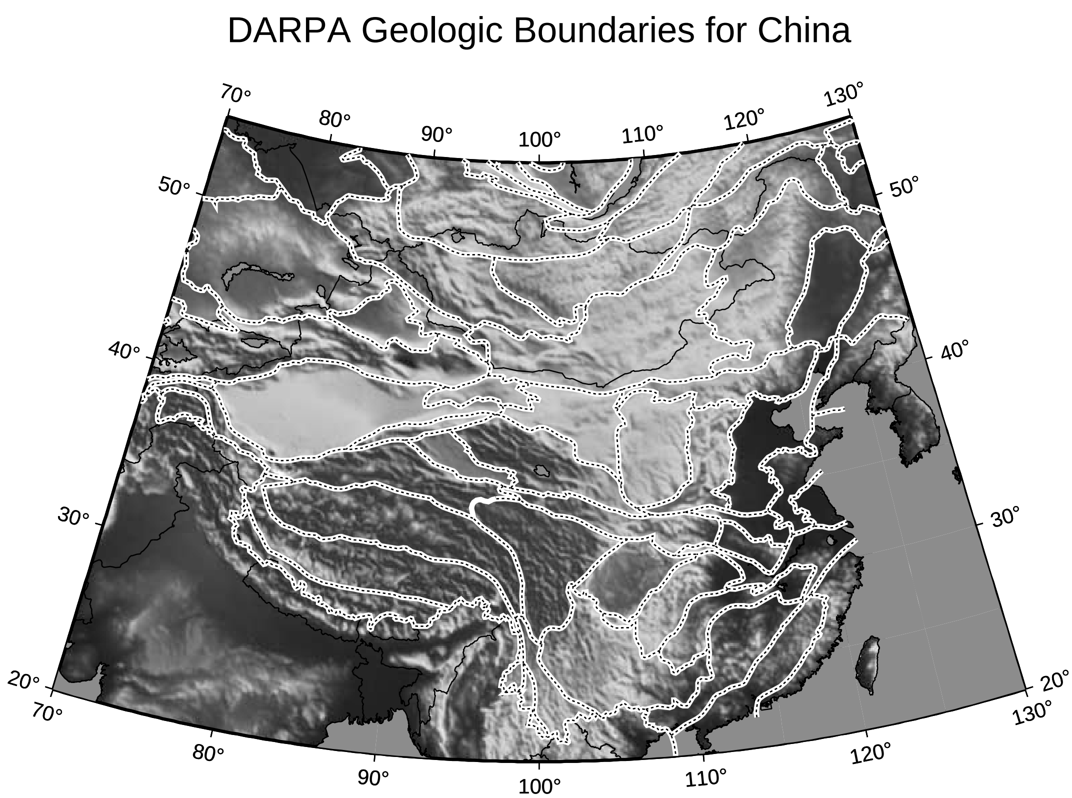

Figure 4. Defense Advanced Research Project Agency (DARPA) boundaries used in the initial velocity model. These 33 geophysical provinces have a 1-D velocity model associated (not necessarily unique) and are used to enforce a structural change in the model generated by Stratamodel.

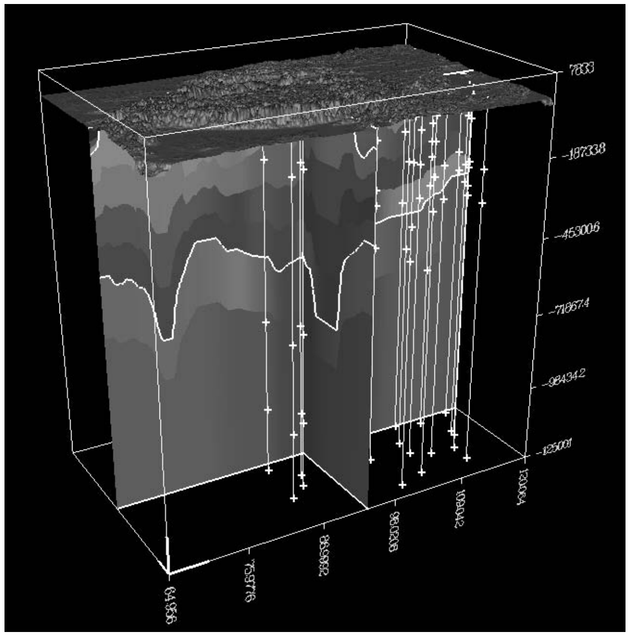

Figure 5. Velocity model for China from Latitude 22 N to 56 N, Longitude 65 E to 130 E. Topography shown as the uppermost surface. Two orthogonal cross sections show the depth and detail of the current model: 12 heterogeneous layes in 3 sequences, depth extent 125 km.

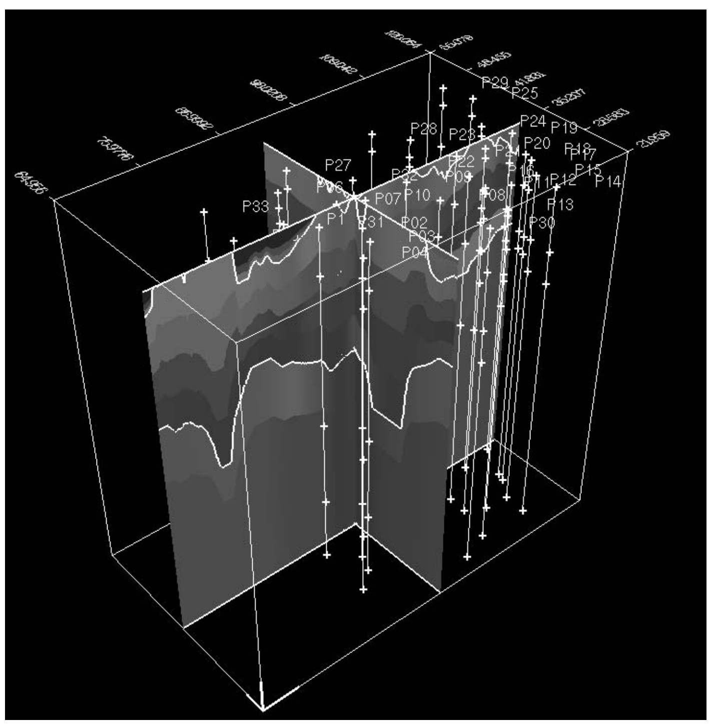

Figure 6. The topography has been stripped away from figure 4 to show the layer sequences in more detail. The 33 1-D velocity models are shown in as "wells".