

## **GEOPHYSICAL MODELS FOR NUCLEAR EXPLOSION MONITORING**

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### **ABSTRACT**

Geophysical models are increasingly recognized as an important component of regional calibrations for seismic monitoring. The models can be used to predict geophysical measurements, such as body wave travel times, and can be derived from direct regional studies or even by geophysical analogy. While empirical measurements of these geophysical parameters might be preferred, in aseismic regions or regions without seismic stations, this data might not exist. In these cases, models represent a “best guess” of the seismic properties in a region, which improves on global models such as the PREM (Preliminary Reference Earth Model) or the IASPEI (International Association of Seismology and Physics of the Earth's Interior) models. The model-based predictions can also serve as a useful background for the empirical measurements by removing trends in the data. To this end, Lawrence Livermore National Laboratory (LLNL) has developed the WENA model for Western Eurasia and North Africa. This model is constructed using a regionalization of several dozen lithospheric (crust and uppermost mantle) models, combined with the Laske sediment model and 3SMAC upper mantle. We have evaluated this model using a number of data sets, including travel times, surface waves, receiver functions, and waveform analysis. Similarly, Los Alamos National Laboratory (LANL) has developed a geophysical model for East Asia, allowing LLNL/LANL to construct a model for all of Eurasia and North Africa. These models continue to evolve as new and updated datasets are used to critically assess the predictive powers of the model. Research results from this meeting and other reports and papers can be used to update and refine the regional boundaries and regional models. A number of other groups involved in monitoring have also developed geophysical models. As these become available, we will be assessing the models and their constitutive components for their suitability for inclusion in the National Nuclear Security Administration (NNSA) Knowledge Base (KB).

## **OBJECTIVE**

The objective of regional-scale geophysical models is to improve predictions for location and identification of regional seismic events by improving the resolution compared to global-scale models. As such, we wish to provide the highest resolution model possible that can be used to reliably derive parameters such as body wave travel times, group velocity dispersion, waveforms, etc. In addition, the models should also convey proper uncertainty estimates which can be mapped into uncertainties in the derived products.

Geophysical models can serve as background values for correction surfaces and other derived parameters. This can be particularly important in aseismic regions, which might only have a limited number of empirical measurements. Additionally, models can provide guidance on spatial parameters, such as tectonic boundaries and correlation lengths. Furthermore, models can be used to evaluate new stations before they are installed and special events, such as dedicated shots, before they occur. Finally, models can serve as an integrated geophysical repository for research community results.

## **RESEARCH ACCOMPLISHED**

### **WENA Construction**

We have constructed an *a priori* 3-D geophysical model for Western Eurasia and North Africa (WENA). Details of the construction and validation of the model can be found in Pasyanos et al., 2003. The WENA model is constructed from separate sediment, crust, and upper mantle models. Sediments are taken from Laske and Masters (1997), a 1° 3-layer sediment model based on the 1985 Exxon map. Crustal regionalizations and velocity profiles are taken from a series of Lawrence Livermore National Laboratory (LLNL) reports (Walter et al., 2000; Bhattacharyya et al., 2000; Sweeney et al., 1998) and based on CRUST 5.1, Exxon, and many published studies. Our regionalizations are shown in Figure 1. The crustal regionalizations also include velocities in the uppermost mantle layer. We use the 3SMAC model (Nataf and Ricard, 1996) for the remainder of the WENA model upper mantle, extending down to 660 km depth. 3SMAC is an *a priori* model based on tectonics, heat flow, and geophysical knowledge.

Until now, the WENA model has exclusively been an *a priori* geophysical model. While we will continue to maintain this model by correcting any newly discovered problems, updating the model with new information as it becomes available, and integrating results from the research community, we now shift our focus to data driven models. These new models will use the *a priori* model as a starting model, but will be driven by data from several different types of geophysical measurements, which are sensitive to different portions of our model.

### **WENA Validation**

The WENA model has been validated using many different types of geophysical data, including body wave travel times, gravity, surface wave group velocities, receiver functions, and waveform modeling (Pasyanos et al., 2003). We will focus on several of the validations here. The first is the travel-time validation test that assesses how well the WENA model does in predicting P and Pn travel times. Figure 2a shows a P-wave correction surface for station ARU in Russia. To compute model-based correction surfaces we subtract the iasp91 (Montagner and Kennett, 1996) predicted time from the WENA predicted time along a regular grid in latitude, longitude and at a depth of 10 km. Blue indicates fast regions and red indicates slow. Each correction surface provides station-specific travel time corrections for regional to near-teleseismic distances, which can be used to improve location capability. We find travel time differences of up to 6 seconds relative to iasp91, most in areas of very thick crust or sediment. The (observed-iasp91) P-wave residuals are plotted on top of the correction surfaces. To test the predictive power of the model we compute the median residuals between the observed arrival times at each station and those predicted by both the WENA model and iasp91. We use P and Pn travel times from a global dataset of relocated events (Engdahl et al., 1998), which have been further processed with a declustering algorithm. To compute these residuals we interpolate between grid nodes to calculate the predicted travel time for an exact source-station path. This is done for both the WENA travel time volume and the iasp91 travel time volume computed with the FD code. These residuals (observed - predicted time) are shown as histograms in Figure 2. Note the reduction in the SMAD (scaled median average deviation) produced by the WENA model over iasp91.

Another way of validating the model was to compare the surface wave group velocities predicted from the model against a tomography model of the same data. Figure 2b shows a comparison of 20 second Rayleigh wave group velocities between the WENA model and a surface wave tomography (Pasyanos et al., 2001). At this period, surface waves are sensitive to the top 20 km and illustrate crustal thickness variations between oceanic and continental crust, as well as the effect of deep sedimentary basins. There is good agreement between the two figures, with both well-outlining oceanic and continental crust in addition to large sedimentary basins.

### **Access Tools**

Working with Sandia National Laboratories (SNL), we have created a utility designed to view and extract geophysical models. VEXtool (or Viewing and EXtraction tool) allows users to extract 1-D profiles (boreholes), 2-D profiles (cross-sections), and 3-D profiles (volumes) from the models. These portions of the model can either be viewed graphically or exported into a series of export formats, including those for the TauP travel time generator (Crotwell et al., 1999), Randall's reflectivity codes (based on Kennett, 1985), or Herrmann's surface wave package SURF (based on Russell, 1988). For example, one could select a point and generate Love and Rayleigh group and phase velocities from the profile (Figure 3a), or select a cross-section and generate body wave travel times from an average velocity structure along the profile (Figure 3b), or generate reflectivity synthetics (Figure 3c). Finally, one can export the 3-D model and port the results to a finite difference code, which can be used to trace rays through the model and compute travel times.

### **Other Geophysical Models**

There are a number of other geophysical models that have been developed in the context of improved regional monitoring. Los Alamos National Laboratory (LANL) has created the CEA model that covers China and East Asia. This effort has paralleled some of LLNL's work on geophysical models in Western Eurasia and North Africa. We have worked with LANL to insure that the regionalizations of the two individual models are consistent, allowing us to build a unified model for the broader region.

Other such models have been developed completely independently of the LLNL geophysical modeling effort. Examples covering portions of Western Eurasia and North Africa include CRUST 5.1, WINPAK3D, CUB, and EurID. CRUST 5.1 is a global crust (and uppermost mantle) model at 5° resolution (Mooney et al., 1998), now updated to CRUST 2.0 (Laske and Masters, written communication). WINPAK3D is a model for India and Pakistan that was developed by Weston Geophysical (Johnson and Vincent, 2002). Another model is the CUB model, a global mantle model developed by the University of Colorado at Boulder and their Group 2 consortium partners (Shapiro and Ritzwoller, 2002). The EurID model (Du et al., 1998) is a model covering Europe. Other models, such as those from the Group 1 consortia, cover regions of Eastern Eurasia.

In each case, when the selected models are made available, they will be converted into a format accessible by VEXtool, so that the model can be viewed and portions of the model extracted for further analysis. The models can then be validated using many data types, similar to those performed for the WENA model, and independently assessed. Once the models have been evaluated, the model or portions of the model can be integrated into the National Nuclear Security Administration (NNSA) Knowledge Base (KB). Potential issues related to integration of research include: how to handle multiple inconsistent models, and how best to quantify and validate model uncertainty.

### **Model Evaluation**

We have been working with researchers Gabi Laske, Guy Masters, and Christine Reif from the University of California, San Diego (UCSD) Scripps on reviewing the literature for geophysical parameters, such as crustal thickness (Figure 4a). These points can be used to assess or build models. Alternatively, this data can be used to understand some of the fundamental quantities of these parameters, such as uncertainty and correlation length. For example, in Figure 4b, we plot the variogram of crustal thicknesses in Europe, Asia, and North Africa, which provides the spatial statistics for kriging. The sill is the background variance of the data, the range is the distance at which correlation between data points is zero, and the nugget is the covariance of co-located points. From this analysis, we find that the uncertainty on individual point is about 1.5 km, the correlation length of crustal thickness is about 15 degrees, and that uncorrelated points have a variance of about 10 km. Figure 4c shows the kriged

surface of crustal thickness data for Europe, Asia, and North Africa. This surface is interpolated at 2° resolution using the kriging algorithm and the variogram statistics specified above.

We are currently assessing the travel-time prediction uncertainty of our WENA model in a region-specific framework (i.e., 3D). Figure 5 shows variograms of travel time residuals at station ARU for both the WENA and iasp91 velocity models. Triangles are the data variogram values in 1.0 degree bins; solid lines are the model variograms determined by curve fitting. Note the variograms do not approach zero for points that are closely co-located (i.e., data are not perfectly correlated) due to errors associated with determining travel time residuals. However, it is apparent that the variograms reach minima (correlation is maximum) for points close together, and the variograms increase (correlation decreases) as points become separated by greater distance. Travel time prediction uncertainty for the WENA model compares favorably to iasp91. Not only is the overall variance reduced (from  $\sigma^2=3.5$  to  $\sigma^2=2.5$ ), but the travel time residuals are more stationary for the 3-D model. Three-dimensional models reduce the dimensionality of the uncertainties by accounting for the non-stationary component.

## **CONCLUSIONS AND RECOMMENDATIONS**

In conclusion, we have developed a 3-D geophysical model for Western Eurasia and North Africa, along with sophisticated access tools, which are directly usable for generating a number of geophysical parameters of interest. Geophysical models are an important way of calibrating regions in the absence of direct measurements. In addition to providing a background for measurements, geophysical models also improve our interpolation by reducing the non-stationarity of the uncertainties. We will be evaluating a number of geophysical models for inclusion in the NNSA Knowledge Base.

Models can be a repository for a vast array of geological and geophysical datasets of all types - receiver functions, refraction profiles, tomographic inversions, travel time models, etc. This product integrates results from many contractors and can be used to integrate future results.

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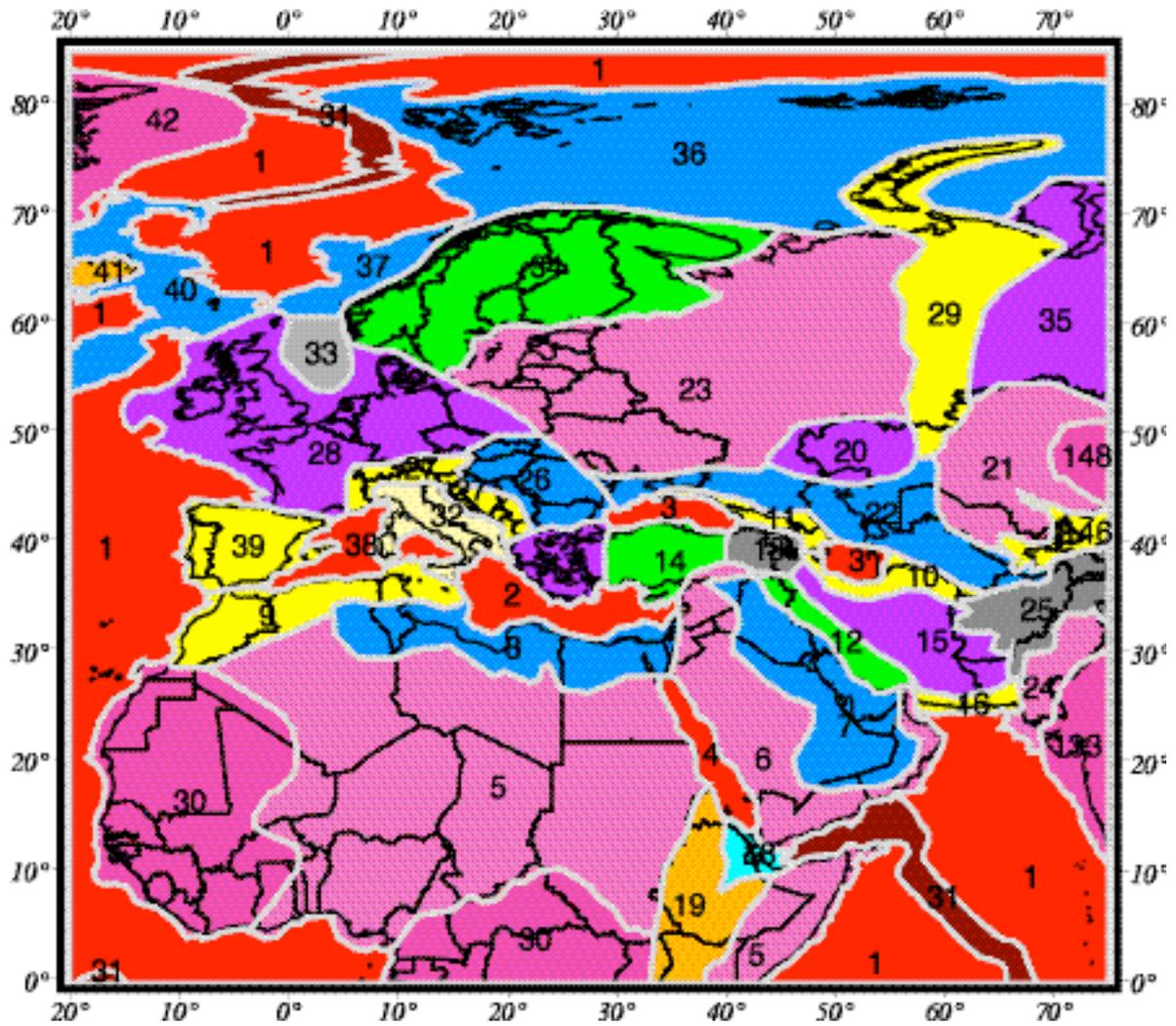


Figure 1. Regionalization of the crust and upper mantle in the WENA model.

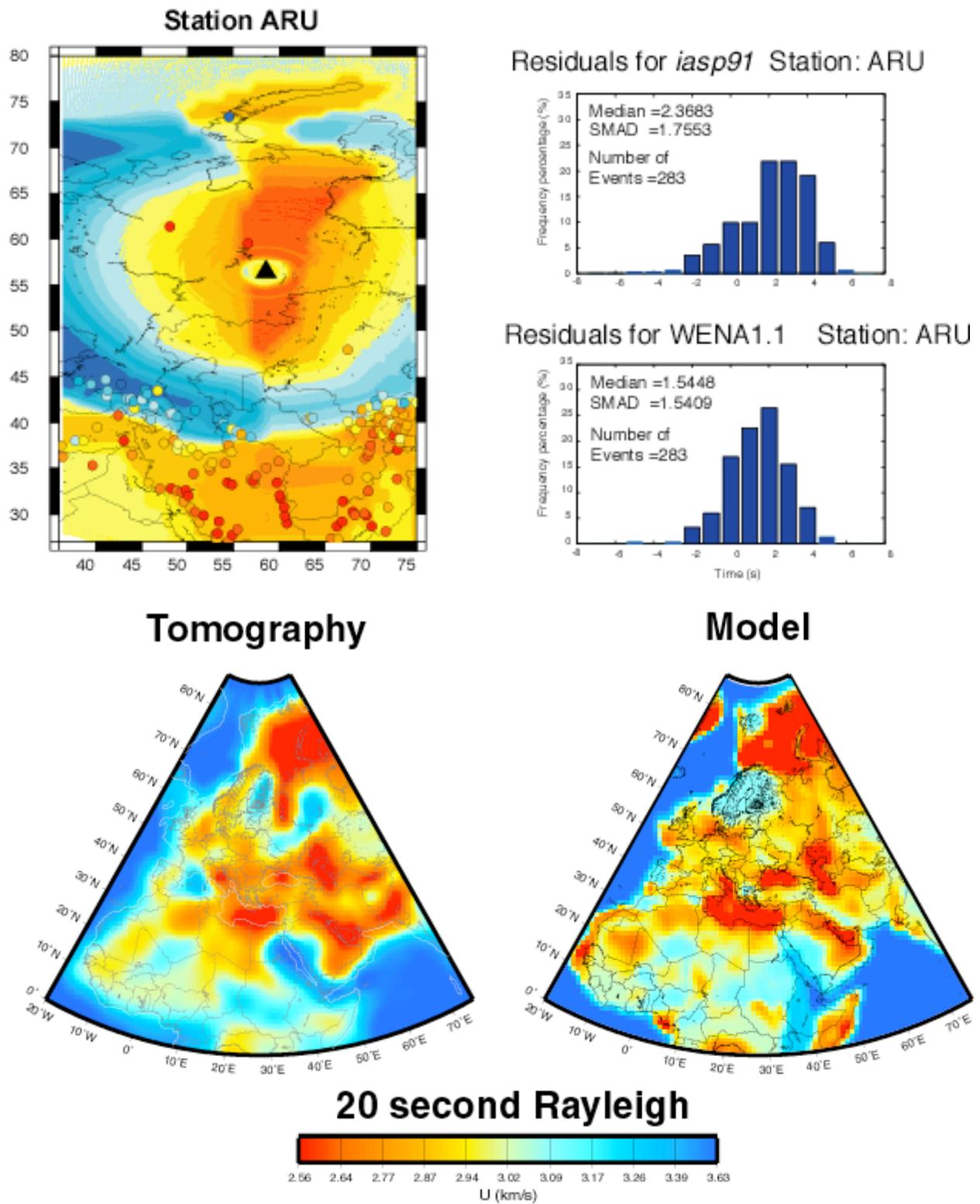
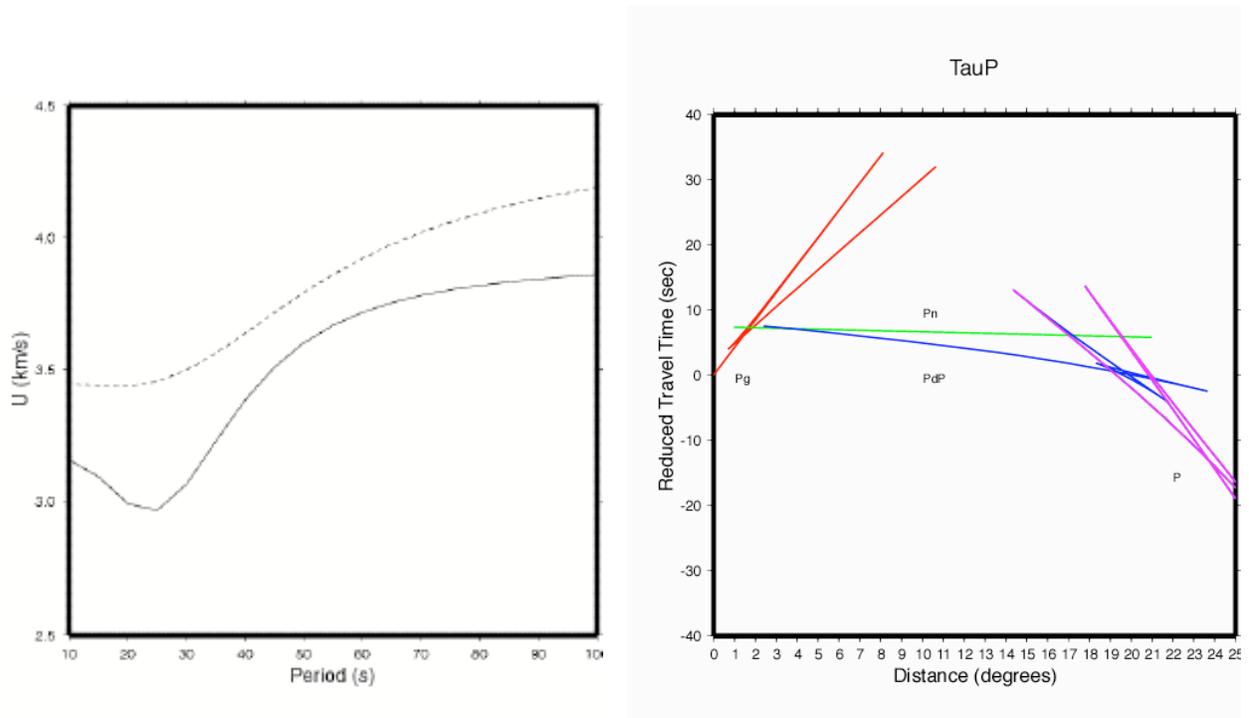


Figure 2. WENA model validations using surface wave group velocities and P-wave travel times



Reflectivity 1 Hz Synthetic Seismograms from WENA Model velocity profile at 25°N and 45°E

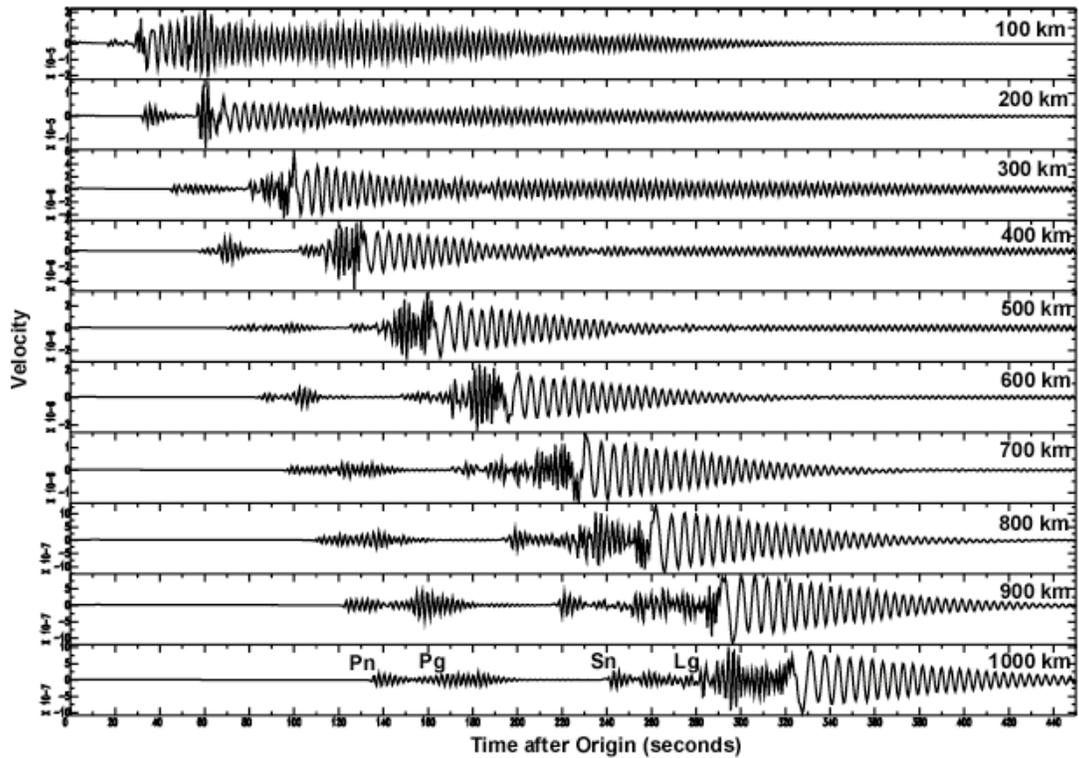


Figure 3. The WENA model can be accessed to predict surface wave dispersion values, body wave travel times, and reflectivity synthetics.



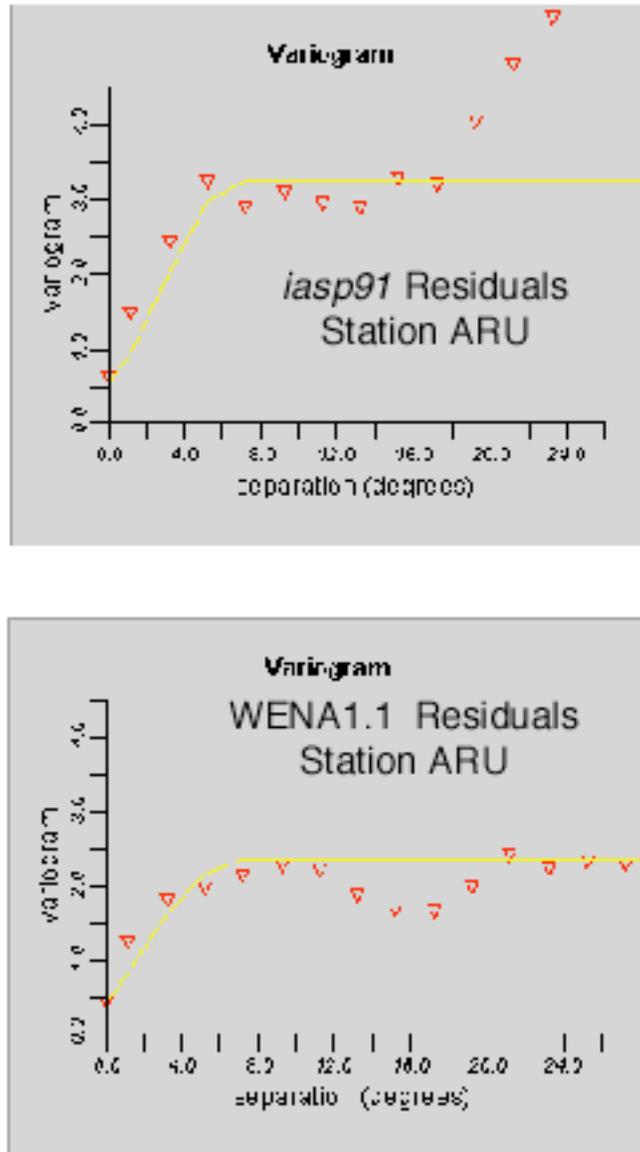


Figure 5. Variograms of P-wave travel time residuals for a 1-D model (iasp91) and a 3-D model (WENA).