GEOPHYSICAL MODEL RESEARCH AND RESULTS

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ABSTRACT

Geophysical models constitute an important component of calibration for nuclear explosion monitoring. We will focus on four major topics: 1) *a priori* geophysical models, 2) surface wave models, 3) receiver function derived profiles, and 4) stochastic geophysical models. The first, *a priori* models, can be used to predict a host of geophysical measurements, such as body wave travel times, and can be derived from direct regional studies or even by geophysical analogy. Use of these models is particularly important in aseismic regions or regions without seismic stations, where data of direct measurements might not exist. Lawrence Livermore National Laboratory (LLNL) has developed the Western Eurasia and North Africa (WENA) model which has been evaluated using a number of datasets, including travel times, surface waves, receiver functions, and waveform analysis (Pasyanos *et al.*, 2004). We have joined this model with our Yellow Sea – Korean Peninsula (YSKP) model and the Los Alamos National Laboratory (LANL) East Asia model to construct a model for all of Eurasia and North Africa. In addition, we continue to improve upon our surface wave model by adding more paths. This has allowed us to expand the region to all of Eurasia and into Africa, increase the resolution of our model, and extend results to even shorter periods (7s). High-resolution models exist for the Middle East and the YSKP region. The surface wave results can be inverted either alone, or in conjunction with other data, to derive models of the crust and upper mantle structure. We are also using receiver functions, in joint inversions with the surface waves, to produce profiles directly under seismic stations throughout the region. A collaborative project (Ammon, et al.) has been focusing on stations throughout western Eurasia and North Africa, while we have been focusing on LLNL deployments in the Middle East, including Kuwait, Jordan, and the United Arab Emirates. Finally, we have been exploring methodologies such as Markov Chain Monte Carlo (MCMC) to generate data-driven stochastic models. We have applied this technique to the YSKP region using surface wave dispersion data, body wave travel time data, and receiver functions.

OBJECTIVE

The objective of regional-scale geophysical models is to improve predictions for the location and identification of regional seismic events by improving the resolution in comparison to global-scale models. As such, we wish to provide models of the highest possible resolution that can 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 take a number of forms. We consider several types here. The first are *a priori* geophysical models. These can serve as background values for travel time correction surfaces and other derived parameters. This can be particularly important in aseismic regions, which might only have a limited number of empirical measurements. These models can also serve as an integrated geophysical repository for research community results. The second type are surface wave models. By themselves, these stand-alone models can be used to construct phase-matched filters, which can improve weak surface wave signal and calculate regionally determined M_S. In addition, they can be used either alone or in conjunction with other data to construct 3-D velocity models of the lithosphere. They can also be a method to evaluate *a priori* geophysical models.

Receiver functions are a reliable way of obtaining the local velocity structure near a station from teleseismic events. While the results are only applicable to the limited portions of our model area covered by seismic stations, they are important to constrain precisely because they represent the structure at the station locations. Improvements in the model at the location of the seismic stations will improve the results of all recordings made at that station. Finally, we present some of the first results from data-driven models generated using a “stochastic engine” inversion technique. This method combines *a priori* information with geophysical data from multiple sources (and varying sensitivities) to produce models that are most consistent with the constraints.

RESEARCH ACCOMPLISHED

Geophysical Models

Geophysical models, such as *a priori* models, can be used to predict a host of geophysical measurements, such as body wave travel times, and can be derived from direct regional studies or even by geophysical analogy. Use of these models is particularly important in aseismic regions or regions without seismic stations, where data of direct measurements might not exist. LLNL has developed the WENA model, an *a priori* model for Western Eurasia and North Africa.

Details of the construction and validation of the model can be found in Pasyanos et al., 2004. Briefly, the WENA model is constructed from separate sediment, crust, and upper mantle models. Sediments are taken from Laske and Masters (1997), a 1º 3-layer sediment model based on the 1985 Exxon map. Crustal regionalizations and velocity profiles are taken from a series of LLNL reports (Walter et al., 2000; Bhattacharyya et al., 2000; Sweeney et al., 1998) and based on Exxon, the global crustal model CRUST 5.1, and many published studies. Overall, we have subdivided the region into 45 base models, each representing a different tectonic region (i.e. Russian Platform, Zagros Mts., etc.). Our regionalizations are shown in Figure 1. The crustal regionalizations also include velocities in the uppermost mantle layer. The 3-Dimensional Seismological Model *A Priori* Constrained (3SMAC) (Nataf and Ricard, 1996) is an *a priori* model based on tectonics, heat flow, and geophysical knowledge, and is used for the remainder of the upper mantle extending down to 660 km depth.

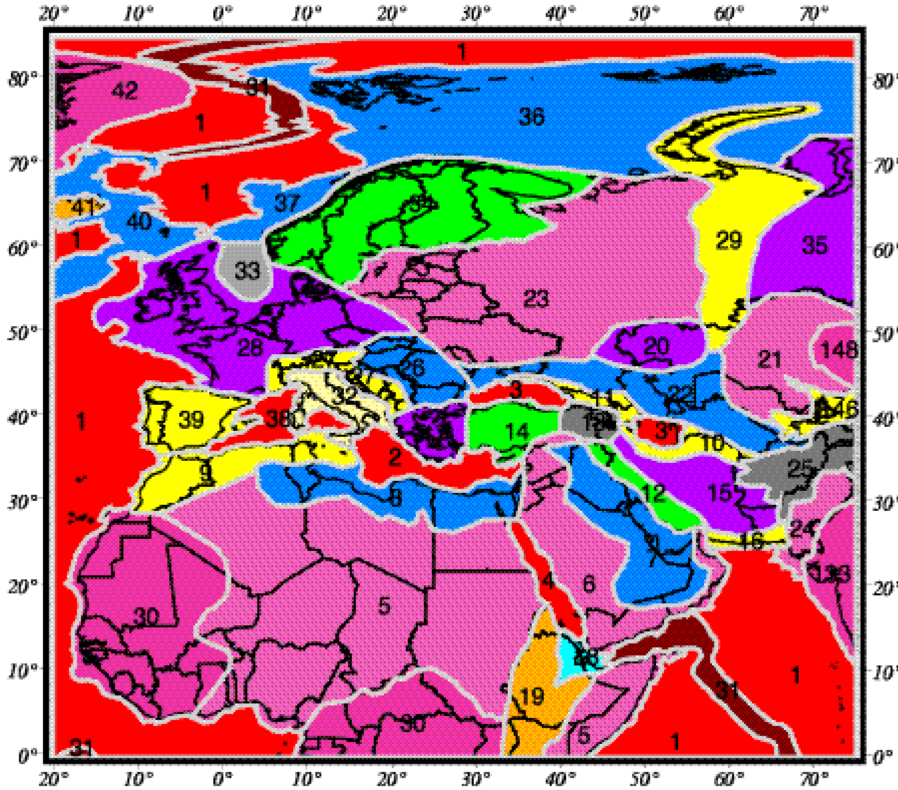

Figure 1. Crustal regionalization used in the WENA geophysical model. There are about 45 base models for the region.

The WENA model has been extensively evaluated using a number of datasets, including body wave travel times, surface wave dispersion measurements, teleseismic receiver functions, gravity, and waveform analysis (Pasyanos et al., 2004). It has been shown to significantly improve the fit to these datasets with respect to global models. Furthermore, it has been shown to improve travel time correction surfaces by reducing the overall amplitude of the corrections and accounting for the non-stationary component of travel times.

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 Commissariat à l'Energie Atomique (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 ensure that the regionalizations of the two individual models are consistent, allowing us join the models. The result is a Unified Geophysical Model for all of Eurasia. WINPAK3D is a model for India and Pakistan that was developed by Weston Geophysical (Johnson and Vincent, 2002). We have recently worked with Weston to convert this model into a format consistent with tools developed to access geophysical models.

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 several input formats for Herrmann's Computer Programs in Seismology and surface wave package SURF (based on Russell, 1988). Most recently, we have added the capability of outputting 1-D and 2-D portions of the model to Xgbm (Davis and Henson, 1993), a travel time predictor that uses a Gaussian beam method.

Surface Wave Models

Over the past several years, LLNL has been developing surface wave models in Eurasia for nuclear explosion monitoring (Pasyanos et al., 2001). Dispersion measurements are made using multiple narrow-band filters on deconvolved displacement data from the LLNL SRKB. We continue to improve upon our surface wave model by adding more paths, generally by taking advantage of new datasets, but also by revisiting stations with more recent events. Most recently, we have added measurements from stations in Central Asia and central and southern Africa, as well as from PASSCAL deployments in Eastern Turkey, Ethiopia/Kenya, China, and South Africa.

To date, over 55,000 seismograms have been analyzed to determine the individual group velocities of 7 – 150s Rayleigh and Love waves. Overall, we have made good quality dispersion measurements for 23,000 Rayleigh and 13,500 Love wave paths. We then tomographically invert these measurements to produce group velocity maps for Love and Rayleigh waves. A conjugate gradient method is used for the tomography. Accurate group velocity maps can be used to construct phase-matched filters, which can improve weak surface wave signal and calculate regionally determined M_S.

The group velocity models continue to improve in several ways. First, with more measurements, we have been able to expand the region of coverage to all of Eurasia and into Africa. By increasing the density of coverage in existing regions, we have increased the resolution of our model. Finally, we have been able to provide more reliable maps at short periods, expanding the frequency coverage down to 7s period. With the group velocities, we are able to resolve structural features associated with the tectonics of the region. Short period surface waves correspond well to sedimentary basins. At intermediate periods, we find a good correspondence to crustal thickness, but still see the effect of the deepest sedimentary basins. At long periods, we are primarily sensitive to upper mantle structure with fast cratons, slow convergence zones, and very slow ridges.

We have created high-resolution models for the Middle East and the YSKP region. Figure 2 shows an example of our results from the Middle East for 15s Rayleigh waves, which are sensitive to relatively-shallow crustal structure. Here, we compare the results to a sediment thickness map and the results are excellent. Details like the extent of basins in the eastern Mediterranean, Persian Gulf, Mesopotamian Foredeep, and Caspian Sea are well resolved, as is the thin oceanic crust in the Red Sea.

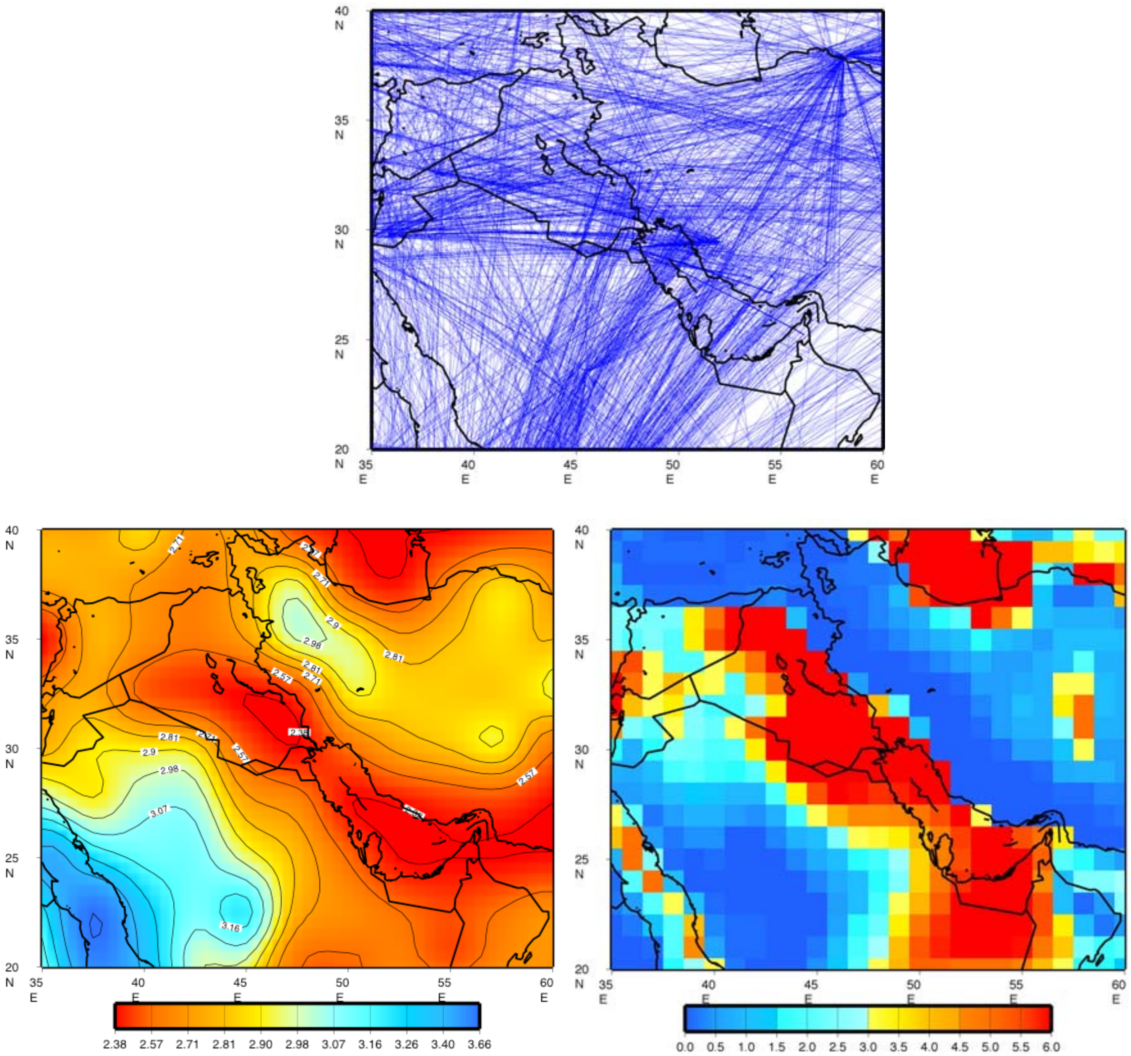

Figure 2. A path map of 15s Rayleigh wave group velocities for the Middle East, followed by a tomographic model of 15s Rayleigh waves and a comparison of the results to a sediment thickness map of the region.

The surface wave results can be inverted either alone, or in conjunction with other data, to derive models of the local crust and upper mantle structure. By combining the surface wave data with other data, we can reduce the non-uniqueness inherent in the profile inversions performed using only surface wave data. In the next section, for example, we will be using the surface wave data in combination with teleseismic receiver functions.

Receiver Function Profiles

We are also using receiver functions, in joint inversions with the surface waves, to produce profiles directly under seismic stations throughout the region. These two data types are complementary since receiver functions are sensitive to velocity contrasts and surface waves are sensitive to depth-averaged velocity. In a collaborative ROA with Pennsylvania State University, Ammon et al., have been focusing on stations throughout Western Eurasia and North Africa, while we have been focusing on LLNL deployments in the Middle East, including Kuwait, Jordan, and the United Arab Emirates.

Figure 3 shows an example of a joint inversion for station KBD in Kuwait. We were able to fit the surface waves without significantly degrading the fit to the receiver functions. The resulting models were similar between various ray parameters and back azimuths, giving us confidence in our results. The profiles were also consistent with the tectonic setting of the region. In Kuwait, we find the thick sediments that would be expected for the Arabian Platform. We also find a crustal thickness of 45 km, which is thicker than models of the region that have looked at the western portions of the platform. The thicker crust that we find, however, is consistent with the general trend of increasing thickness to the northeast and the thick crustal root from the nearby Zagros Mountains. orogenic zone.

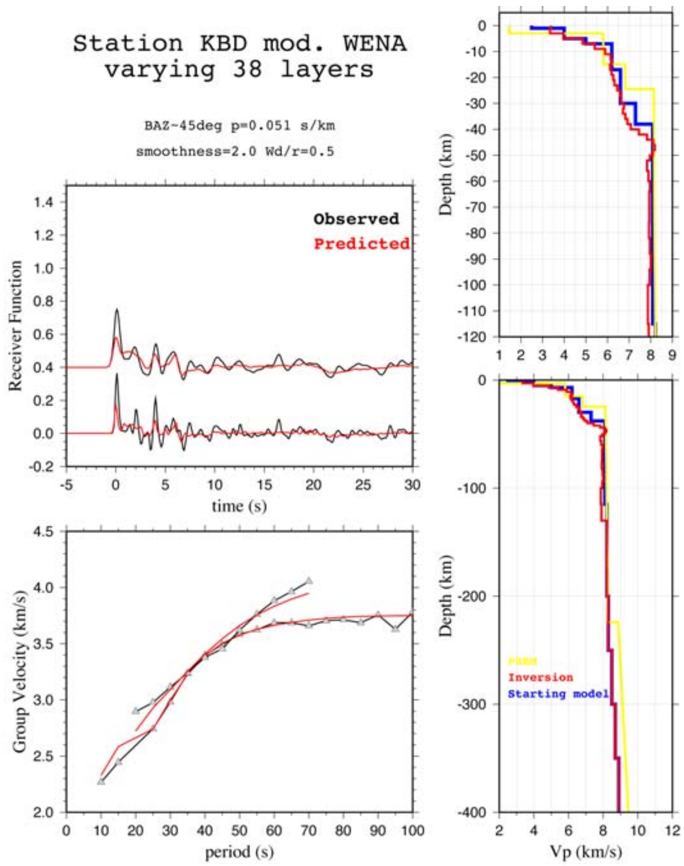

Figure 3. Joint inversion of receiver functions and surface waves to produce a velocity profile for Kuwait. On the left, the black lines are observed data and red lines data predicted from the model. On the right, blue and red lines indicate the starting model and the inversion.

Stochastic Geophysical Models

We have been exploring methodologies such as MCMC to generate data-driven stochastic models. In an effort to build seismic models that are most consistent with multiple seismic datasets, we have applied a new method known as the Stochastic Engine (SE). The SE uses MCMC to sample models from a prior distribution and to test them against multiple data types in a staged approach to generate a posterior distribution of models.

While computationally expensive, this approach has several advantages over a single deterministic model. First, we are able to easily incorporate prior information on the model, such as the *a priori* geophysical models that we considered earlier. Secondly, with this technique, we are able to reconcile different data types that can be used to constrain the model. We can also estimate the uncertainties of model parameters, properly migrating data uncertainties into model uncertainties. The method does not constrain models to be normally distributed, but instead allows non-Gaussian or multi-modal distributions. Finally, we can estimate uncertainties on predicted observable signals, such as would be required to apply this model as a correction surface.

We use this method to determine the crust and upper mantle structure of the YSKP region using surface wave dispersion data, body wave travel time data, and receiver functions. We have had great success using this approach. Where little or no data exist, the posterior model simply reflects the prior distribution. Where data exists, however, the model is driven by the data. Figure 4 shows a crustal thickness map and corresponding uncertainties, taken by calculating the mean and standard deviation of the posterior distribution. One can see the thinning associated with the oceanic crust of the Pacific Ocean and Sea of Japan. One can also see crustal thickening in the westernmost portion of our study area. In the future, we aim to improve the model by incorporating more datasets (i.e., amplitude information, waveforms, etc.) and increasing the resolution.

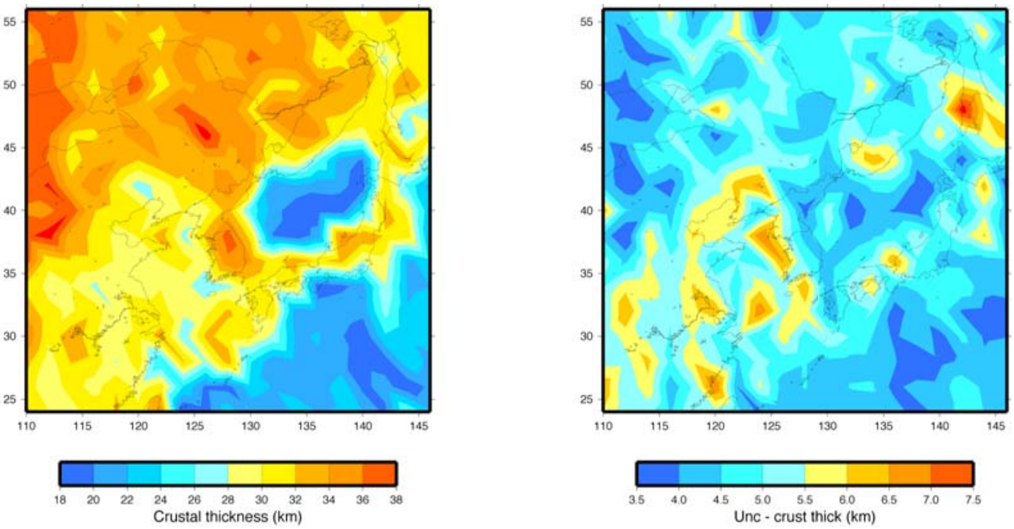

Figure 4. A crustal thickness map of the YSKP region determined using stochastic inversion methods, along with its associated uncertainties.

In short, stochastic methods are an innovative technique for producing next-generation data-driven models. Geophysical models shown in the first section can be used as starting models for the inversion. Other model information such as surface wave dispersion measurements and teleseismic receiver functions (shown in the second and third sections) can be included as additional constraints. Stochastic models have a number of advantages compared to traditional models, such as the ability to reconcile different types of geophysical data. An important component of this is the ability to predict new observables with proper uncertainties.

CONCLUSIONS AND RECOMMENDATIONS

Geophysical models are an important way of calibrating regions in the absence of direct measurements. 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, amplitude measurements, etc. This product integrates results from many sources and can be used to incorporate future results from current research.

Geophysical model research at LLNL has developed along a number of lines. 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. The surface wave measurements and model for greater Eurasia and receiver functions throughout the region provide additional model constraints. We are now moving toward developing data-driven geophysical models that can use all of these results to produce reliable geophysical models.

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