CRUSTAL AND UPPER MANTLE STRUCTURE FROM JOINT INVERSION OF BODY WAVE AND GRAVITY DATA

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ABSTRACT

We present a preliminary model of the three-dimensional seismic structure of the Iran region obtained via simultaneous, joint inversion of body wave travel time and gravity observations. The body wave data set is derived from location calibration efforts and includes a large (>1000 events) subset of GT5-level events. The arrival time data sets for these events include many readings of direct crustal P and S phases, as well as regional (Pn and Sn) and teleseismic phases. These data have been groomed to identify and remove outlier readings; empirical reading errors are estimated for most arrivals from multiple event relocation analysis.

We use both free-air and Bouguer gravity anomalies derived from the global gravity model of the GRACE satellite mission. The gravity data provide information on shallow density variations with short spatial wavelengths, and deeper density structures with longer spatial wavelengths. To increase the usefulness of the gravity data, we apply high-pass filtering, yielding gravity anomalies that possess higher resolving power for crustal and lithospheric structures. To integrate both data sets into a single inversion a functional relationship between seismic velocities and density is required. We first use a combination of two empirical relations: one most appropriate for sedimentary rocks, and a linear Birch's Law that is more applicable to basement rocks. These relationships, however, assume a constant Poisson ratio throughout the inversion. We therefore also apply a method that allows the Poisson ratio to vary by mapping densities to V_P and V_S independently for different earth materials.

Final results of the simultaneous inversion will help us to better understand the crustal and lithospheric structures associated with early-stage continental collision. Such models also provide an important starting model for computationally more expensive and time-consuming fully 3D waveform inversions.

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14. ABSTRACT

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OBJECTIVES

Our objective in this project is to gain increased understanding of the lateral variations of velocity structure in the crust and upper mantle of the region expressing the continental collision between the Arabian and Eurasian plates. Our strategy is to combine different types of geophysical data sets, in this case, body wave travel time data and gravity data, in a formal joint inversion for velocity structure. Preliminary work has shown that body wave data and gravity data can be combined to yield improved resolution of the variability of crustal and upper mantle velocities. A key element to this success is careful filtering of the gravity data so that the signal source region corresponds to the depth range that is sampled by the seismic data.

Our choice of region for this study is driven in part by the availability of an exceptional data set of body wave travel time data that results from a series of research projects on calibrated locations in the region. No other area of monitoring interest is so well sampled by ground truth events. This project is one effort to make maximum use of this unique data set.

RESEARCH ACCOMPLISHED

We have made progress in all major areas of this project, acquiring the earthquake and gravity data sets, development of the joint inversion code, and performing preliminary inversions.

Calibrated Earthquake Dataset

We have imported a large data set of calibrated earthquake locations and associated station information and arrival times into the Ground Truth Database that is maintained at Los Alamos National Laboratory (LANL). This data set was developed in several previous projects in the Nuclear Explosion Monitoring Research and Development (NEM R&D) research program (Bergman et al., 2009). These are all available calibrated events for the study region at this time, although we expect to be able to add some additional calibrated clusters during the project.

By “calibrated” we mean that the hypocenters have been estimated with a specialized multiple event relocation process that removes systematic location errors from clusters of earthquakes, by establishing the location of the cluster using only near-source data that are insensitive to unknown velocity structure. Such data includes seismic recordings at short epicentral distances, field mapping of faulting, and remote sensing analyses of ground displacements such as Interferometric Synthetic Aperture Radar (InSAR). The accuracy of relative locations of clustered events is also improved in the relocation analysis. The majority of events in the data set qualify as $GT5_{90}$ and many qualify at lower levels of location accuracy. In the relocation process the arrival time data sets are groomed to remove outlier readings and to estimate empirical reading errors.

The import process required extensive review of station codes and coordinates to maintain the correct associations with station information and associated arrival time data already in the database. The calibrated earthquake data set is now easily accessible for input to the joint inversion code that is maintained at LANL, and it is also easy to incorporate other (non-calibrated) earthquake data in the region in the inversion as needed. The calibrated earthquake data set includes 1902 events recorded at 376 stations, yielding 26,043 P readings and 6,390 S readings that we have used in the joint inversion. The distribution of calibrated events is shown in Figure 1 and the ray coverage for the Pn phase is shown in Figure 2.

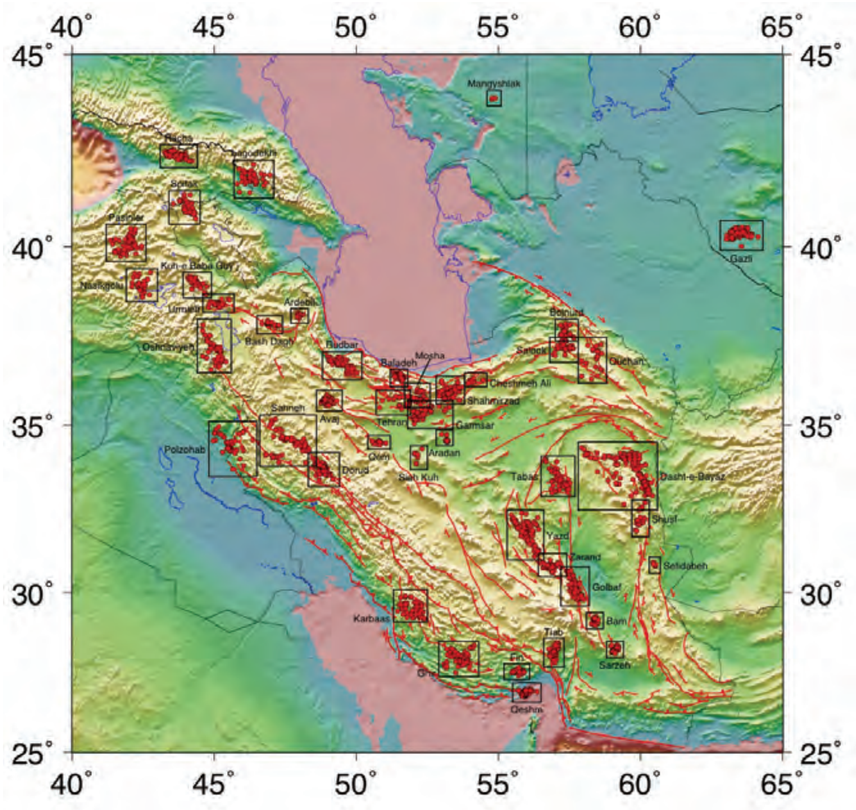

Figure 1. Map of the study region, showing the locations of earthquakes with calibrated locations that are used in this study. Calibrated relocations have been done with a multiple event analysis applied to clusters. The bounding boxes of the clusters are shown.

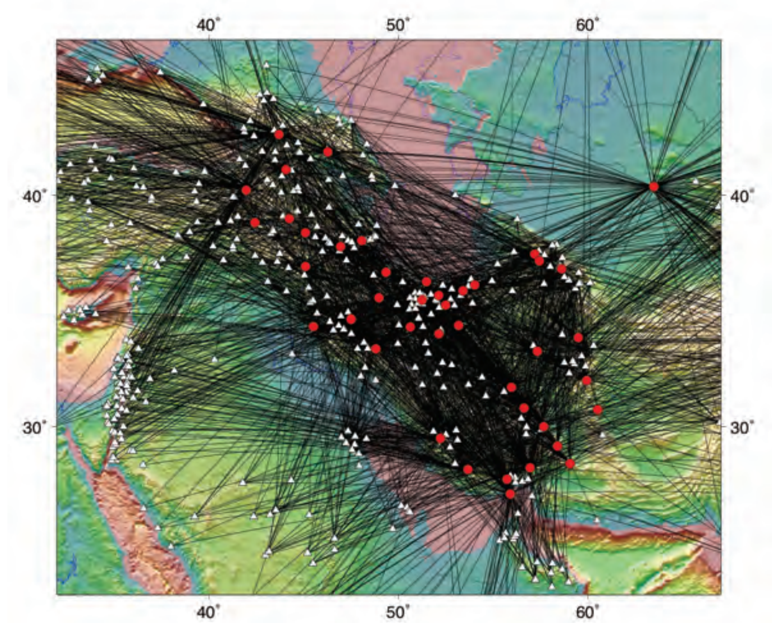

Figure 2. Pn raypaths in the calibrated earthquake data set. The data set also contains Sn arrivals, as well as crustal (Pg, Sg) and teleseismic arrivals. The raypaths shown are summary rays from individual clusters (Figure 1), shown as red circles, to stations (white triangles). Most raypaths are sampled many times, providing useful information on variability of the input data.

Gravity Data

We used gravity observations extracted from the global gravity model derived from the Gravity Recovery and Climate Experiment (GRACE) satellite mission. A detailed description of the satellite data and the computation of the gravity field are given by Tapley et al. (2005). The new gravity field is more accurate than previous data and reveals previously unobserved tectonic features. Figure 3 shows the free-air gravity anomalies for the study region. Blue colors represent gravity highs and gravity lows are represented in red. Free-air gravity anomalies contain information not only of the subsurface density but also topography. While in flat regions this may not be a problem, in areas of high topographic relief this effect needs to be removed; thus, we converted free-air anomalies into Bouguer anomalies assuming a standard density for crustal rocks of 2670 kg/m^3.

To increase the usefulness of the gravity data for investigating 3-D seismic structure, we are exploring high-pass gravity filtering. Though commonly applied in gravity forward modeling (e.g., Simiyu and Keller, 1997), such techniques are not usually applied in joint inversion studies (e.g., Zeyen and Achauer 1997; Tiberi et al., 2003; Maceira and Ammon, 2009). Filtered gravity anomalies are expected to possess their highest resolving power at short wavelengths and thus enhance resolution of lithospheric structure. Maceira et al. (2011) have shown the possible benefits of filtering. After high-pass filtering, the remaining short-wavelength signal can be assigned with greater confidence to structures within the crust, reducing the mutually degrading effects of smearing between crustal and mantle structures. To high-pass filter the Bouguer gravity data we follow the filtering parameter choices of Tessema and Antoine (2004), who use an upward continuation method and demonstrate correlation with crustal geology.

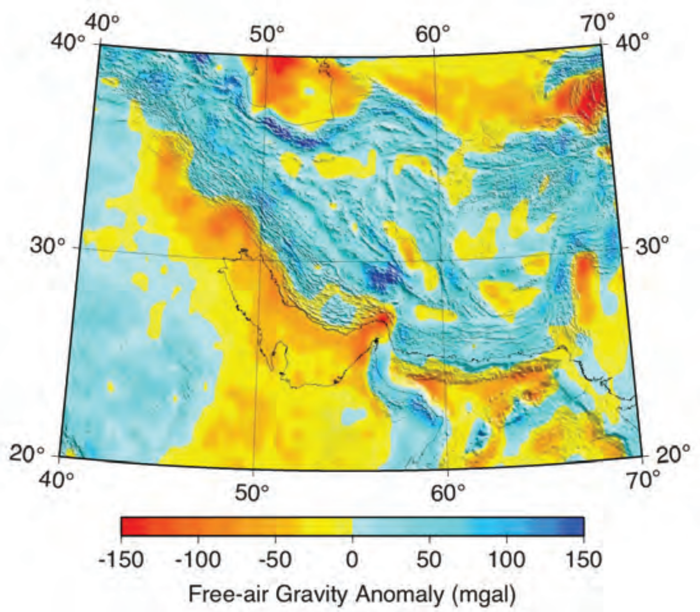

Figure 3. Free Air gravity anomaly field in the study area.

Joint Inversion Code

During a previous project in the NEM R&D research program and in collaboration with MIT, we developed an algorithm named JointTomoDD (Maceira et al., 2010), which is a modification of the Maceira and Ammon (2009) joint inversion code, in combination with the double-difference tomography program tomoFDD (Zhang and Thurber, 2003, 2006), with a fast LSQR solver operating on the gridded values jointly. The model representation is a combination of columns of rectangular prisms (needed for the gravity forward modeling) embedded in a grid whose nodes are located at the center of each prism.

Preliminary Inversions

We first performed several runs using only the seismic body waves (P and S) arrival times. The resulting 3D model depends strongly on the initial model. Figure 4 shows the P and S velocity fields obtained when using ak135 as the starting velocity model. Figure 5 shows the corresponding Moho isosurface (choosing a velocity of 8 km/s) in which quite unrealistically deep Moho depths can be seen. Figure 6 shows the velocity fields obtained by starting with a modified ak135 model in which the Moho is set to ~ 50 km depth (as compared to 35 km in ak135), which is known to be a more reasonable average Moho depth for this region. Figure 7 shows the corresponding Moho isosurface, which is still too deep in some places.

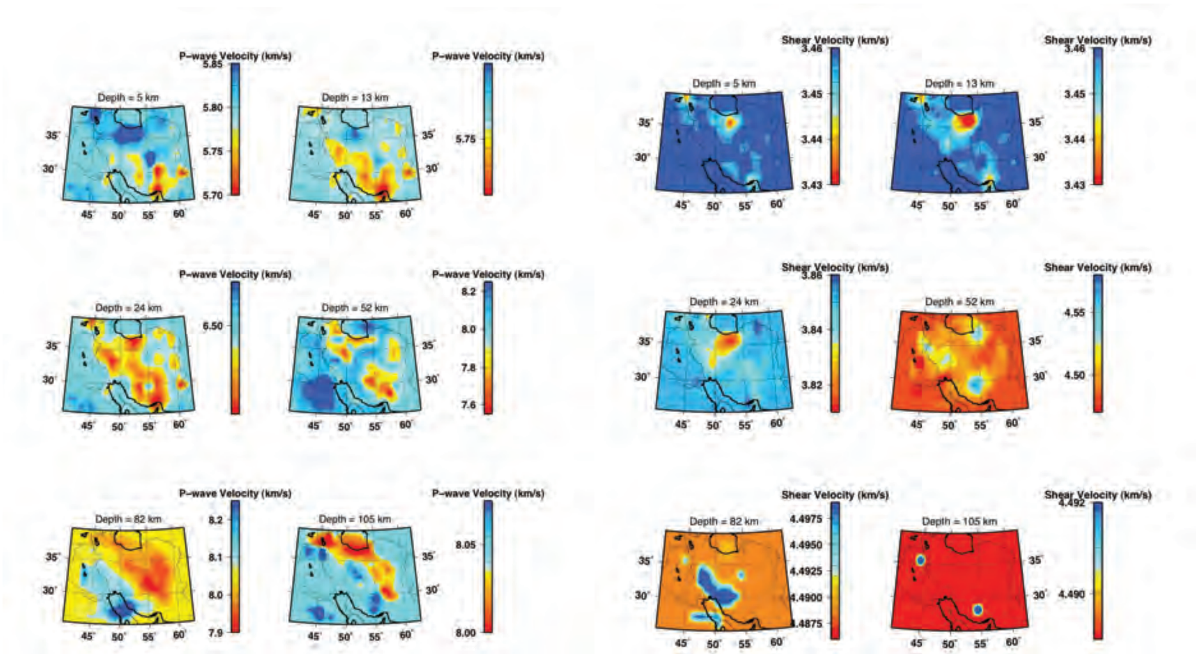

Figure 4. Results of inversion of the seismic data only (P velocities on the left, S velocities on the right), shown at depths of 5, 13, 24, 52, 82 and 105 km. The starting model is ak135.

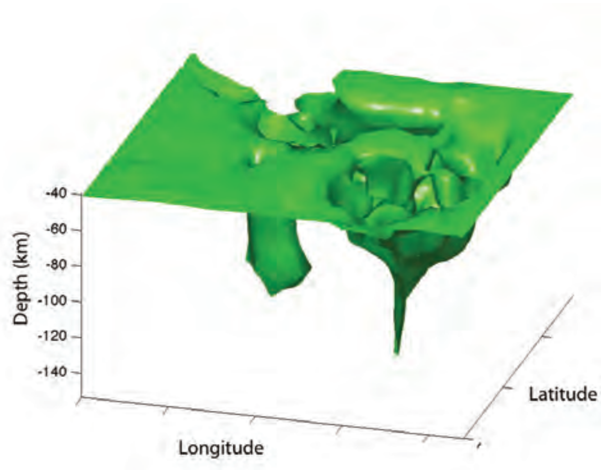

Figure 5. Moho isosurface (at 8 km/s) derived from the velocity model of the inversion using only seismic data (Figure 4).

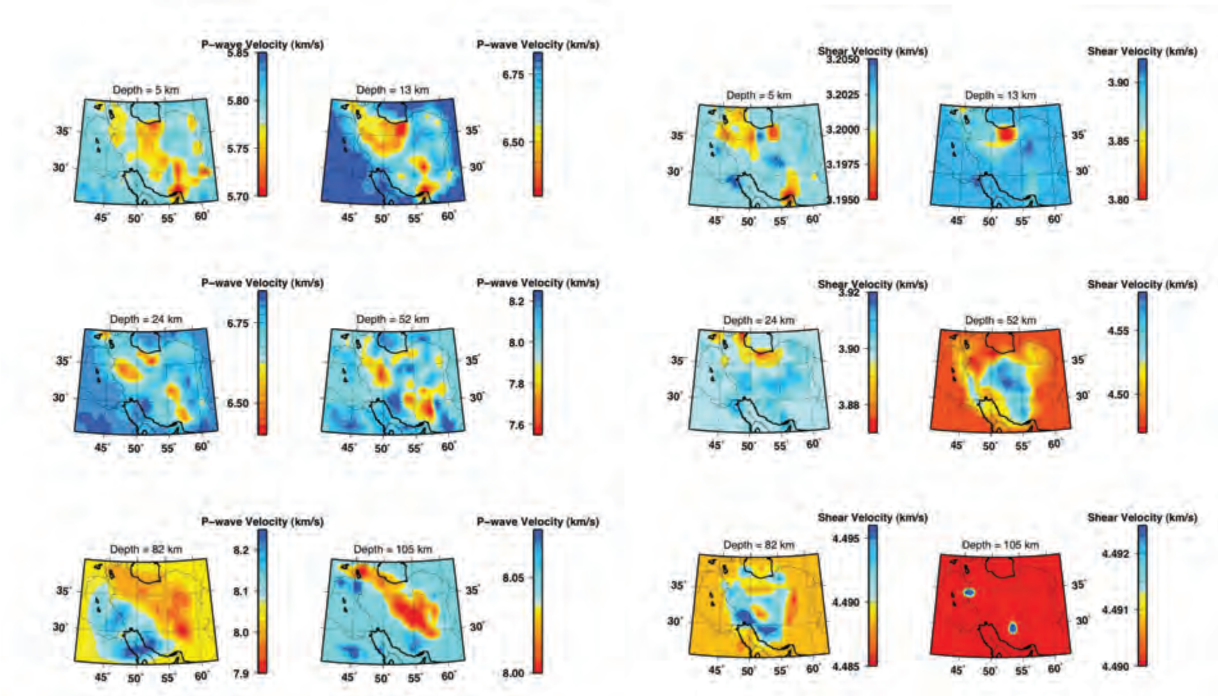

Figure 6. Results of inversion of the seismic data only, with a modified version of ak135 (Moho at 50 km) as the starting model. Otherwise, as Figure 4.

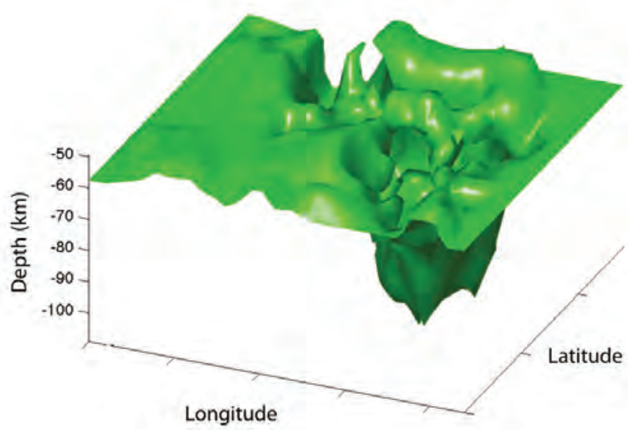

Figure 7. Isosurface of the Moho derived from the inversion of seismic data alone, using a modified version of ak135 (with Moho at 50 km) as the starting model (Fig. 6).

In either case, the fit of the gravity field inferred from the final velocity model to the observed gravity field is very poor (Figure 8). In fact there appears to be a significant degree of anti-correlation.

We then performed some initial joint inversions combining the seismic data with the free-air gravity anomalies for the region and using the modified version of ak135 as the initial model. Figure 9 shows the compressional (left) and shear-wave (right) velocity models from the joint inversion. The Moho isosurface derived from this inversion is shown in Figure 10. These results are very preliminary so we do not attempt an interpretation. Even though the fit to the gravity data has greatly improved (compare Figures 8 and 11), we can already see signs of leakage of the high wavenumber gravity signal into the upper mantle velocity structure. Gravity filtering of the Bouguer anomalies will help alleviate this problem and we are now in the process of performing those runs.

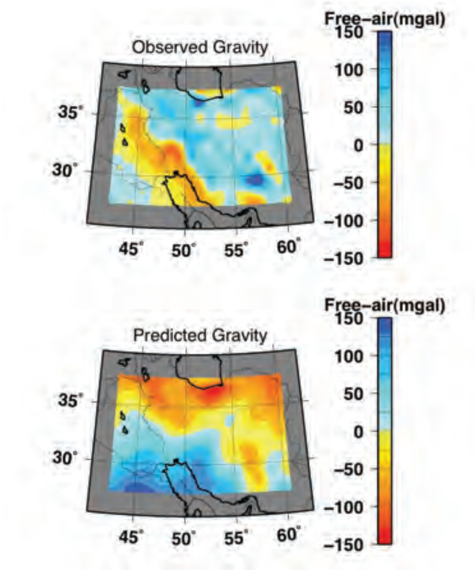

Figure 8. Comparison of the gravity field predicted from the velocity model shown in Figure 6 with the observed gravity field. There is a significant degree of anti-correlation.

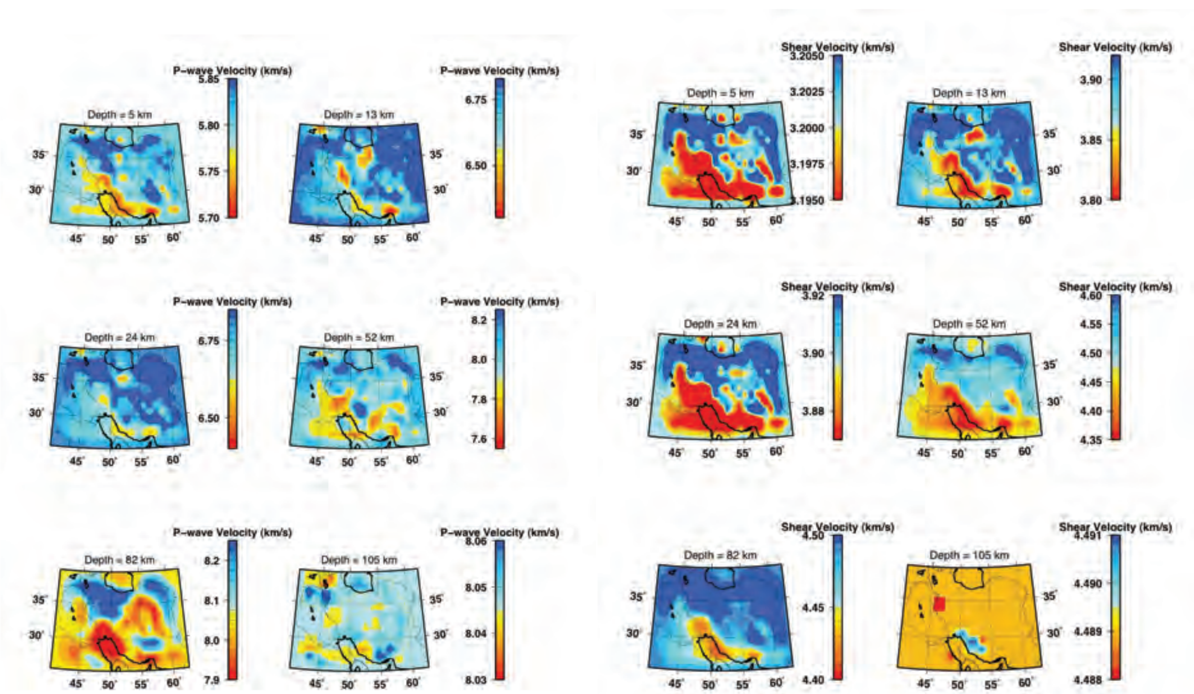

Figure 9. Results of the joint inversion of seismic and gravity data (P velocities on the left, S velocities on the right), shown at depths of 5, 13, 24, 52, 82 and 105 km. The starting model is ak135, modified to have a 50 km thick crust.

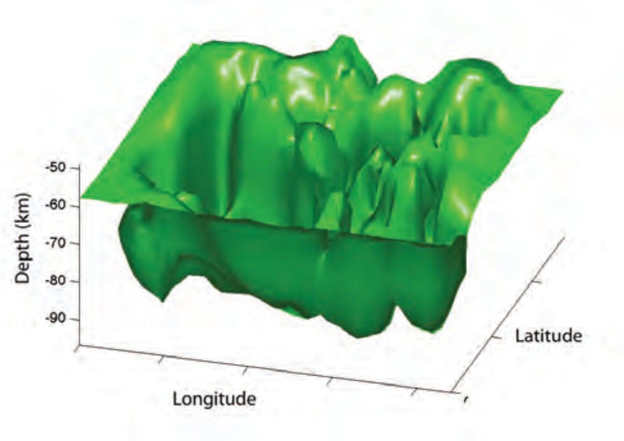

Figure 10. Isosurface of the Moho (8 km/s) based on the velocity field from joint inversion of seismic and gravity data (Figure 9).

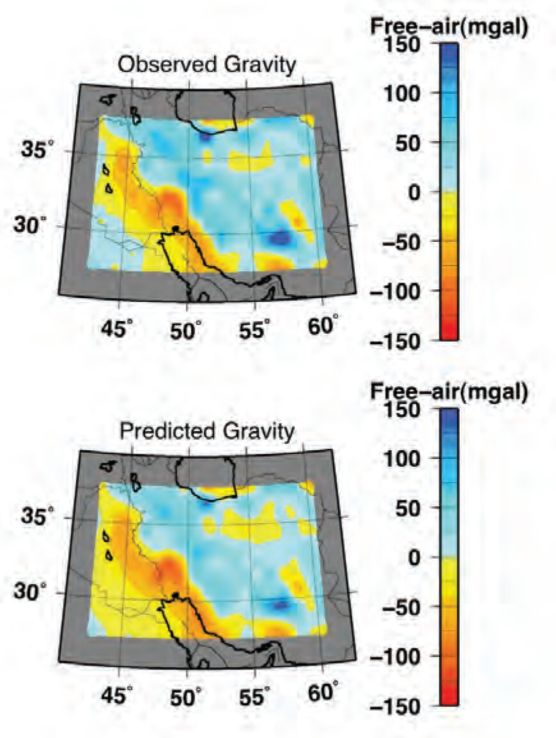

Figure 11. Comparison of the gravity field predicted from the velocity model shown in Figure 9 (joint inversion of seismic and gravity data) with the observed gravity field. The agreement is, unsurprisingly, much better than the case where the velocity model is determined using only seismic data (Figure 8).

In our modeling we couple seismic and gravity data through a density-velocity relationship. This is an ambiguous relationship, however, because seismic wavespeeds are governed not only by rock density but also by bulk and shear moduli, which vary independently and are influenced by many factors, including lithology, temperature and lithostatic pressure. Our initial inversions have used a combination of traditional empirical relationships: one appropriate for sedimentary rocks (after Nafe and Drake, 1963) and one for basement rock (Birch, 1961). Both require the additional assumption of a fixed Poisson ratio in order to obtain shear wave velocity. In subsequent modeling we are employing a shear velocity vs. density relationship proposed by Ludwig et al. (1970), as implemented in a code provided by D.G. Harkrider. This method allows us to treat Poisson's ratio as a variable in the joint inversion, although the degree to which the data will permit this variable to be resolved needs to be explored.

CONCLUSIONS AND RECOMMENDATIONS

We have set up the seismic (body wave travel times) and gravity data sets, finished modification and testing of the code for the joint inversion, and begun running inversions to learn how best to combine these types of data to infer features of the 3-D velocity structure of a continental collision zone. We have performed inversions using only the seismic data, finding that they are inadequate to accurately image the 3-D velocity field in the study region, except perhaps for a few areas with especially good coverage. Adding the unfiltered gravity data to the inversion leads to results that are far more consistent with the observed gravity field, as expected, but much work will be needed to explore issues of resolution and uniqueness for the seismic velocity fields determined in this type of inversion.

We are also exploring the usefulness of filtering the gravity data to create data sets whose signal is dominated by certain ranges in depth that can be associated with specific seismic phases and epicentral distance ranges. Our code is also able to incorporate seismic surface wave data and we will consider this as a way to improve the sampling coverage by seismic data in the study region.

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We acknowledge the assistance of Richard Stead in importing the data set of calibrated earthquake locations and arrival time data into the database used for the joint inversions.

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