AN UPDATED EURASIAN CRUSTAL MODEL USING MULTIPLE SEISMIC METHODS

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ABSTRACT

An updated 2° × 2° crustal model for greater Eurasia is being completed from (1) synthesizing existing models, such as WENA 1.0, the new Barents Sea model, and P-wave velocity model for India and Pakistan (WINPAK); (2) regional seismic compressional phase/regional seismic shear phase (Pn/Sn) tomography data; (3) our ongoing compilation of published seismic models for the crust, based on active- and passive-source seismology; and (4) observed and calculated seismic surface wave group and phase velocity maps. In particular, three controlled source studies from China and India completed by the U.S. Geological Survey and colleagues in the past year are contributing to this updated Eurasian crustal model. These include: (1) three short (20–35 km) seismic reflection profiles from the immediate region of the 2001 Mw 7.7 Bhuj (western India) earthquake that yielded a crustal thickening from 35 to 45 km over a distance of about 50 km from the northern margin of the Gulf of Kutch to the epicentral zone of the earthquake; (2) a compilation of over 90 seismic refraction/wide-angle reflection profiles, with a cumulative length of more than sixty thousand kilometers, across mainland China that have shown a mid-crustal low-velocity layer in unstable regions; and (3) a 1000-km-long geophysical profile from Darlag-Lanzhou-Jingbian extending from the Songpan-Ganzi terrane to the Ordos basin in the NE margin of the Tibetan plateau that yielded a 2-D seismic velocity profile from which crustal composition and continental dynamics of the Tibetan plateau are inferred. New crustal depth and velocity maps for greater Eurasia have been compiled, which incorporate the results from the above three studies and other relevant controlled source experiments. This updated compilation of Eurasian Pn and Sn data in CRUST 2.2 will yield more detailed models of the Earth’s structure and subsequently more accurate seismic monitoring. Well-resolved crustal models are critical for determining event locations and size estimations.
OBJECTIVE

Our primary objective is to produce an updated 2° × 2° Eurasian Crustal and Pn/Sn model that can be applied to the problem of improving seismic event location accuracy. The compilation of additional data from previously unavailable regions will add to the understanding of lithospheric structure, and will allow us to develop new and more accurate models for the region. These models will in turn, give better resolution and detection capabilities for individuals wishing to: (1) locate and constrain seismic events, (2) determine regional magnitude equivalents, (3) calculate attenuation coefficients, and (4) describe amplitude variations.

RESEARCH ACCOMPLISHED

In order to meet the above objective, we have completed several investigations of crustal structure in Asia that improve the resolution of the 2° × 2° model. These investigations include seismic reflection profiles in the Kutch (Bhuj) epicentral region of western India and the northeastern Tibetan Plateau, as well as a refined determination of Pn velocity structure throughout mainland China. Data from these studies and those of other researchers are being compiled into an updated CRUST 2.2 Eurasian Model.

Data quality is mainly dependent on the general amount and distribution of appropriate first-order data such as deep seismic wide-angle experiments covering the entire crustal column down to the Moho-discontinuity. On the basis of regional geological and tectonic history, nearby and statistical data, second-order parameters (e.g., thermodynamic) and other model compilations, a model may be “derived.” During later steps these models are tested and validated against independent geophysical data. Therefore, acquiring new and accurate wide-angle seismic data, especially in complex boundary regimes such as the contact between the Indian and Eurasian plates, is critical to the improvement of a 2° × 2° Eurasian Crustal model by significantly reducing the effect of interpolating a priori estimations of crustal velocity. This paper presents the results of three reflection, refraction, or deep seismic sounding surveys in the complex boundary regime between the Indian and Eurasian plates.

In India, research was done to determine the seismic structure and thickness of the crust at and adjacent to the epicenter of the 2001 Mw 7.7 Bhuj earthquake, fortuitously near the Indian nuclear test site. Seismic refraction data was taken from a 1997 survey with three seismic lines that were 20–35-km-long (Figure 1). Data from these seismic profiles were used to determine crustal reflectivity patterns and to bring out the lateral variations in the crustal configuration, which may significantly increase our understanding of the seismicity in the region. Each seismic reflection profile imaged a highly reflective 35–45-km-thick crust.

Seismic refraction data were collected using two 60-channel DFS-V recording systems (NGRI, 2000). The receiver spacing was 100 m, while the shot interval was 7–8 km. Holes drilled up to 20–30 m were utilized to detonate explosives varying between 50–500 kg, depending upon the shot-receiver distances. The data were reprocessed into three common-depth point (CDP) reflection profiles. The seismic survey delineated the basement configuration and the sediments that are sometimes “hidden” under higher velocity Deccan volcanics. The refraction data, however, indicated some basement faults, either directly observable in the form of fault-plane-reflections or in terms of a sudden change in the basement depth, suggesting that a re-analysis of the data sets is likely to bring out seismotectonically important information for the upper and lower crust.

The single-fold ‘refraction’ data were next subjected to Kirchhoff pre-stack depth migration along each of the three line segments A, B and C, with 4, 3 and 4 shots, respectively (Figure 1). Pre-stack depth migration has become an important tool for obtaining quality images from seismic data acquired in geologically complex regions (Yilmaz, 1987; Audebert et al., 1997). The depth migration consists of an estimation of a velocity-depth model and the calculation of an appropriate Green’s function. The migration places structures in their true spatial locations by applying the Green’s function to each reflecting location using a travel-time map that relates time and amplitude from each surface location to a region of subsurface points.

The results indicated that away from the epicentral region of the 2001 Bhuj earthquake (lines A and B), the crust is generally highly reflective, while the crust beneath line C is less reflective. Prominent sub-basement
near horizontal reflection horizons evident at depths of 18–20 km and 30 km beneath lines B and C correspond to the upper and lower crust, respectively. The thickness of the crust increases from 35 km near the coast to nearly 45 km in the region near the Bhuj earthquake. In addition, an upper mantle reflective horizon was imaged ~10–15 km below the Moho, which suggests an earlier period of extension. Figure 2 is a 3-D model of all reflective surfaces discovered through this re-analysis of the 1997 survey data. Overall, the Kutch tectonic setting was revealed to be a complex system rather than a simple rift model of extended and thinned crust. The region may be undergoing compressive deformation under the stress regime of the India-Eurasia collision, resulting in a thickened, highly reflective crust.

Similar work was done in mainland China, with the goal of producing new, updated contour maps of crustal thickness (Figure 3) and Pn velocity (Figure 4) for inclusion in our Eurasian model. The results of more than 90 seismic refraction / wide-angle surveys were used for our new crustal model, compared to 41 profiles used in previous studies.

One such useful Chinese profile was 1,000-km-long and ran from Darlag-Lanzhou-Jingbian extending from the Songpan-Ganzi terrane to the Ordos basin in the NE margin of the Tibetan plateau (Figure 5). This profile examined the interaction between the Tibetan plateau and the Sino-Korean platform, and also imaged the deep driving mechanisms of tectonic deformation. A 2-D velocity structure was constructed from P- and S-waves, from which we inferred the composition of the crust using Poisson’s ratio, and evaluated the continental dynamics in the NE margin of the Tibetan plateau based on the seismic refraction data (Figure 6; Li et al., 2002; Liu et al., 2003).

Along the Darlag-Lanzhou-Jingbian seismic profile, twelve charges were fired at nine shot points numbered SP1 to SP9 (Figure 5). All charges were fired in boreholes except for the water shot at SP1. Each charge size was about 2 tons. The seismic energy was recorded by 200 portable digital seismographs, DAS-1, developed by the Geophysical Exploration Center of the China Earthquake Administration (CEA). Three-component geophones were used for the whole profile and the receiver spacing was 1.5–2 km. High-quality P- and S-wave data were acquired. The vertical-component and the horizontal-component parallel with the profile were used to identify P- and S-waves, respectively. Record sections were plotted with reduction velocities of 6.00 km/s and 3.46 km/s for P- and S-waves, respectively. In order to match the P-wave arrival times, the timescale used for S-waves was compressed by a factor of 0.58 on the S-wave record section. To improve the signal-to-noise ratio, the data were filtered with band passes of 0–10 Hz and 0–6 Hz, respectively, for P- and S-waves. A 3-D velocity structure was derived from Vp-σ values, which indicated that the crust had a more felsic composition in the upper layers that changed into a more intermediate composition at the base (Figure 7).

From the calculated P- and S-wave velocity structure and Poisson’s ratio, it was also discovered that the crust could be divided into two layers and its thickness increased from northeast to southwest (Figure 7). While the thickness of the lower crust increased from 22 km to 38 km, the total crustal thickness increased from 42 km beneath the Ordos basin to 63 km in the Songpan-Ganzi terrane south of the Kunlun fault. Low-velocity zones, possibly indicative of partial melting, were also discovered in the West-Oinling Shan and in the Haiyuan arcuate tectonic region, in addition to other anomalous structures that resulted from tectonic activity between the Tibetan Plateau and the Sino-Korean and Gobi Ala Shan platforms. The tectonic setting throughout China ranges from the Archean core of the Sino-Korean Platform to the active continent-continent collision in the Tibetan Plateau, and a well-defined knowledge of crustal structure in these diverse geologic settings can be extrapolated throughout other regions in our Eurasian crustal model.

As mentioned previously, increased data coverage with improvements in data quality has led to a significantly more accurate crustal contour map (Figure 3). This highly detailed map revealed a north-south-trending belt at 103°–105° E with a strong lateral gradient in crustal thickness, and an apparent relationship between crustal thickness and tectonic setting. The crust appears thinner near depressions and basins, including the Tarim basin, the Junggar basin, the Qaidam basin, the Sichuan basin, and the Jiang-Han basin. However, in tectonically uplifted areas such as the Tibetan plateau, the Thailhanf and Daxingan Ling mountains, and the Tianshan mountains, the crust is thicker than in its surroundings.
The Chinese DSS profiles were compared to tomographic studies, revealing that the earthquake tomography techniques tended to yield more reliable Pn velocities. We reasoned that the DSS profiles had a higher density of shot points and recording stations, and were therefore more useful for determining the Moho depth. Earthquake tomography however, with a larger number of travel-time paths, could be averaged to yield more accurate estimates of actual Pn velocities. Crustal thicknesses derived from these two techniques generally were within ± 3–5 km of each other. These observations regarding the usefulness of various seismic techniques to determine particular crustal parameters can be applied to our updated Eurasian crustal model.

One of the first steps in compiling a new Eurasian crustal model is comparing previously existing regional models (e.g., Nataf and Ricard, 1996; Mooney et al., 1998; Pasyanos et al., 2004), and evaluating them based on their technique and data quality. We constructed separate databases for each technique, e.g., (1) active source models, (2) surface wave models, (3) seismic tomography models, and (4) receiver function models. Integration of such varied models required some discrimination of data and model quality, and we expect that a suite of models will emerge from which we will develop a “best fit” composite model. Discrepancies between input models are resolved based on the best available data, sometimes on a subjective basis.

Following past practice, we are creating our 2º × 2º Eurasian model in terms of eight layers: (1) ice, (2) water, (3) soft sediments, (4) hard sediments, (5) crystalline upper, (6) middle, (7) lower crust, and (8) uppermost mantle (Pn and Sn). The first seven layers are required so that we can accurately model the thickness of the crust, and therefore, obtain accurate Pn/Sn results. Both P- and S-wave velocities are specified in each layer. Only with this information will we be better able to resolve and compensate for transition zone structures and the mantle gradient effect, thus improving accuracy in our location/discrimination efforts. At present, the USGS database includes more than 9,000 data points (more than seven times the number available for CRUST 2.0). A preliminary Eurasian depth to Moho map (Figure 8) at 2º × 2º resolution has already been developed, though this will improve dramatically once the CRUST 2.2 database is complete.

CONCLUSIONS & RECOMMENDATIONS

The accumulated efforts that have gone into developing these numerous regional seismic models, such as this one, are well-justified by several factors. First, new seismic constraints accumulate rapidly each year, and a focused regional approach permits the careful consideration and inclusion of all new measurements. Second, whereas previous models were mainly based on active-source seismic profiles, the new regional models make use of many more data types, such as receiver functions, short-period surface wave inversions, travel-time tomography, and gravity data. The result is that regional models often provide better locations than global models when tested with GT05 and GT10 ground truth events.

CRUST 2.2 incorporates the most recent crustal velocity measurements throughout Eurasia. Relationships between phase and group velocities and three-dimensional isotropic Earth structure form the basis of forward and inverse modeling procedures that are routinely implemented (e.g., Trampert and Woodhouse, 1995; Ekström et al., 1997; Pollitz, 1999; Hazler et al., 2001). Once the model is complete, we shall test both the consistency of group velocity measurements with existing Earth models and invert available measurements for three-dimensional crust and upper mantle structure in Eurasia. The additional resolution provided by these data is expected to fill in numerous gaps in crust and upper mantle structure provided by other means (primarily seismic refraction). It is our recommendation that this improved crustal model be expanded to incorporate the entire globe.
REFERENCES


Figure 1. Tectonic map of Kutch showing major fault systems (adapted from Malik et al., 2000). The epicenters of the 2001 Bhuj earthquake (23.6N, 70.34E) as well as two earlier events of 1819 and 1956 are indicated by asterisks. The focal mechanism of the 2001 earthquake is also shown. The three seismic lines (A, B, C) that were studied are shown by thick solid lines with corresponding shot points (open circles). Solid circles indicate towns.

Figure 2. This is a 3-D representation of reflective surfaces within the crust and the location of 2001 seismic activity in the Bhuj region (red dots). Shot points are indicated by black stars, the epicenters of historical earthquakes are marked by red stars. Surface faults are also labeled.
Figure 3. Contour map of crustal thickness obtained from DSS data. Contour internal is 2 km. Crustal thickness ranges from 28–46 km in eastern China, and from 42–74 km in western China. The margins of the Tibetan Plateau are marked by a steep gradient in crustal thickness (from Li et al., 2006).

Figure 4. Seismic velocities of the uppermost mantle from Pn waves. Pn velocities are generally lower in eastern China as compared with those of the Tibetan Plateau (from Li et al., 2006).
Figure 5. Tectonic map of the NE Tibetan plateau. The seismic profile is indicated by a solid black line with circled numbers 1 through 9, which indicate shot point locations. The southernmost shot point (SP1) is located in the Songpan-Ganzi terrane near Darlag. The northernmost shot point (SP9) is located in the Ordos basin near Jingbian. The seismic profile crosses, in addition, the Qinling-Qilian fold system (SP2 to SP6) and the Haiyuan arcuate tectonic belt (SP7).
Figure 6. Two-dimensional crustal velocity structure along the Darlag-Lanzhou-Jingbian profile reaching from the Songpan-Ganzi terrane in the southwest to Ordos basin in the northeast. The top panel shows the tectonic units, faults, and thrust which are crossed by the profile. (a) Crustal P-wave velocity model ($V_p$), (b) the crustal S-wave velocity model ($V_s$), and (c) Poisson’s ratio $\sigma$ (equivalently, $V_p/V_s$ ratio). The top of the crystalline basement is indicated by B, the Conrad discontinuity by a C and the crust-mantle boundary by M. The upper crust lies between B and the C, and the lower crust between C and M. C1 and C3 to C5 indicate further interfaces in the upper and lower crust, respectively. The cross-sections are shown with a vertical exaggeration of 1:5.
Figure 7. Three-dimensional perspective view of the compositional structure of the crust along the Darlag-Lanzhou-Jingbian profile. The composition is derived from the P-wave velocity structure whereby felsic, intermediate and mafic material is identified through velocity intervals according to Christensen and Mooney (1995).

Figure 8. The USGS CRUST 2.1 model covering Eurasia, the Middle East and Northern Africa. This map is depth to Moho, with crustal types shown. This map was compiled using six times the number of active and passive source seismic data points than were used to construct the earlier CRUST 2.0 model (Bassin, et al., 2000).