EXTENSION OF THE CAUCASUS SEISMIC INFORMATION NETWORK STUDY INTO CENTRAL ASIA

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ABSTRACT

The active tectonics of Central Asia is the result of ongoing, active continental collision between the Indian and the Eurasian plates. This geologically and tectonically complex area is also one of the most seismically active regions in the world. Due to many different reasons, access to the local seismic data in this area was very limited. Previous studies in this region mostly depended on teleseismic data as well as local and regional data from the stations located in western and southern China. In this study we used the local travel time data from Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan to study the crustal structure in this region. We selected the events and stations between 32°N-65°E and 45°N-85°E and focused on the areas of Pamir and western Tien Shan. In this dataset, there are more than 3000 *P* and *S* arrivals recorded at 68 stations from about 220 events. Double difference tomography is applied to relocate events and to invert for seismic structures simultaneously. Our results provide accurate locations of earthquakes and high resolution crustal structure in this region. We use local and regional travel times to invert the 3D crustal velocity structure in this region. More than 2200 *P*-wave phase picks were used in the inversion. The average grid spacing is 100 km and the inverted grids lay on six layers. Then we use the double difference tomography method developed by Zhang and Thurber (2003, 2006) to invert for the 3D *P*-wave velocity structure.

Our tomographic results show strong heterogeneities in the crust and upper mantle of the Central Asia. The crustal low velocity zones are found near Tien Shan, the northern Pamir, and the Tajik depression, while high velocity anomalies are found beneath the Kazakh shield, the southern Pamir, and the Tarim basin. The Moho discontinuity can be illustrated as a velocity contour line. If an average *Pn* velocity of 8.0 km/s is chosen for the Moho, then most Moho depths are greater than 70 km.

OBJECTIVES

The main goal of this project is to develop a database consisting of: new waveform data, seismic event catalogs, and information on the geology and active tectonics in the Central Asian region. Over the past years, we have collected geologic, geophysical, seismic event catalog and phase arrival data from local networks in the Caucasus region; this project extends the work into the CASRI (Central Asia Seismic Research Initiative) region (Kazakhstan, Kyrgyzstan, Uzbekistan, and Tajikistan). The new database is crucial in generating a detailed crust and mantle structure model and characterizing seismic wave propagation and attenuation in Central Asia. The local seismic networks, calibration events, improved crust and mantle structure models and better location algorithms (e.g., multiple-event grid search, double-difference methods) will improve the event locations. This new database will form the basis for mitigating earthquake hazard in Central Asia, and it will aid in the monitoring of these regions of strategic interest to U.S. national security.

RESEARCH ACCOMPLISHED

The Central Asian Tectonic Setting

The active tectonics of Asia is predominantly the result of the continental collision and the continuing continental convergence between the Indian and the Eurasian Plates. As a result, large scale structures such as the Himalayas, Tibet, Hindu Kush-Pamir, and the Tien Shan have been produced by the collision and the post-collisional convergence. The overall continental deformation of Asia was explained by the lateral escape of rigid lithospheric blocks bounded by major strike-slip faults due to the continental collision of the Indian and Eurasian Plates based on the analysis of geological and seismological data (Molnar and Tapponnier, 1975).

The India-Eurasia collision is also accommodated by major thrusting and crustal shortening as evidenced by the high elevation and compressional structures such as the Himalayas, Hindu Kush-Pamir, and the Tien Shan regions (Figure 1). An alternative model suggesting that the mode of continental deformation can be explained by continuum mechanics was proposed to explain the continental deformation of Asia (England and Houseman, 1986; Houseman and England, 1993). This alternative model assumes that the collision and convergence of the Indian and Eurasian Plates are mainly accommodated by lithospheric thickening, and the resultant increased gravitational body forces drive the active tectonics of Asia. The Global Positioning System (GPS) measurements and crustal rheology modeling in Asia provide evidence that the deformation in the shallow brittle crust occurs on a distributed network of faults, and some regions such as the Tarim Basin, the Ordos and South China behave as rigid blocks; however, deformation of a continuous medium at depth is the best description of the present day tectonics of Asia (Royden et al., 1997; Wang et al., 2001; Calais et al., 2003; Zhang and Gan, 2008).

The countries that are within the interest area of the CASRI project are primarily affected by the tectonic deformations and associated seismic activity of the Tien Shan and the Pamir-Hindu Kush regions. Since we have covered the Neotectonic analysis of the Tien Shan region previously, we will briefly summarize the active tectonics of the Pamir-Hindu Kush region in this paper.

The Pamir-Hindu Kush Region

The Pamir-Hindu Kush region is located at the western syntaxis of the Himalayan belt and it has an elevation of 4000–5000 m. This orojenic syntaxis consists of several terranes that were accreted to the southern margin of Asia during the Paleozoic-Mesozoic closure of the Tethys Ocean (Tapponnier et al., 1981; Burtman and Molnar, 1993; Yin and Harrison, 2000; Schwab et al., 2004; Robinson et al., 2007). Before the India-Asia continental collision took place about 45–50 my ago, the Pamir region was an Andean-style plate margin. The post-collisional indentation of the Indian Plate into the Eurasian Plate caused intense deformation and crustal shortening and created major thrusts and strike-slip faults bounding the region (Figure 1). The Main Pamir Thrust forms the northern boundary separating the Pamirs from the Tien Shan. The left-lateral strike-slip Darvaz-Karakul Fault Zone marks the boundary in the west between the Tadjik Depression and the Pamirs. The right-lateral strike-slip Karakorum fault zone forms the eastern boundary that separates the Pamirs from the western Kunlun and the Tarim Basin (Molnar and Tapponnier, 1978). The Main Pamir Thrust has been interpreted to have accommodated about 300 km of crustal shortening, and additionally at least 300 km of shortening was also accommodated internally by thrusting and faulting within the Pamirs during the Cenozoic (Burtman and Molnar, 1993).

The Pamir-Hindu Kush region has high seismic activity and many large earthquakes have occurred in the region. The focal mechanism solutions for the earthquakes in this region indicate predominantly thrust events, as would be expected, and some strike-slip events along major shear zones that form the boundaries of the region (Figure 2).

The most interesting aspect of the Pamir-Hindu Kush seismicity is that this region is one of the most active regions of intermediate depth seismicity. Many studies have been carried out to evaluate the seismicity of the Pamir-Hindu Kush region (Chatelain et al., 1980; Roecker 1982; Fan and Ni, 1989; Burtman and Molnar, 1993; Fan et al., 1994; Pegler and Das, 1998). More recently, seismic tomographic studies of the mantle structure beneath the Pamir-Hindu Kush region have revealed that the intermediate depth seismicity is the result of the existence of two opposing sense subduction zones (Freiderich, 2003; Kumar et al., 2005; Koulakov and Sobolev, 2006; Negredo et al., 2007). The Indian lithosphere subducts steeply northward beneath the Hindu Kush, and the Asian lithosphere subducts southward beneath the Pamirs; the interface of the two converging lithospheres, at mantle depths beneath the Pamir-Hindu Kush region, forms the zone of intermediate depth seismicity.

Travel-Time Data

An important task under this project is to collect arrival time data from seismic stations situated in the Central Asia. A significant number of these stations are in networks whose data are not available from global data centers such as IRIS (Incorporated Research Institutions for Seismology) or ISC (International Seismological Centre). Figure 3 shows seismic stations in the region from which we have obtained data either through data centers or by bilateral arrangements. In the previous studies of this region, teleseismic data and surface wave data were the main data sources. Although teleseismic data provide us with much information about the mantle, shallow structure is still unclear. The horizontal resolution is also limited by available periods of surface waves. Therefore, we use the local and regional travel times to invert for the 3D crustal velocity structure in this region. We selected the stations and events between 32°N-65°E and 45°N-85°E where there are 68 stations and 220 events (Figure 3). More than 2200 *P*-wave phase picks are employed in the inversion. The average grid spacing is 100 km and the inverted grids lay on six layers. The source-station ray paths are also shown in Figure 3 and the ray density is dense enough to obtain good tomographic resolution.

P- and *S*-Wave Travel-Time Tomography of the Crust and Upper Mantle

A high-resolution tomographic model for the heterogeneous crust is constructed by iterative, non-linear tomography. To generate adequate starting models for the nonlinear inversion, we combine pertinent information from global (Mooney et al., 1998; Stevens et al., 2001; Ritzwoller et al., 2002), regional, and local crust and uppermost mantle models. Next, we use the adaptive moving window (AMW) approach (Sun et al., 2004, 2008) to obtain crustal velocities and *Pn* and *Sn* models from a 1D Monte Carlo inversion of local (≤ 20°) arrival time data in the whole region, building these into the next model (Model #2). The third step is a tomographic inversion of the local and regional arrival time data for 3D variations in the *P*- and *S*-wave speed, using Model #2 as the initial input model.

For this purpose we use a modified version of Zhao's tomographic method (Zhao et al., 1992, 1994; Zhao, 2001; Sun and Toksöz, 2006), which allows for 3D velocity variations everywhere in the model and can accommodate velocity discontinuities. The velocity structure is discretized using a 3D grid. The velocity perturbation at each point is calculated by linear interpolation of the velocity perturbations at surrounding (adjacent) grid nodes. The velocity perturbations at grid nodes are the unknown parameters for the inversion procedure. To calculate travel-times and ray paths accurately and rapidly, the pseudo-bending technique (Um and Thurber, 1987) is used iteratively. We correct for station elevations by including station correction terms in the inversion. The nonlinear tomographic problem is solved by repeated linear inversions. At each iteration, perturbations to hypocentral parameters and velocity structure are determined simultaneously.

Starting from the *P* and *S* models obtained from the above strategy, we apply an adaptive-mesh double-difference tomography method to the newly assembled data set to further improve event locations and velocity models (Zhang and Thurber, 2003; 2006). In this approach, the configuration of model cells is adjusted to sampling density to stabilize the inversion and (locally) optimize spatial resolution. Figure 4 shows the *P* and *S* travel-time, distance graphs, and *P*-wave travel-time residual distribution before and after the 3D inversion. The standard deviation improved from 2.1 seconds to 0.9 seconds as a result of the 3D inversion.

The Moho depth is set to 50 km in the relocation of events, but no Moho discontinuity is used in our starting model. Figures 5 and 6 show the tomographic results obtained for the central Asian crustal structure. Since most phase arrivals are *Pn*, the layers around the Moho (50 km and 70 km) are imaged with the best resolution. In addition, the shallower structure can also be recovered along the China boundary. Figure 7 shows the upper mantle velocity structure at the depths of 100, 200, 400 and 700 km obtained by the double difference tomography method.

CONCLUSIONS AND RECOMMENDATIONS

Our results show strong crustal and mantle heterogeneities in Central Asia. The low velocity zones are found near the Tien Shan, northern Pamirs, and Tajik depression, whereas high velocity anomalies exist beneath the southern Pamir, Kazakh shield, and the Tarim basin.

The Moho discontinuity can be illustrated as a velocity contour line. If an average Pn velocity of 8.0 km/s is chosen for the Moho, then most Moho depths are greater than 70 km.

We will coordinate the installation of three broadband seismic stations in Tajikistan, in cooperation with the Seismic Monitoring Center in Georgia, to improve the quality of regional seismic networks, and to obtain near real-time access to data throughout the Central Asia region.

The extension of the velocity models into the mantle transition zone will be accomplished by adding the teleseismic data from the 1964–2007 ISC/EHB database, which contains over 10 million *P*-wave travel-times, and from datasets obtained by the various national data centers.

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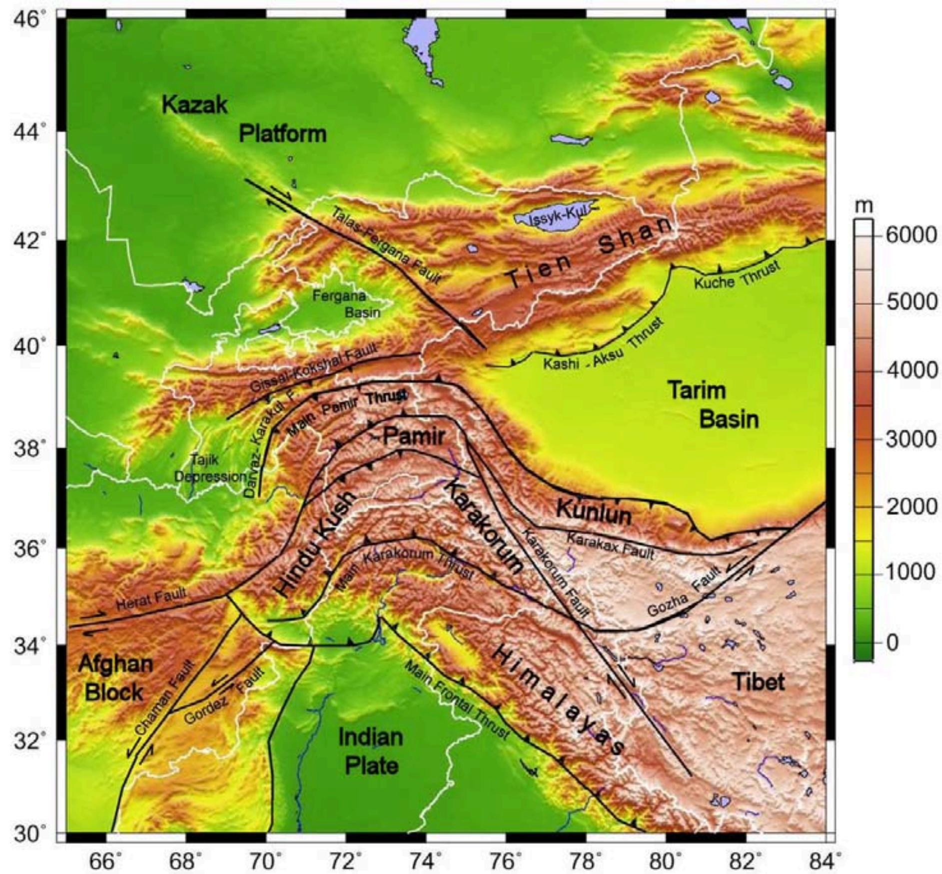

Figure 1. Map of the Pamir-Hindu Kush and surrounding areas showing major tectonic features.

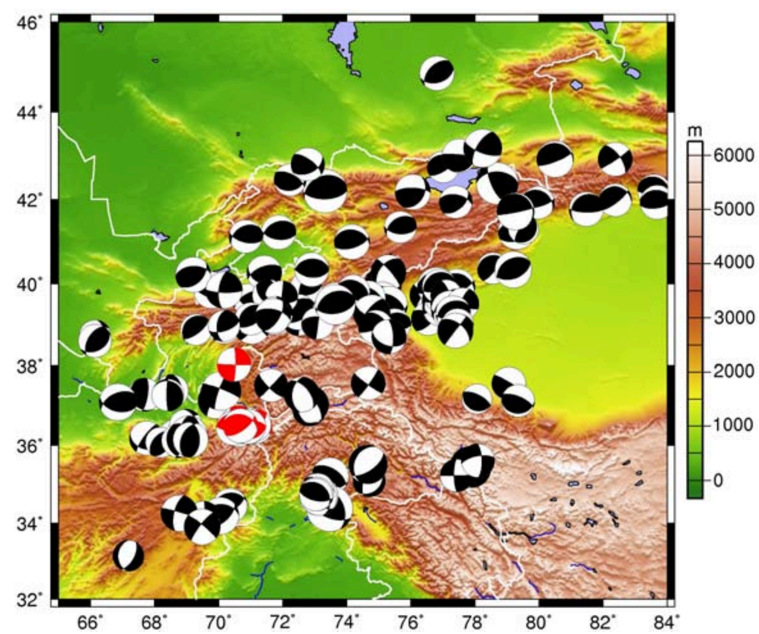

Figure 2. Digital topographic image of the Pamir-Hindu Kush and the Tien Shan regions showing the focal mechanism solutions from the Global Centroid Moment Tensor (CMT) catalog for the events with M>5.0 (1976-2009 period, compressional quadrants are black for the events with <70 km depth, and red for the events with >70 km depth).

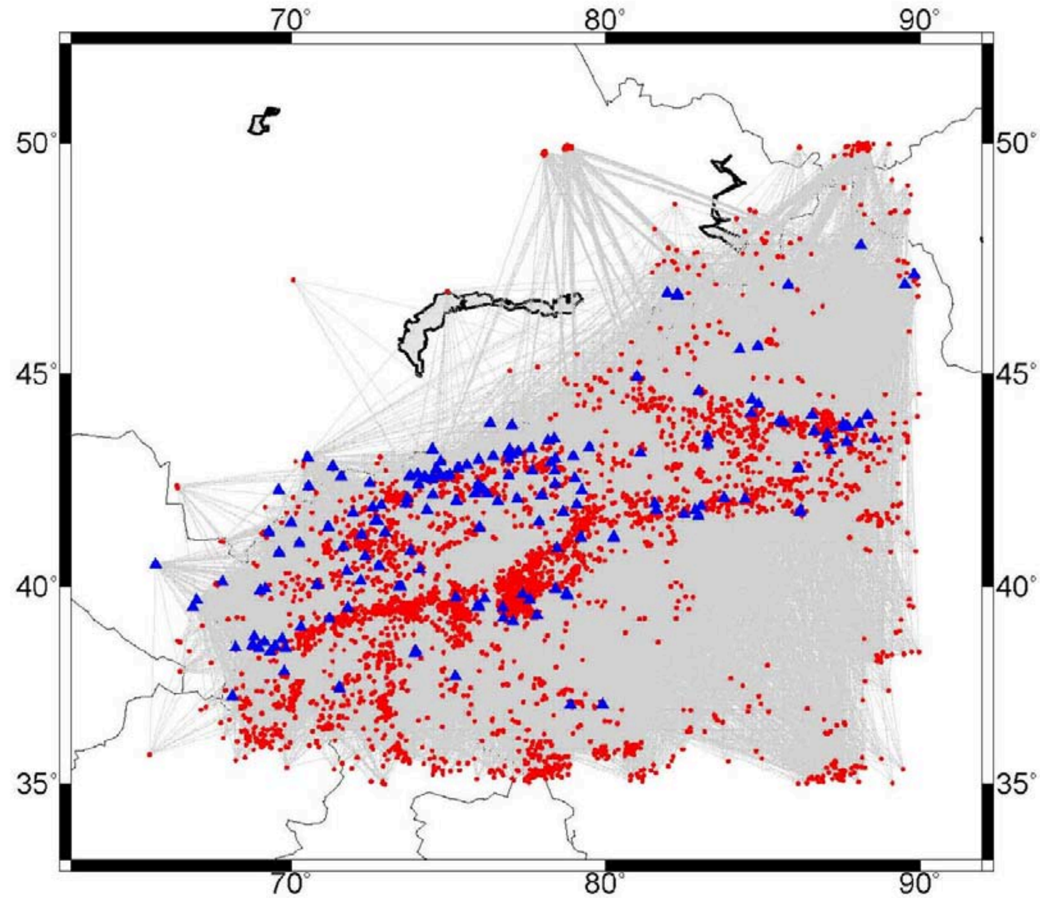

Figure 3. Ray path distribution in Central Asia. The stations are shown with blue triangles and the events are shown with red dots.

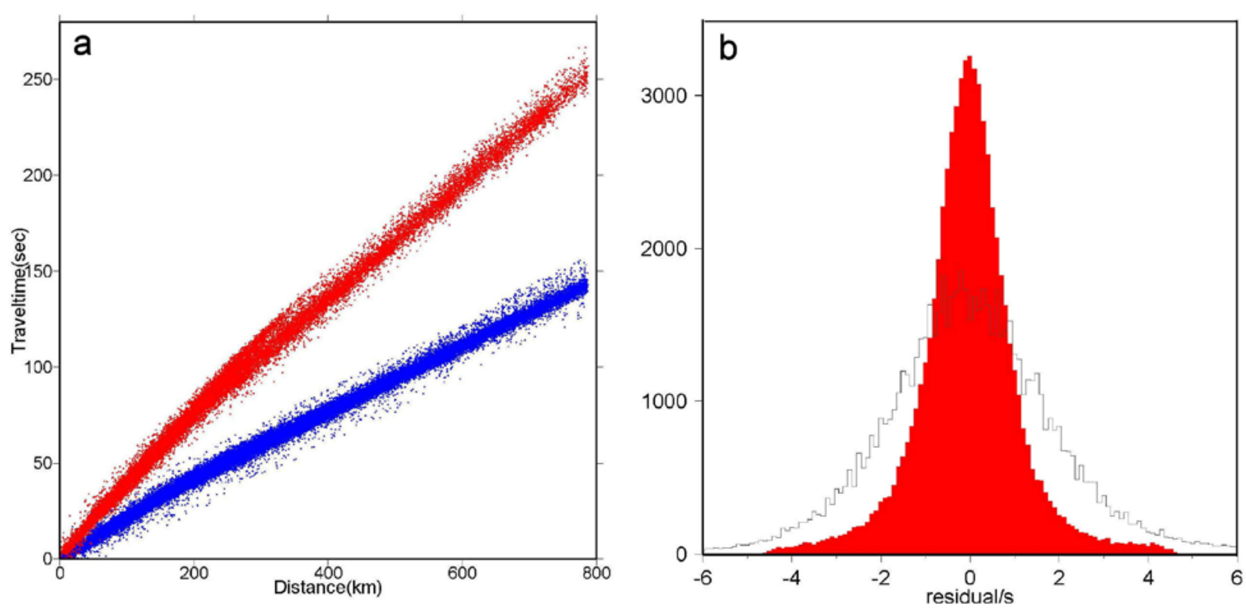

Figure 4. (a) *P* and *S* travel time distribution in the study area. (b) *P*-wave travel time residual distribution before and after (red) 3-D inversion. The standard deviation decreased from 2.1 seconds to 0.9 seconds.

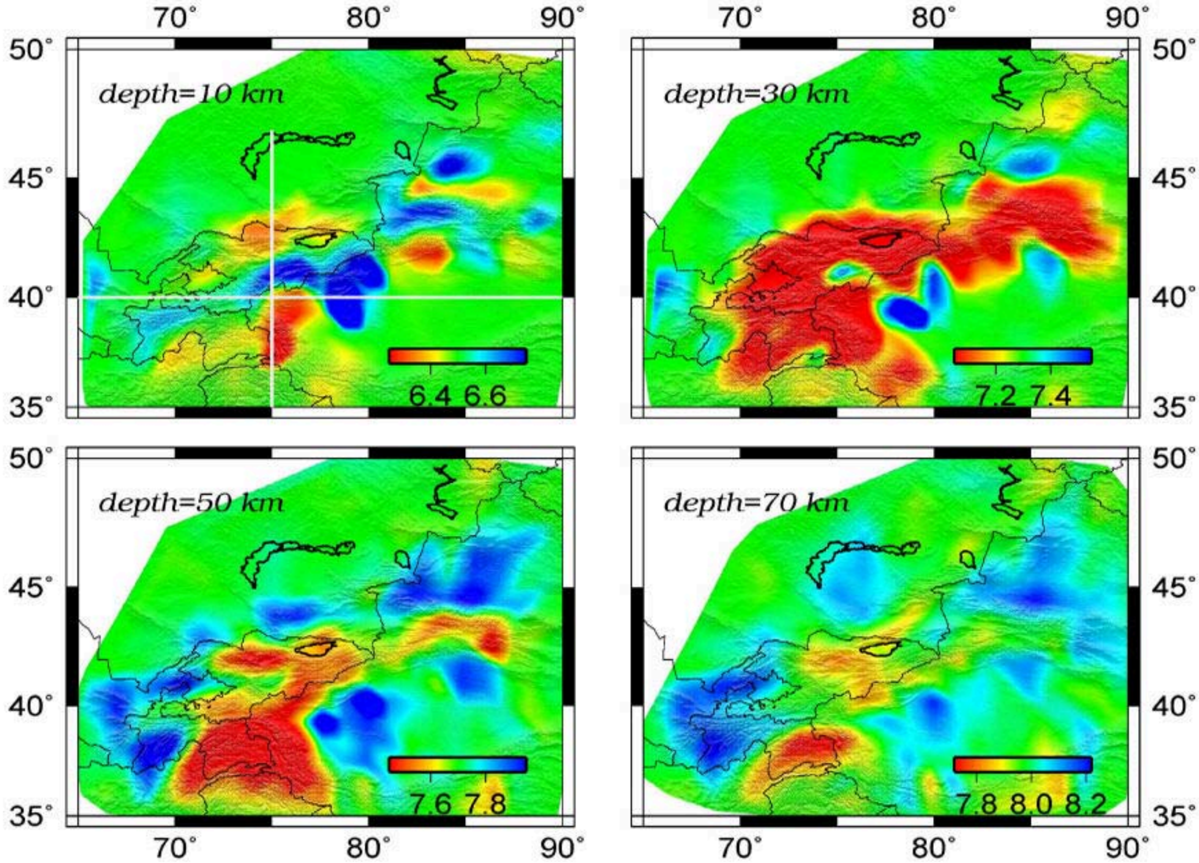

Figure 5. 3-D *P*-wave velocity structure for different depths in Central Asia. These maps were generated by assuming different *P*-wave reference velocities for each depth.

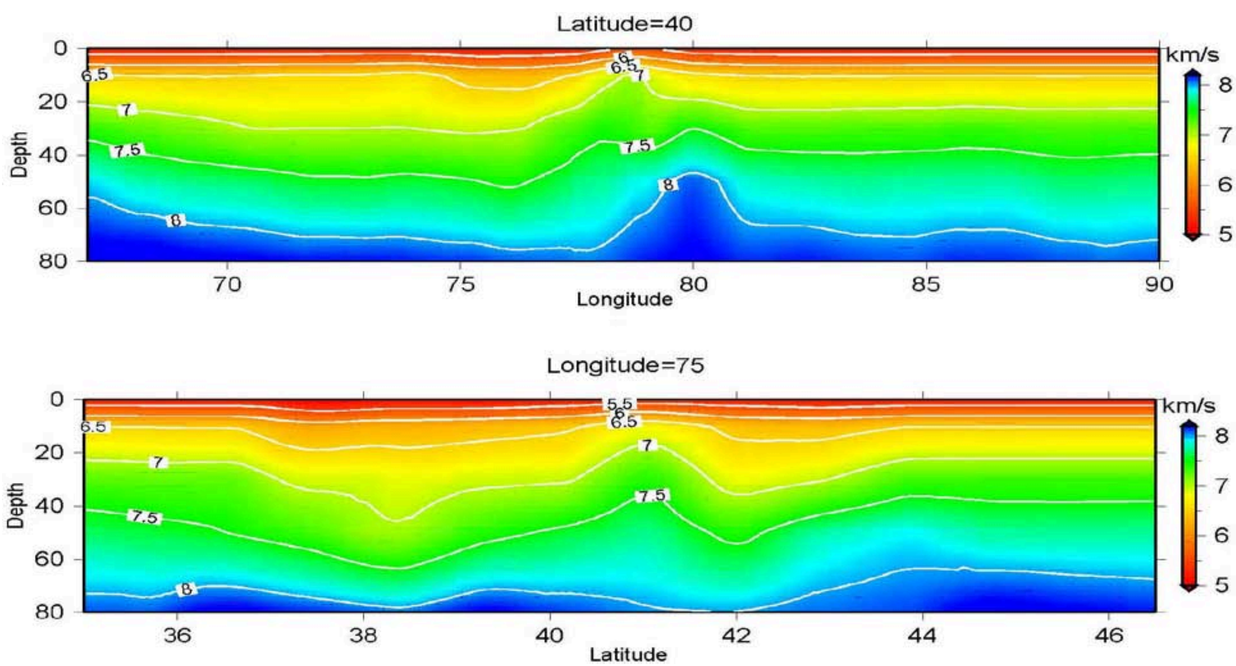

Figure 6. Vertical velocity profiles (the locations are shown in Figure 5).

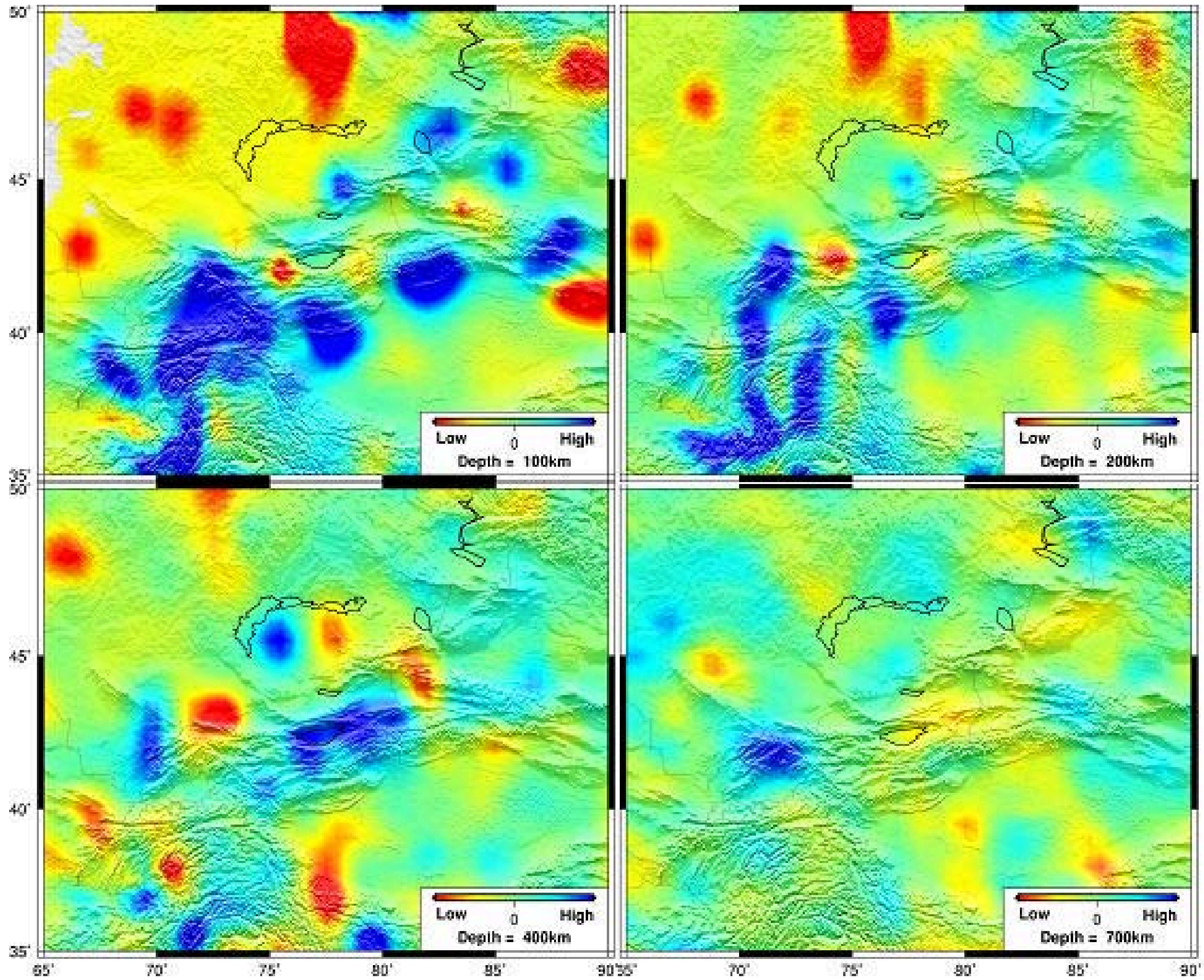

Figure 7. Upper mantle velocity structure at the depths of 100, 200, 400, and 700 km obtained by the double difference tomography method.