A REVIEW OF NEW SEISMIC CONSTRAINTS OF CRUST AND MANTLE STRUCTURE FROM CHINA AND INDIA COUPLED WITH SEISMIC Q_S AND TEMPERATURE ESTIMATES FOR THE UPPER MANTLE

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ABSTRACT

Reliable data regarding the seismic structure of China and India significantly improve the determination of seismic source parameters for the purposes of monitoring nuclear test explosions in those countries. To provide some of this information, we present seismic cross-sections for China and India and new maps of S-wave attenuation in Eurasia.

We present a new deep crustal section across northwest China and the northeastern Tibetan Plateau based on seismic refraction experiments and geologic mapping. The crustal velocity structure and Poisson's ratio (σ) for the 2,700-km-long transect, which provide a constraint on crustal composition, were determined from P- and S-wave data. The crustal thickness along the profile was determined, and the crust was found to have three layers with P-wave velocities (Vp) of 6.0-6.3 km/s, 6.3-6.6 km/s, and 6.9-7.0 km/s, respectively. We interpret the consistent three-layer stratification of the crust to indicate that the crust has undergone partial melting and differentiation after Paleozoic terrane accretion. P_n velocities are ~7.7 to 7.8 km/s.

We likewise present deep structural details of central India using reprocessed seismic data. A shallow mid-crust and a thick high-velocity lower crust are found to be characteristic features of the region. The study area exhibits high mantle heat flow and shallow lithospheric thickness compared with other cratons and mobile belts of the Indian shield. The geophysical anomalies of the region are thought to be in response to mantle plume and other tectonic activities during the Neoproterozoic-Phanerozoic period. Some of the magmatic and tectonic events of this region have been correlated to global tectonics and episodes of supercontinent formation during the Neoproterozoic.

Finally, we compare maps of the thermal structure of the continental lithosphere with the seismic attenuation of shear waves (Q_S) determined from surface wave amplitudes. The thermal structure is taken from a recent study (Artemieva and Mooney, 2001) that utilizes thermal parameters (radiogenic heat production and conductivity). Q_S values are taken from the study of Billien et al. (2001) that used the Trampert and Woodhouse (2001) data set. We find that maps of Q_S correlate more closely with lithospheric temperature than any other physical parameter, such as P- or S-wave velocities. We compare values of Q_S and temperature at depths of 50 km and 100 km in the continental lithosphere. The correlation coefficient between temperature and seismic parameters is low and ranges from 0.2 to 0.4.

KEY WORDS: crustal velocity structure, Poisson's ratio, collision, Qs, seismic attenuation, China, India

OBJECTIVE

Seismic refraction profiling is one method of collecting ground truth data that may be used to evaluate the performance of monitoring networks and data analysis systems. A vast amount of seismic refraction data has been collected in India and China, with new data being added every year. For example, a 2,700-km-long seismic refraction survey was conducted across northwest China and the Tibetan Plateau (Figure 1) by the former Ministry of Geology and Mineral Resources (MGMR). Likewise, deep seismic studies in the cratons and mobile belts of India have provided valuable information on the structure and tectonic evolution of that region. Though there have been only a limited number of seismic reflection studies in both of these regions, there so far seems to be evidence that the geodynamic processes that occur there also occur on a global scale. The goal of this project, then, is to gain a better understanding of the deep crustal structure beneath different tectonic provinces in the area, which may be used in the monitoring of nuclear explosions in these and other regions.

As part of these efforts, we also include information about seismic attenuation (Qs). Qs is another parameter which can be measured and utilized effectively when attempting to calibrate instruments to monitor nuclear explosions at large distances. The rate of degradation of seismic signal is imperative to know, if one is to accurately locate where an event has occurred.

RESEARCH ACCOMPLISHED

China

Western China is a showcase of complex geological and geophysical features, including sedimentary basins, regimes of continental collisional tectonics, and the thickest crust found on earth. To be able to accurately monitor western China for nuclear explosions, we must first understand as much as possible about the crustal structure there. In this paper, we present results of a seismic refraction profile across western China (Wang et al., 2001). Seismic energy for this profile was provided by 12 chemical explosive shots fired in boreholes. The charge size ranged from 1500 to 4000 kg, sufficient to provide clear first arrivals to a maximum distance of 300 km. The distance between shotpoints ranged from 63 to 205 km, and the interval between portable seismographs was between 2 and 4 km. The profile was recorded along existing roads, and provided nearly straight profile segments.

During the experiments, both P- and S-wave data were acquired, even for data recorded by single-component geophones. The reflection from the Moho was especially strong, and this made it possible for us to derive the crustal composition using the crustal Poisson's ratio or Vp/Vs ratio which could be obtained from the crustal P- and S-wave velocity structures.

In the correlation of phases, reduction velocities of 6.0 km/s and 3.46 km/s were used for P- and S-waves, respectively. The time scales used for S-waves were multiplied by a factor of 0.58 in the S-wave record section so they would match the P-wave arrival times. Because digital filtering introduces a slight time shift, the unfiltered P-wave data were used for phase correlation and travel-time picking. In order to improve the signal-to-noise ratio for phase correlation, the S-wave data were filtered with a band pass of 0-6 Hz.

Based on the phase correlation, the first arrivals of the P_g phase were used to invert the upper crustal velocity structure using the finite-difference tomographic method of Hole (1992). The reflection phases were used to determine the one-dimensional crustal velocity structure using the X^2-T^2 method (Giese, Prodehl and Stein, 1976) and the Reflectivity method (Fuchs and Muller, 1971). With one-dimensional crustal velocity structures from each shotpoint, a crustal P-wave velocity structure was established using a 2-D dynamic ray-tracing program to model both kinetic and dynamic features of the observed seismic wave field (Cerveny, Molotkov, and Psencik, 1977; Cerveny and Psencik, 1984). The different phases on the record sections were all appropriately fitted for travel times and amplitudes. Figures 2 and 3 show our final velocity models. We have divided the seismic profile into two segments- the northern segment from the Altai Mountains to the Altyn Tagh fault (Figure 2), and the southern segment from the Altyn Tagh fault to the Longmen Shan (Figure 3). It is clear that the transect shows three-layer stratification with P-wave velocities of 6.0-6.3 km/s, 6.3-6.6 km/s, and 6.9-7.0 km/s. Upper mantle (Pn) velocities of 7.7-7.8 km/s were found.

The accuracy of the final model is dependent on a number of factors, including the shotpoint interval, receiver density, and thickness of sediments in the shallow crust. Model accuracy primarily depends on the correct identification of the various phases and the density of rays penetrating a particular volume of the model, however. Perturbation of the models has shown that, depending on the uniformity of structure and the density of rays, the resolution of velocity and depth to interface may be accepted as better than 2% and 5%, respectively. By the relationship between the Poisson's ratio and the Vp/Vs ratio, the Poisson's ratio is determined to within an uncertainty of less than 2%.

India

Like China, the Indian subcontinent has a complex geological and geophysical history that must be better understood for the purposes of accurately monitoring nuclear explosions. To accomplish this, we have recently obtained P-wave data from the Indian subcontinent. Twenty DSS profiles have been conducted since 1972 totaling more than 6000 km. Long-range refraction and wide-angle reflection techniques with a dense detector spacing of 80-200 m and a shot point interval of 10-40 km were used to acquire these data. Measurements of crustal thickness fall into the range of 35-40 km (Figure 4), with the biggest exception being the Himalayas, which are known to have thicknesses of up to 80 km (Mahadevan, 1994). We show three velocity models that were developed as a result of these experiments in Figures 4a-c. The Moho depth is seen to be around 38 km, and we note several deep lenses of 7.3 km/s velocity across the subcontinent. Also, the transition depth from the lithospheric to the asthenospheric mantle fluctuates by about 50 km across the profile.

The velocity model of Kaila et al. (1990) for the SW Marwar Terrain (Figure 4c) shows a shallow midcrust with 6.6 km/s velocity and a lower crustal velocity of 7.3 km/s. The high-velocity lower crustal layer in this region is believed to be due to the underplating of the crust by mantle upwelling, crustal extension and continental rifting related to the Reunion hotspot. A thick, high-velocity lower crustal layer (7.0-7.5 km/s) is often observed between the lower crust and upper mantle in areas of continental rifts, where extension has been the last deformation process to occur (Mooney et al., 1983; Catchings and Mooney, 1988).

This extensional process is attributed to igneous accretion of the upper mantle material at the base of the crust (White and McKenzie, 1989; Furlong and Fountain, 1986) and is observed at several rift zones of the world. In this case, this plume activity coincides with the breaking up of the Rodinian supercontinent, of which the Indian continent was a part, during the Mid-Neoproterozoic (750 Ma). During periods of supercontinent break-up, rifting generally takes place at old suture zones, as these are relatively weak and therefore prone to rifting (Vink et al., 1984). The location of the rifting event (750 Ma) in the Marwar Terrain is in close proximity to the earlier Delhi Suture (1100 Ma), and strikes in the same direction (NE-SW) as the earlier Aravalli Delhi Fold Belts. It seems then that there is much to support the idea that the Indian shield has evolved through processes that are known to be active on a global scale.

S-Wave Seismic Attenutation (Qs) and Temperatures (T) in the Mantle

Attenuation is important for monitoring nuclear explosions because researchers need the ability to model how seismic waves travel through the crust in order to accurately locate events. Attenuation is determined by modeling the temperatures in the lithosphere. The thermal structure of the continental lithosphere has previously been estimated from heat flow data by numerous authors (e.g. Pollack and Chapman, 1977; Sclater et al., 1980), and borehole measurements have been used to constrain these data. Models of heat production and thermal conductivity are discussed in Artemieva and Mooney (2001), and it was found that the results are reliable for stable continental regions where the assumption of a steady-state thermal regime is valid. The Tibetan plateau, however, is less well constrained, and results there are based on petrologic and non-steady-state constraints.

In order to quantify the effects of seismic attenuation on the crust, we performed a two-step inversion. First, from phase and amplitude measurements, we estimated phase velocity and Qs for several periods. Then, we performed a depth-inversion to obtain a 3-D model of the shear wave attenuation factor. We took into account the focusing effects of wave amplitude, but did not specifically model variations due to scattering effects.

At 50-km depth, the crustal influence is too large for us to accurately model the shear-wave velocity of the lithosphere, shear-wave quality factor and temperature. At 100-km depth (Figure 5), however, the resolution of velocity and Q are at a maximum. In northern Eurasia, the velocity anomaly maps show positive values to depths where temperature is 130 degrees, where the Q map shows an alteration from high to low Q. In contrast, the southern Eurasian suture zone is evident only in the map of temperature. Resolution is lower at 150-km depth (Figure 6), with temperatures in non-cratonic regions reaching 1300 degrees. Northern Eurasia is clearly seen on these maps to oscillate laterally (west to east) in both shear velocities and temperatures. Eastern Eurasia, by contrast, shows low velocity, low Qs, and high temperature.

CONCLUSIONS AND RECOMMENDATIONS

Crustal and Upper Mantle Structure of China and India

Our work to date has formed a firm basis for understanding the crust and upper mantle structure of China and India. However, gaps in our knowledge remain, and any new information regarding the seismic structure of China or India would significantly improve the determination of seismic source parameters for the purposes of monitoring nuclear explosions. As much of the data for both nations is now being made available to Western researchers, we should take advantage of this opportunity and analyze this wealth of new data for greater insight and understanding into the crustal structure of Asia. It is thus imperative that institutes in China, India and the United States be allowed to continue their cooperative exchange programs. Such a reasonable exchange of data will foster new research and collaborative efforts that may lead to long-term, stable relationships among our nations.

S-Wave Seismic Attenutation (Qs) and Temperatures (T) in the Mantle

There exists a good correlation between seismic attenuation and temperature. This is likely due to the fact that anelasticity is primarily due to thermal effects. In addition, high Q was found to correlate with cratonic regions. It is notable that the relation between temperature and seismic properties is not linear, and these are likely not the only variables we need to study in order to more fully understand how attenuation varies throughout the crust. Once we have improved our modeling of seismic Q, efforts to locate seismic events at large distances should vastly improve. When we know how seismic waves propagate through the crust, we can then pinpoint with more accuracy where those waves originated.

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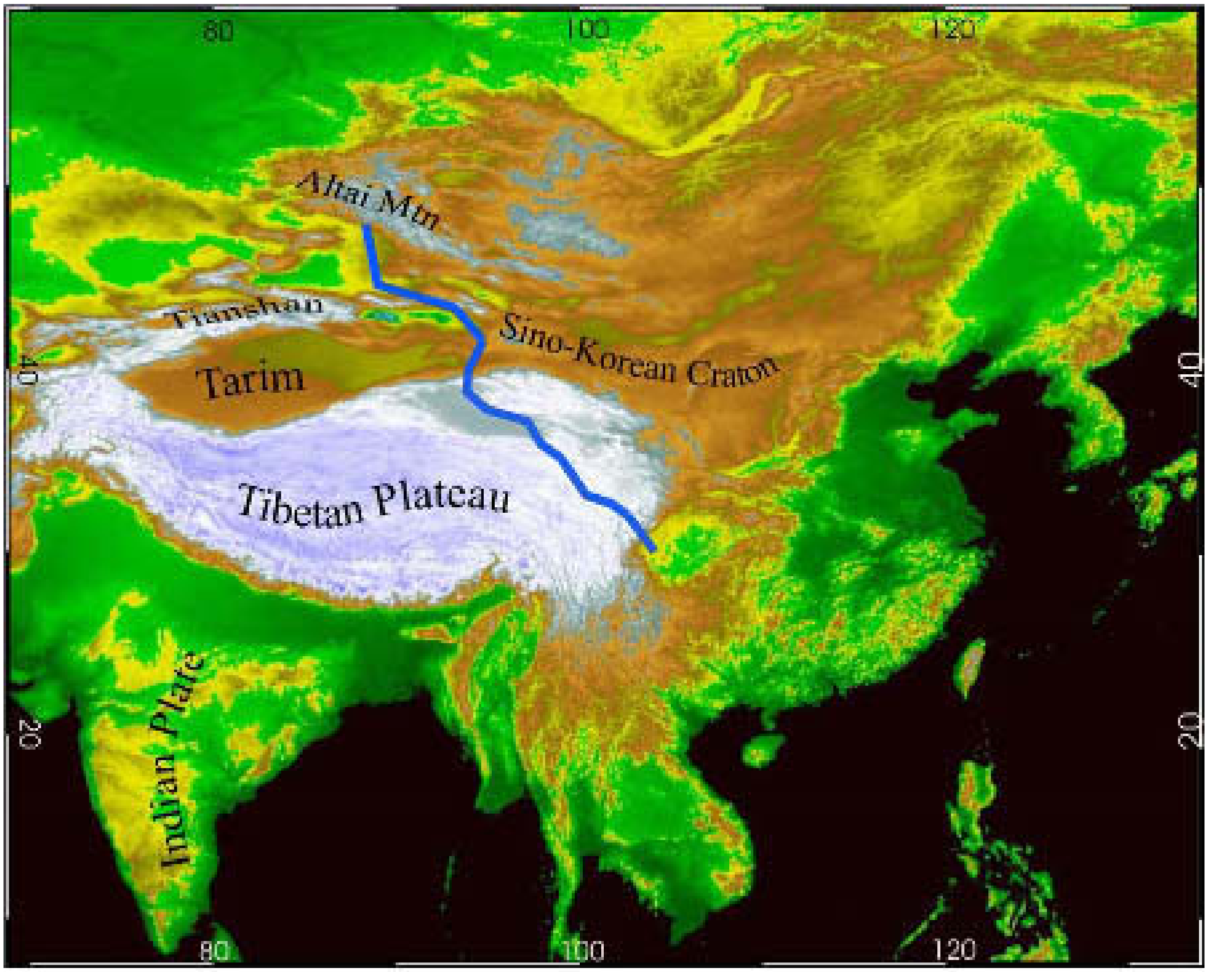


Figure 1. Topographic relief map of southeast Asia with seismic transect indicated by a heavy, dark line. The entire transect is composed of linear segments, and runs from the Altai mountains in the north to the Longmen mountains in the south, crossing the Tibetan plateau.

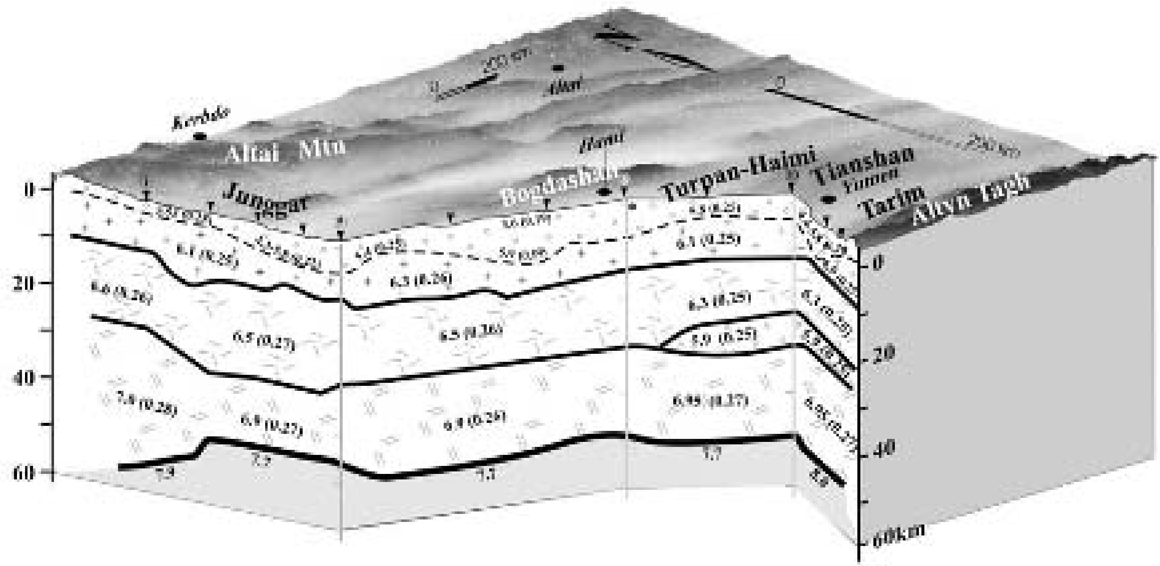


Figure 2. Crustal structure along the seismic transect from the Altai mountains to the Altyn Tagh fault. Dashed lines indicate the top of the crystalline basement. Three distinct layers are present along this transect which we identify as the upper, middle, and lower crust. Velocity values are given, as is Poisson's ratio (in parenthesis). The Moho is shown as a heavy, dark line.

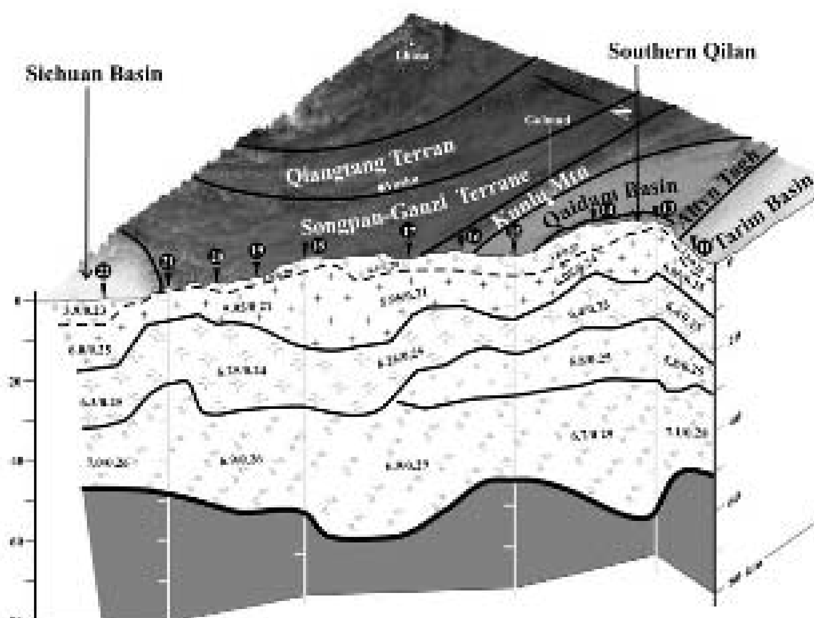
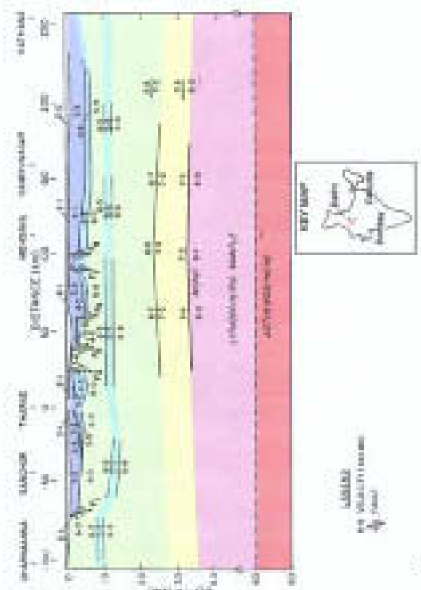
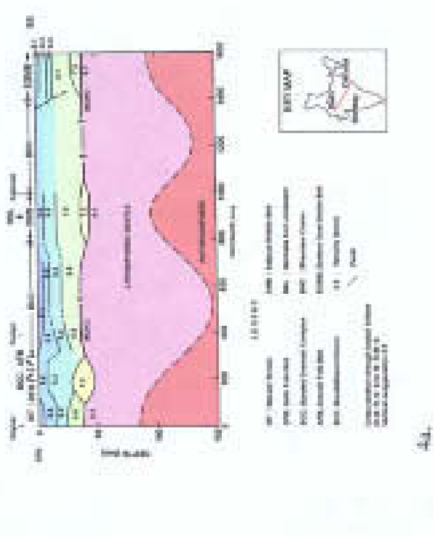


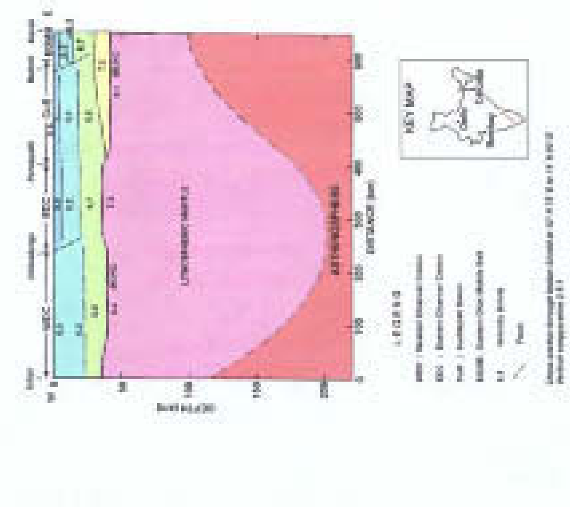
Figure 3. Crustal structure along the seismic transect from the Altyn Tagh fault to the Longmen mountains. Dashed lines indicate the top of the crystalline basement. Three distinct layers are present along this transect which we identify as the upper, middle, and lower crust. Velocity values are given, as is Poisson's ratio (in parenthesis). The Moho is shown as a heavy, dark line.



4c.



4a.



4b.

Figures 4a-c. Seismic velocity-depth models of various regions of the Indian sub-continent. Locations are shown in red in the inset maps.

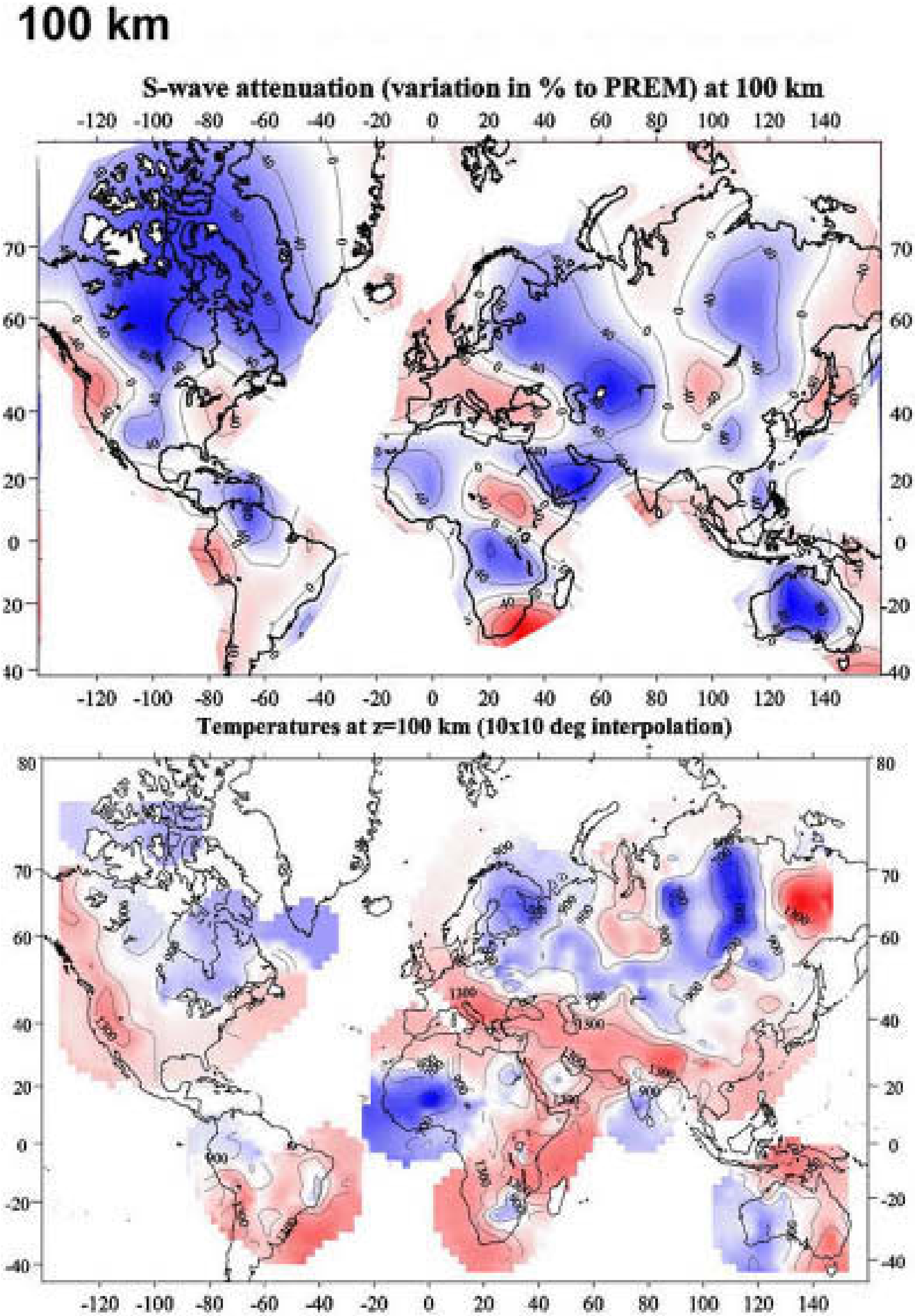


Figure 5. Seismic attenuation as a percentage of PREM at 100 km. Bottom figure shows temperatures at 100 km depth.

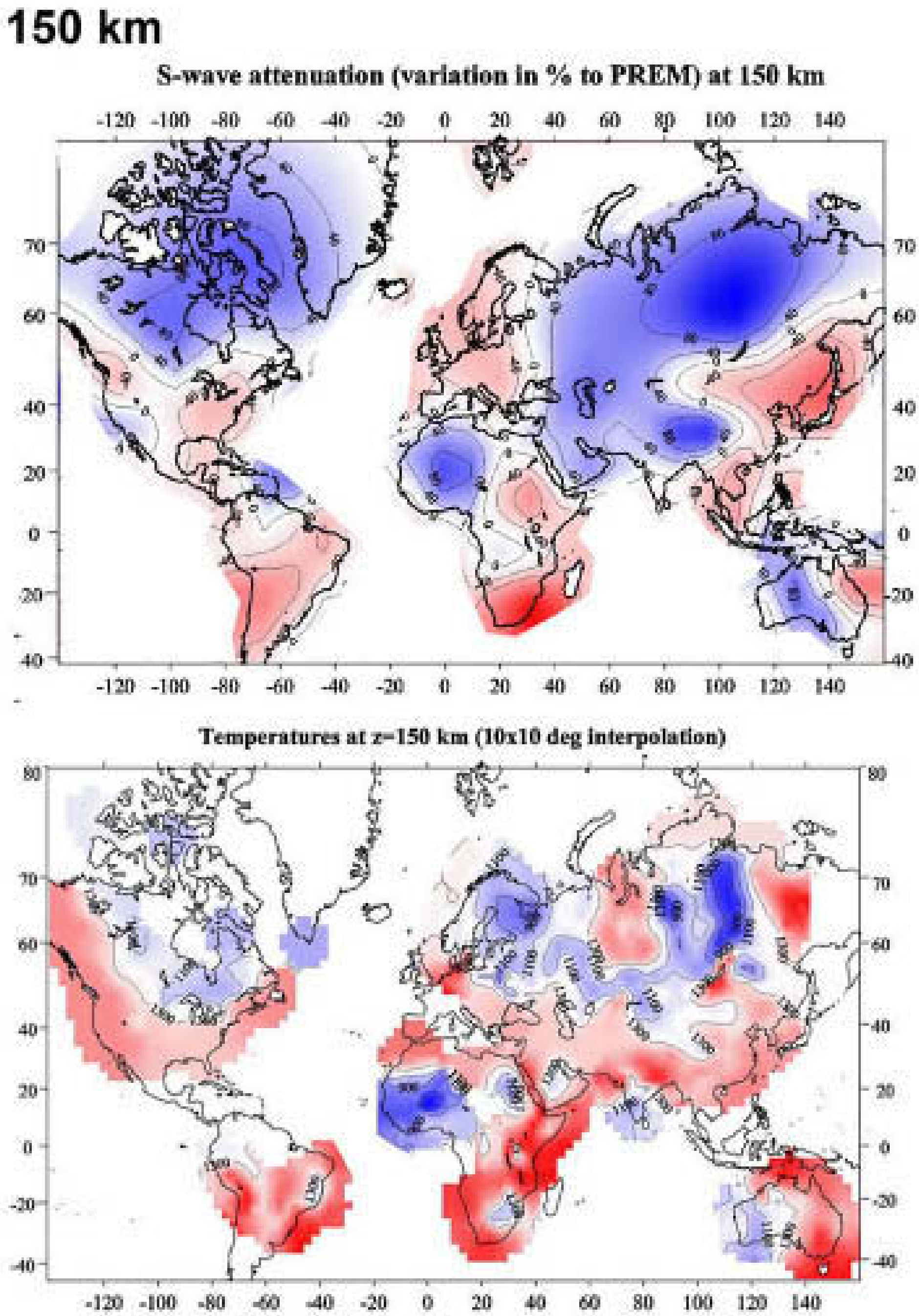


Figure 6. Seismic attenuation as a percentage of PREM at 150 km. Bottom figure shows temperatures at 150 km depth.