LATERAL VARIATIONS OF LG Q IN THE TIBETAN PLATEAU

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ABSTRACT

In the past year we have been processing a large amount of regional wave data from various broad-band seismic stations in eastern Eurasia. Fourier spectra of the Lg waves are computed for many events and paths to study path attenuations. Among the Lg spectra that are obtained are those from (a) the 1991-1992 PASSCAL Tibetan Plateau, the INDEPTH II and III experiments, (b) some new Chinese digital seismic stations (with spectra processed in China), and (c) the broad-band Incorporated Research Institutions for Seismology (IRIS) and regional network stations archived at the IRIS Data Management Center (DMC). We estimate values of Q_0 and _ (Lg Q at 1 Hz and its power-law frequency dependence, respectively) in the Tibetan Plateau and its surrounding regions using various methods. Using a standard two-station method, we consistently find low inter-station Lg Q_0 values (typically < 200) in various parts of the Plateau. We also find that Q_0 values vary laterally by at least a factor of two inside the plateau. A least-squares inversion method was adapted to map lateral variations in Lg Q_0 along the INDEPTH profiles. The average value of Q_0 is about 126 over the southeastern part of the plateau, and drops to below 100 in the central part where the INDEPTH III experiment was conducted. In the southern part of the plateau, Q_0 becomes even lower (60-90) in the vicinity of the Yalong-Tsangbu Suture behind the crest of the High Himalayas. This kind of low (two-digit) Lg Q_0 is extremely rare in continental areas; it causes the Lg to be blocked within a propagation distance of about 100 km. The area where the lowest Lg Q_0 is found coincides with the prominent mid-crust reflectors found during the active-source element of the INDEPTH II experiment. Those reflectors were interpreted as being the top of a molten layer. Thus the well-kown phenomenon of Lg blockage across the southern boundary of the plateau is likely caused by a mid-crustal melting, rather than strong scatterings caused by a three-dimensional (3D) Moho topography underneath the high Himalayas. The generally low Lg Q_0 values found in the entire plateau are consistent with high temperature and/or fluid content in the Tibetan crust.

Work is underway to further improve the path coverage in and around the Tibetan Plateau, so that a tomographic mapping of Lg Q may be conducted. An effort is also being made to resolve depth variations in the crustal Q using available surface wave data.

OBJECTIVE

Introduction

The primary objective of this research is to quantify propagation and attenuation of high frequency waves in and around the Tibetan plateau. We wish to measure the laterally-variable Lg and Pn Q, and the travel times of Pn and mantle P waves from ground-truth events to southern and eastern Tibet. Additionally, we wish to invert fundamental-mode surface waves to obtain depth-variations of crustal Q in localized regions inside the plateau, such as the regions behind the high Himalayas where Lg blockage appears to take place.

This research provides an important input to the world-wide monitoring of nuclear explosions. The Q and travel times can be used for the calculation of source spectral characteristics, and location of any future seismic event to infer its nature and size. The depth-varying Q will also enable us to search for a physical mechanism, such as a molten mid-crust, for the well-known phenomenon of Lg blockage observed in several continental areas. Examples of areas of Lg blockage related to low Q include those in the Tibetan plateau just behind the crest of the high Himalayas, and regions with extensive rifting such as eastern Africa.

RESEARCH ACCOMPLISHED

Lateral variations of Lg Q

Xie (2002) calculated the average Lg Q for northeastern Tibet using data from the 1991-1992 PASSCAL Tibetan plateau experiment. He obtained the following result:

$$Q_{Lg}(f) = Q_0 f^{-} = (126 \pm 9) f^{(0.37 \pm 0.02)}$$

between frequencies of 0.2 and 3.6 Hz. The 1 Hz Lg Q (Q_0)of 126 is about the lowest ever reported for any continental regions that are of comparable size to northeastern Tibet (Figure 1 of Xie, 2002). The low Q_0 is also consistent with a higher-than normal temperature or fluid content in the crust under northeastern Tibet.

More recently we have estimated Lg Q_0 in central and southern Tibet, using data from the 1994 INDEPTH II and 1998-1999 INDEPTH III experiments (Figures 1 through 3; see also Nelson *et al*., 1996). Here we report the preliminary results of these estimates. They are subject to refinement and the readers are referred to Gok *et al.* (2002) for the final results. In the INDEPTH II and III experiments, multiple stations are deployed approximately along great-circle profiles. These profiles both recorded Lg from regional moderate events that are off, but aligned with, the profiles. These Lg recordings allow us to measure inter-station Lg Q_0 values between various pairs of the two stations using the standard two-station method (Xie and Michell, 1990b, Xie, 2002). We then input these two-station Q_0 values into a least-squares inverse method to map the lateral variations of Lg Q_0 along the profiles. This inverse method is adapted from the 2D inversion method used by Xie and Mitchell (1990b) and Zhao and Xie (1993), and is described in more detail by Gok *et al.* (2002).

Figure 2 shows the INDEPTH III stations in central Tibet and the great-circle profile (A-A') that goes through them. Two regional events are recorded along the profile and provide Lg spectra for the Q inversion. The bottom of Figure 2 shows the result of the inversion, including the laterally varying Lg Q_0 values along profile A-A', and the estimated error and resolution. The Q_0 values vary between about 80 and 100 along the profile. The errors are below 10 in the central portion of the profile, and increase to about 20 near the two ends. The resolution varies between about 20 km near the ends and over 100 km in the middle. No significant lateral variations in Q_0 are found along this profile when the amount of error is taken into account. In fact one can draw a flat line at a Q_0 of about 90 in Figure 2 that, within the errors, fits all the Q_0 values. The average values of Q_0 of about 90 are lower than the average value for the northeastern Tibet (Xie, 2002), indicating a decrease of Q_0 from northeastern to central Tibet.

Figure 3 shows the INDEPTH II stations in southern Tibet and the great-circle profile (A-A') that goes through these stations. Lg spectra from one regional event (M_b=5.5) is recorded along the profile (Figures 1 and 3). There is a severe Lg attenuation from the northern end into the middle of the profile, visible in the raw seismograms and Lg spectra (bottom of Figure 3). The attenuation is so high that near the southern end of the profile the Lg is almost eliminated (blocked) at stations near point A. We measured inter-station Lg Q_0 values among several two-station pairs. The lowest Q_0 of 65 is found between stations BB05 and BB14. We input these Q_0 values into the least-squares inversion algorithm. The resulting laterally varying Lg Q_0 values, together with the estimated errors and resolution, are shown in Figure 4. The lateral resolution along the INDEPTH II profile varies between about 100 and 200 km, and is generally poorer than that along the INDEPTH III profile. Even with this limited resolution the resulting Lg Q_0 shows a considerable lateral variation along the INDEPTH II profile. Q_0 is about 60 near the northern end (point A'), and increases to above 100 near the southern end (point A). Even when the large error near the southern end (point A) is taken into account, it is certain that Q_0 increases to at least 90 south of the Indus-Yalong Suture (IYS; also known as the Yalong-Tsangbu suture). The segment of low Lg Q_0 of about 60 south of the IYS coincides with the prominent mid-crust reflectors found during the active source element of the INDEPTH II experiment (Nelson *et al.*, 1996; also see the bottom of Figure 4). Nelson *et al.* have previously interpreted these reflectors as being the top of a molten layer. It appears that that molten layer (or layer of terrestrial fluid as an alternative) is the cause of the low Lg Q_0 that is responsible for the virtual Lg blockage across the INDEPTH II profile (Figure 3). Therefore we have pinpointed a zone of low Lg Q behind the crest of the high-Himalayas, which might have been responsible for Lg blockage observed earlier (Ruzaikin *et al.*, 1977; Ni and Barazangi, 1983).

Depth-varying shear wave Q from fundamental mode surface waves

To explore the depth range in which low shear wave Q owing to the melting or terrestrial fluid occurs, we have started to invert for depth-varying Q using fundamental-mode surface waves. Applying a two-station method to shorter period (5-20 s) Rayleigh waves from a regional event recorded by the INDEPTH II stations, we detected a layer of extremely low shear wave Q of about 10. The top of the layer is at 10 to 15 km in depth and coincides with the mid-crust reflector. At greater depths the shorter-period Rayleigh waves lose resolution. A work is going on to use teleseismic Rayleigh waves at periods longer than 20 s to resolve Q at depths greater than about 15-20 km, so that the thickness of the low Q layer can be constrained.

Pn travel times and Q from the 1994 explosions to southern Tibet

The June 10 and Oct. 7, 1994 nuclear explosions north of Tibet are recorded by the INDEPTH II stations. Fisk *et al.* (2002) and Waldhauser (2001) provided high-quality relocations of the explosions. Since Fisk *et al.* jointly used satellite image and seismic signals, their absolute locations should subject to smaller (sub-kilometer) errors. We read the Pn arrivals at the INDEPTH II stations, and calculated the respective Pn travel times from the Fisk et al. locations to these stations, as well as to the Kyrghistan network (KNET) stations (Figure 4). The travel times to the INDEPTH II stations are used to fit an average apparent Pn velocity of 8.42 (± 0.1) km/s.

Previously there has been a disagreement on whether P velocity in the uppermost 150 km of the Tibetan mantle has a gradient (Zhao and Xie, 1993, here after referred to as XZ93; McNamara *et al.*, 1997). Here we examine whether the apparent velocity of 8.42 km/s is compatible with the model of ZX93, in which the uppermost mantle has an average gradient of $3.1 \times 10^{-3}\ s^{-1}$. First we calculate the P wave velocity near the Pn ray turning point using our measured apparent velocity of 8.42 km/s. Since the average distance from the explosions to the to INDEPTH II stations is about 1368 km (Figure 1), the Pn rays should bottom at the maximum depths of about 100-150 km below Moho. Considering the Earth's sphericity, the apparent Pn velocity of 8.42 km/s corresponds to P velocities of 8.14 to 8.20 km/s at the ray turning point if that point is located at a depth of 100 to 150 km below Moho. Geographically, the Pn ray turning points (the mid-points between the explosions and the INDEPTH II stations; Figure 1) are located under central Tibet.

Now we estimate the P velocity at the location based on the model of ZX93, who found a low sub-Moho velocity of 7.78 km in central Tibet. Using this value and the average gradient of $3.1 \times 10^{-3}\ s^{-1}$, the P velocity at 100 to 150 km below Moho in central Tibet is predicted to be 8.09 km/s at 100 km below Moho, and 8.25 km/s at 150 km below Moho. These predictions based on the ZX93 model are very compatible to the estimates of 8.14 to 8.20 km/s made in this study. If the Tibetan mantle has no gradient (McNamara *et al.*, 1997), our measured apparent Pn velocity would have a very different physical meaning, which will be discussed elsewhere.

Amplitude spectra are calculated using Pn from the two Lop Nor explosions at the INDEPTH II stations. These are shown in Figure 5, together with the previously calculated Pn spectra at the KNET stations by Xie and Patton (1999). The average distance of 1368 km to the INDEPTH II stations is similar to the average distance of 1194 km to the KNET stations. Xie and Patton (1999) estimated the Pn seismic moment of the two explosions using the KNET data. Using these estimates and the geometrical spreading of the form of equation (3) of Xie and Patton (1999), we estimate average Pn Q from Lop Nor to the southern Tibetan (INDEPTH II) stations to be

$$Q_{Pn}(f) = (284 \pm 60)f^{(-0.1\pm0.2)}$$

The low _ value of -0.1±0.2 means Pn Q does not grow with frequency. This is contrary to most observations made in other regions and suggests very low Pn Q at higher frequencies (> 1 Hz). The low high-frequency Pn Q is responsible for the rapid decay of Pn spectra at INDEPTH II stations above 1 Hz (Figure 5; note the difference in decay rates of the INDEPTH II and KNET spectra). We note that the Pn Q is estimated with the specific geometrical spreading term, which may not be accurate (Sereno and Given, 1990, Zhu et al, 1991; Xie and Patton, 1999). Nevertheless, the low average _ value to the INDEPTH II stations, when compared to the value of 0.5 to the KNET stations to the west of the explosions, indicate that Pn attenuation at higher-frequencies (above 1 Hz) in the Tibetan mantle is significantly higher than the mantle under the Tarim basin and Tianshan.

CONCLUSIONS AND RECOMMENDATIONS

Lg Q_0 values are measured using high-quality data from three PASSCAL experiments in Tibet, with a two-station method that is a simple, yet the most reliable method. A least-squares inverse method is adapted to map lateral variations of Lg Q_0 along the INDEPTH II and III profiles. The resulting Lg Q_0 values are generally low in the entire Tibetan Plateau, indicating higher-than normal temperature and/or fluid content in the Tibetan crust. The real average of Lg Q_0 is about 126 in northeastern Tibet. Q_0 values drop to below 100 in central Tibet with no resolvable variations across the Bangong-Nujiang Suture. In southern Tibet, Q_0 values decrease further. In a localized zone south of the Indus Yalong Suture and/or Kangmar Dome, Q_0 reaches the lowest value of about 60. This low Q_0 visibly causes a virtual blockage of Lg over a segment of about 100 km-long along the INDEPTH II profile. Further south into the High-Himalayas, Q_0 appears to increase to reach the level of 100 or higher. Therefore we have pinpointed a Lg blockage zone which coincides with the previously mapped prominent mid-crustal reflectors marking the top of a fluid layer. Shear wave Q in this layer as determined by inverting regional Rayleigh waves is as low as 10. It seems that a mid-crust layer of fluid with low shear wave, rather than strong scattering along the high-Himalayas, is responsible for the Lg blockage near the southern boundary of the Tibetan plateau.

Pn travels times are measured over paths that traverse the entire plateau in an N-S direction from two LTS explosions to the INDEPTH II stations. An apparent Pn velocity of 8.42 (± 0.1) km is obtained. Taking into account the mantle velocity gradient and Earth's sphericity, this value is highly consistent with the P velocity model by Zhao and Xie (1993). Pn Q in the uppermost mantle is lower under Tibet than under the Tarim Basin and Tianshan, particularly at higher frequencies (> 1 Hz).

Data from more events and stations in and around Tibet is currently increasing from more temporary and permanent stations. Future research should be directed to analyzing more seismic data in the plateau with reliable methods, to resolve details of the lateral variations of $Q_{Lg}(f)$, $Q_{Pn}(f)$, shear wave Q and seismic velocities under the plateau.

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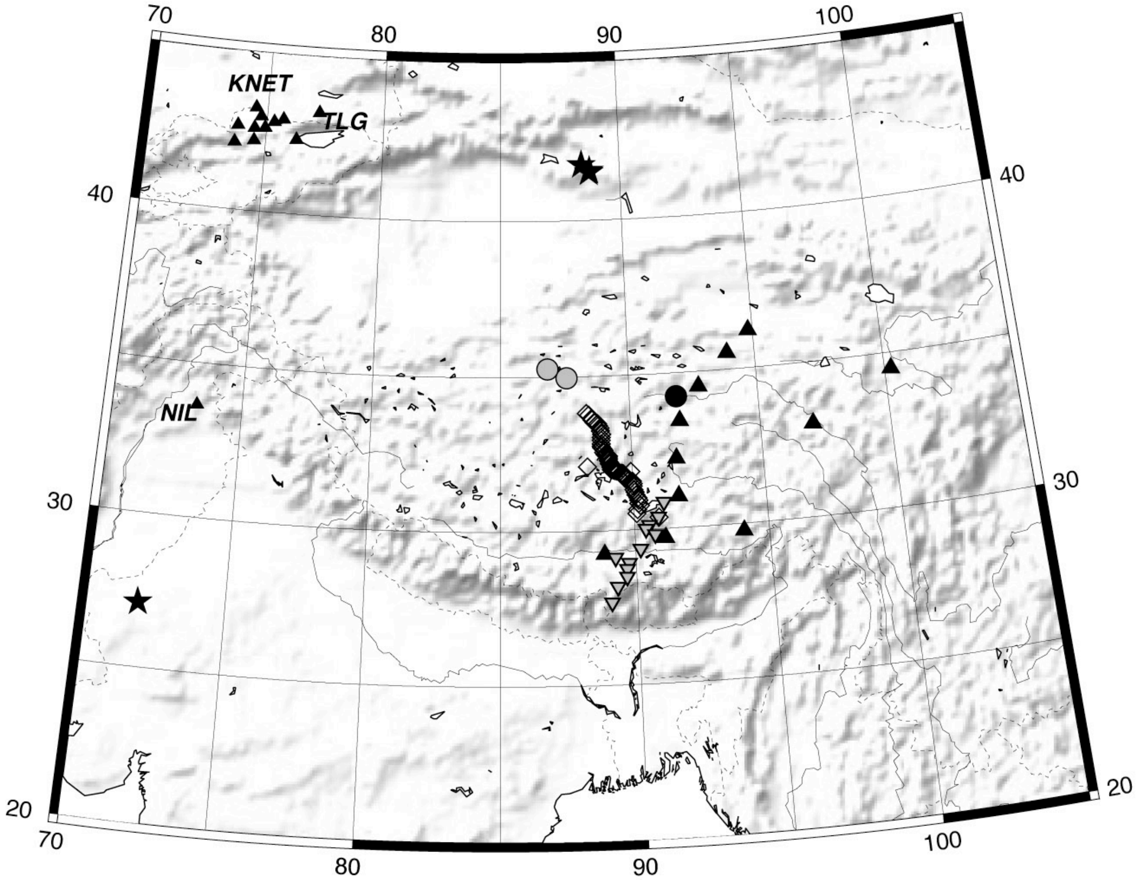

Figure 1. Map showing seismic stations and sources used in this study. Solid triangles are stations deployed during the 1991-1992 Tibetan Plateau experiment. Diamonds and inverted triangles are the INDEPTH II and III PASSCAL experiment stations. Stars are explosions. Gray and filled circles are earthquakes recorded by the INDEPTH III and II stations (Figures 2 and 3), respectively. TLG and KNET are permanent stations in Kyrghistan or Kazakhstan.

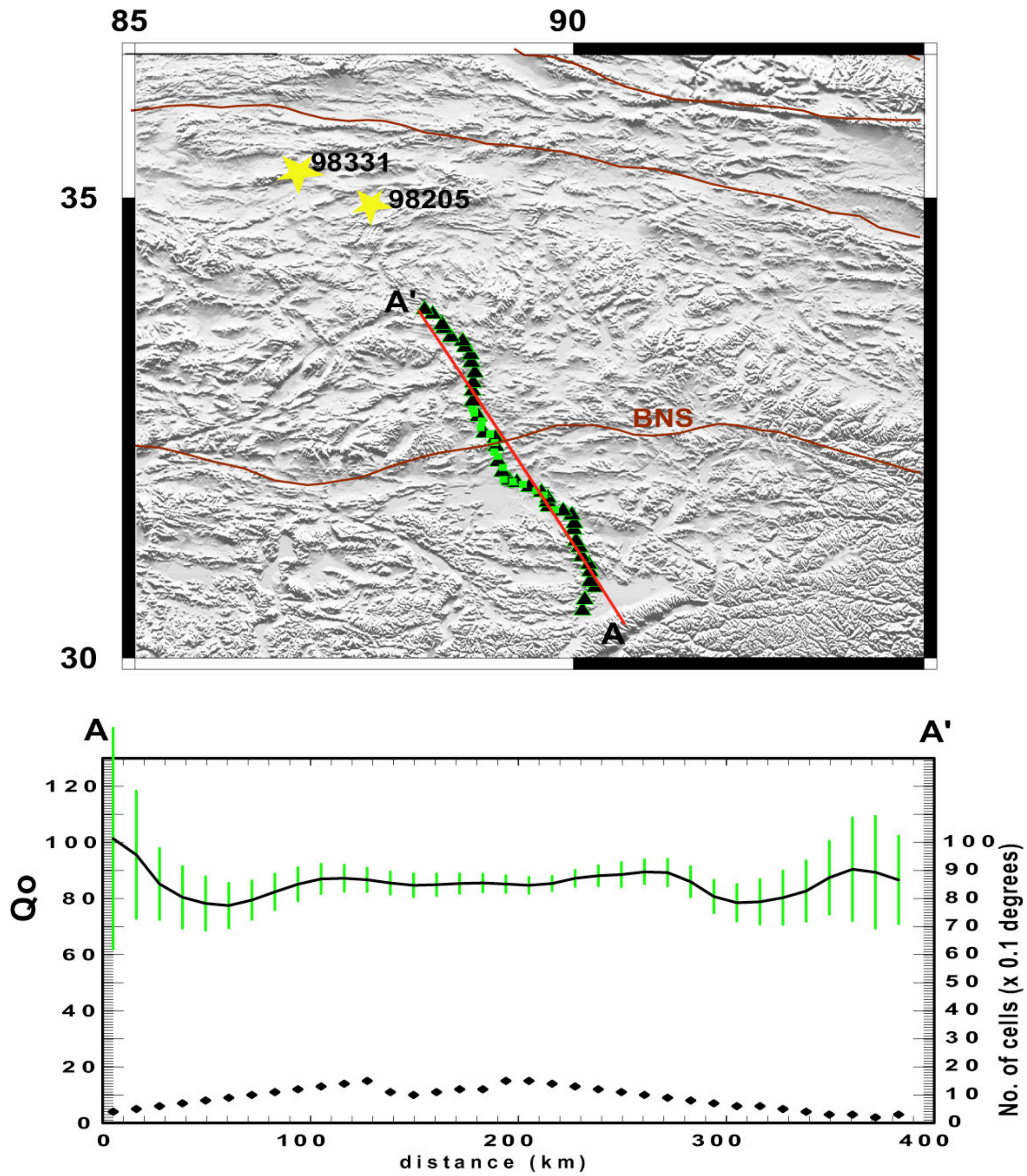

Figure 2. Top: Map showing locations of two regional events and profile A-A' through the INDEPTH III stations. "BNS" stands for Bangong-Nujiang Suture. Bottom: Variations of Lg Q_0 along profile A-A' from least square inversion, error bars and resolution (plotted as dots in the unit of 0.1 degrees).

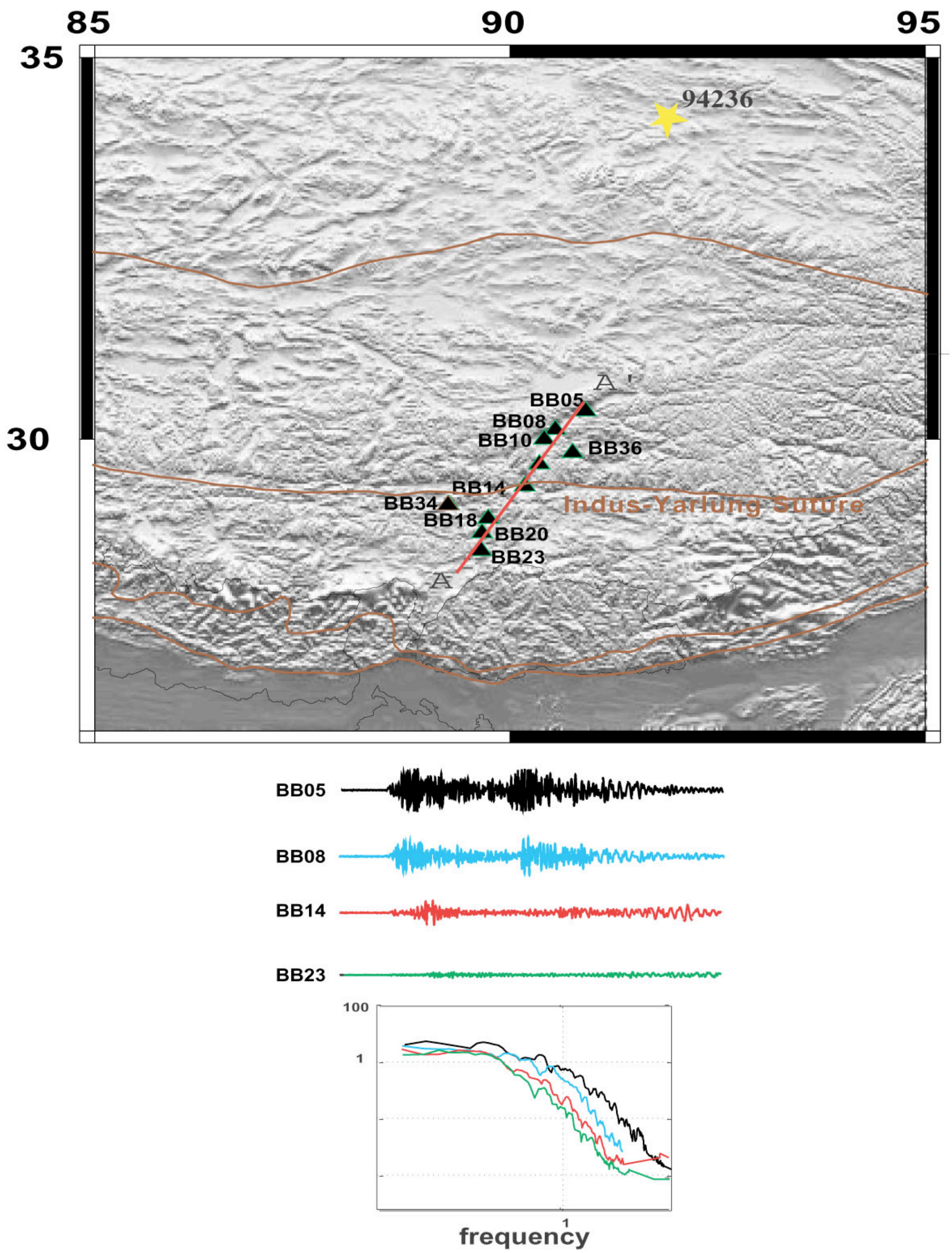

Figure 3. Top: Map showing locations of event 84236 and profile A-A' through the INDEPTH II stations. Bottom: Waveforms and Lg spectra from four stations along profile A-A'. Note the loss of energy over short distances.

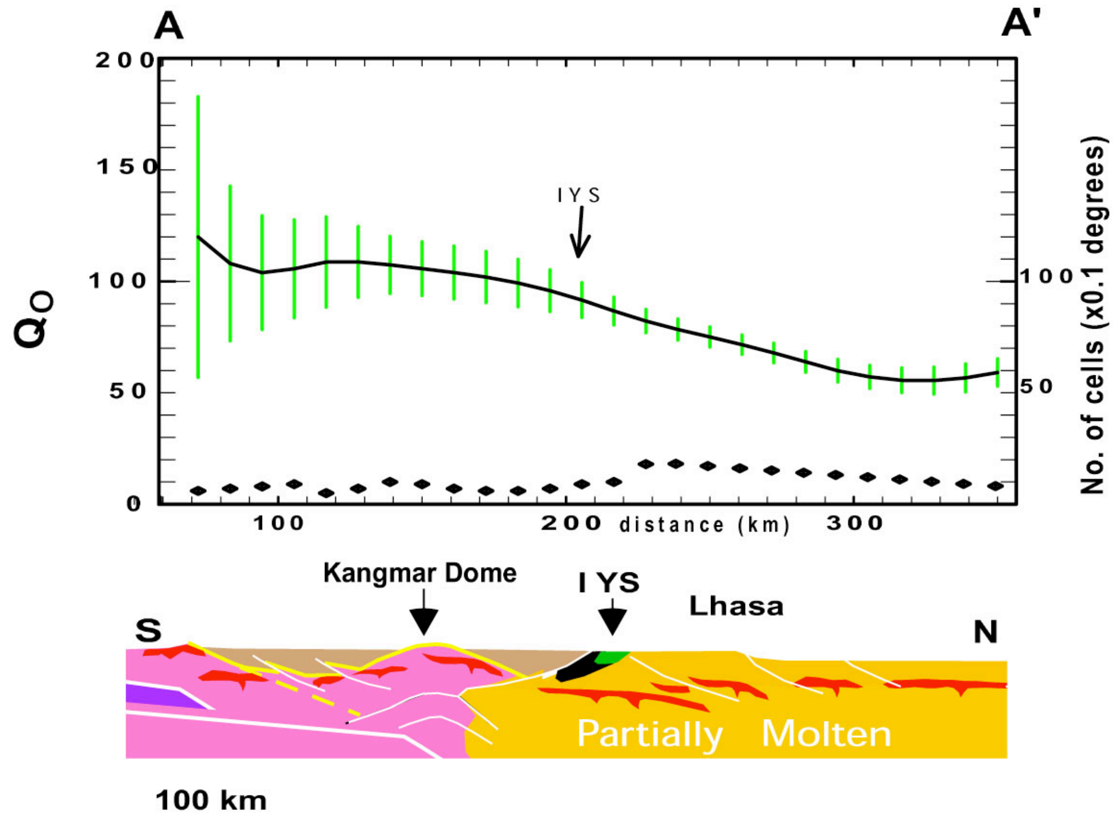

Figure 4. Top: Variations of Lg Q_0 along profile A-A' from least-squares inversion, error bars and resolution (plotted as dots in the unit of 0.1 degrees). Bottom: Cartoon showing along-profile geological structure and mid-crustal bright reflectors (Nelson *et al.* 1996). "IYS" stands for the Indus Yalong Suture.

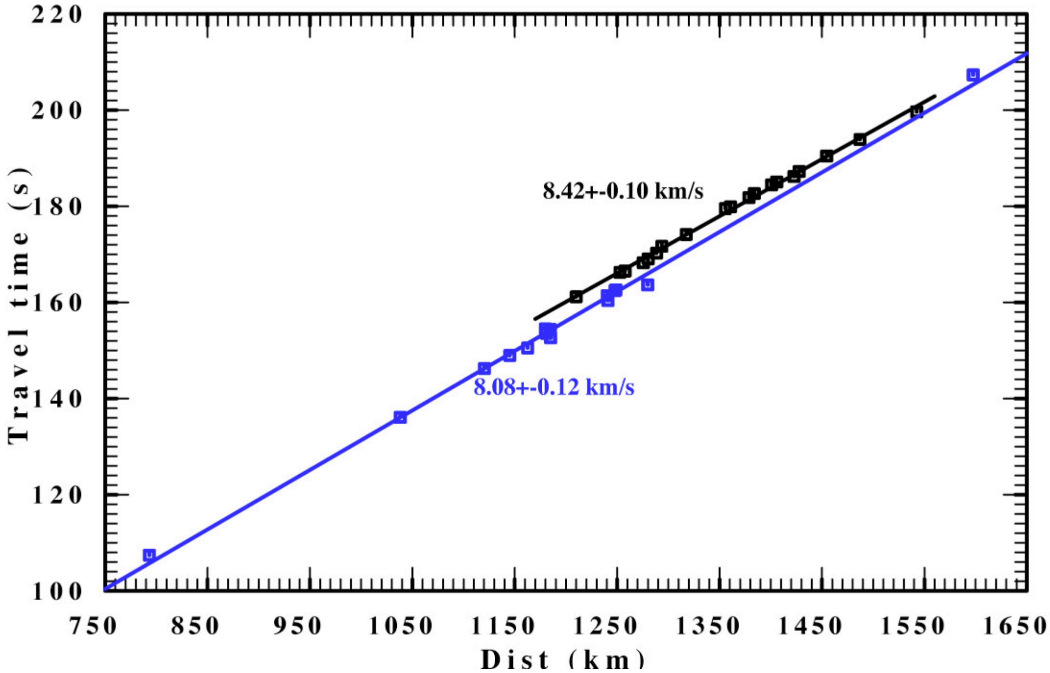

Figure 5. Pn travel time from the two Lop Nor explosions to Kyrghistan, Kazakhstan stations (lower points and line-fit) and INDEPTH II stations (upper points and line-fit). GT0 locations from Fisk *et al.* (2002) were used. Pn apparent velocity from INDEPTH II stations (from the linear fitting) is 8.42 km/s.

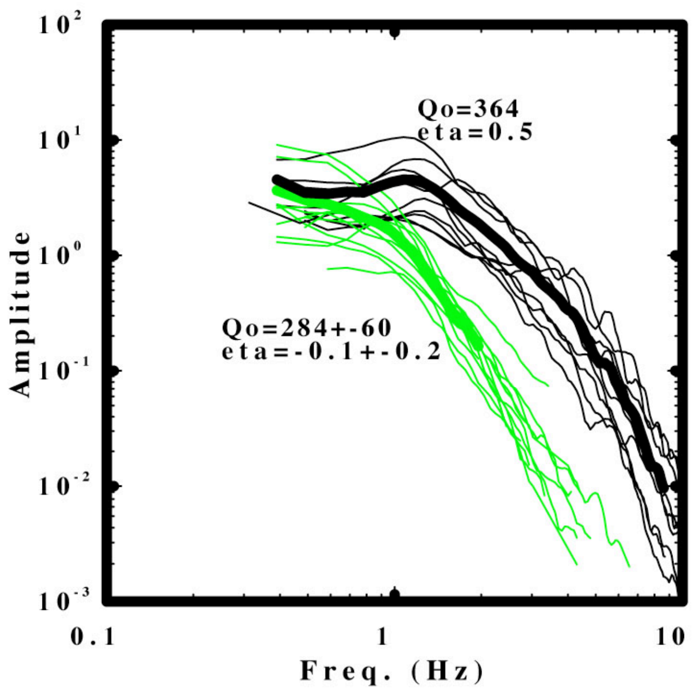

Figure 6. Individual Pn spectra from the Oct. 7, 1994 Lop Nor explosion (thin curves) and their average (thick curves), Black curves are for paths to the west (mainly Kyrghistan stations) and green curves are to the north (INDEPTH II stations). Average Pn Q_0 and n to the west and north are written near the curves.