Short Notes

Strong Lg Attenuation in the Tibetan Plateau

by Guang-Wei Fan and Thorne Lay

Abstract  The widespread existence of strong Lg attenuation in the Tibetan Plateau is further demonstrated by analysis of Lg spectra on many paths within the plateau and quantitative estimates of the Lg attenuation from low-frequency Lg signals for new, localized path geometries. Strong path-length-dependent shifts of the Lg spectra to lower corner frequencies with increasing distance are observed across the plateau, consistent with a low regional average 1-Hz Lg attenuation value, \( Q_0 \), of about 125. There are clearly lateral variations within the plateau found in this and other recent studies, with localized areas having \( Q_0 \) values of 60–90, low enough to eliminate high-frequency Lg energy over path lengths of just several hundred kilometers, while some localized areas may have higher \( Q_0 \) values of up to 147 or higher. A \( Q_0 \) value of 103 is found in south-central Tibet, compatible with recent work by others for higher frequencies on very localized scales, and values from 83 to 147 are found in eastern Tibet. The lowest \( Q_0 \) estimates found in Tibet tend to be in areas for which there is evidence of volcanism and/or partial melting within the crust; however, the strong regional attenuation may have a contribution from scattering by small-scale crustal heterogeneity. The strong Lg attenuation in Tibet gives a new constraint for understanding the tectonic development of the plateau and presents challenges to seismic monitoring of the region for possible clandestine nuclear tests.

Introduction

The Tibetan Plateau (TP) is one of the most dramatic features on the Earth’s surface and is the primary region for seeking to understand the processes of continental collision. The thick crust and high elevation of the plateau are associated with anomalous seismic-wave propagation, which has prompted many studies of regional and teleseismic data in an effort to constrain the crustal structure. Analyses of various seismological data sets indicate that extensive regions of the northern portion of the TP have strong attenuation of the Sn phase (Ni and Barazangi, 1983; McNamara et al., 1995) along with relatively low Pn velocities in north-central Tibet compared to southern Tibet (Barazangi and Ni, 1982; Zhao and Xie, 1993; McNamara et al., 1997). Surface wave analyses also indicate low velocities in the crust and upper mantle under the north-central portions of the plateau and higher mantle velocities under the southern portion of the plateau (e.g., Brandon and Romanowicz, 1986; Bourjot and Romanowicz, 1992; Rodgers and Schwartz, 1998), while teleseismic body-wave arrival times support a decrease in upper mantle velocity from southern Tibet to northern Tibet (e.g., Molnar and Chen, 1984; Molnar, 1990; Zhou et al., 1996). The mantle heterogeneities are variously interpreted as evidence of underthrusting of Indian plate lithosphere to near the center of the TP along the boundary between the Lhasa and Qiantang Terranes and/or downwelling of Indian lithosphere under the Karakorum, Himalaya, and southern Tibet (e.g., Dewey et al., 1988; Molnar, 1988; Tapponnier et al., 2001).

Inefficient transmission of high-frequency Lg has been noted for paths traversing both the northern and southern TP margins (Ruzaikin et al., 1977; Ni and Barazangi, 1983; Rapine et al., 1997), with quantitative estimates of the Lg attenuation function, \( Q_{Lg}(f) \), indicating lower values within the TP than in the surrounding areas of the China platform (e.g., Shih et al., 1994; McNamara et al., 1996; Reese et al., 1999). Recent studies of broadband Lg data for Tibet (e.g., Fan and Lay, 2002, 2003; Xie, 2002; Xie et al., 2002) have indicated even stronger attenuation throughout the TP than the earlier estimates. While a range of values has been estimated, the plateau average for 1-Hz \( Q_{Lg} \) is around \( Q_0 = 125 \), which is low enough that high-frequency (>1-Hz) Lg energy will be eliminated for path lengths longer than about 500 km, consistent with observations of Ruzaikin et al. (1977) and McNamara et al. (1996); however, lower frequency Lg energy can be observed for paths across the entire plateau, allowing the attenuation to be quantified. Localized areas have very low values of \( Q_0 = 79–90 \) in the northern and southeastern plateau (Fan and Lay, 2002, 2003) and in
the south-central TP with $Q_0$ values of 60–100 (Xie et al., 2002). We extend the analysis of $Lg$ phases in the TP, further exploring regional variations of low-frequency $Lg$ attenuation, particularly the north to south variation in central Tibet and the properties of eastern Tibet.

Data Analysis

Given that there is widespread occurrence of strong $Lg$ attenuation in Tibet, one of the major challenges for quantifying the attenuation for a sparse station distribution is that high-frequency (>$1$-Hz) $Lg$ tends to be totally attenuated over paths of about 500 km length (McNamara et al., 1997; Fan and Lay, 2002; Xie, 2000). A series of portable station deployments have provided invaluable observations of regional phases over short paths within the plateau (e.g., McNamara et al., 1995, 1996, 1997; Xie et al., 2002), and a handful of permanent broadband stations within and around the TP provide additional data for longer propagation paths traversing the TP and its margins, but mapping high-frequency attenuation in the region is limited to just a few localized paths. As a result, we have explored the low-frequency (0.2 to 1-Hz) energy in the $Lg$ wave train for many paths in Tibet, finding that while this energy is also strongly attenuated, there is sufficient signal-to-noise ratio even over long paths that we can quantify the low-frequency $Lg$ attenuation over most of the TP. Figure 1 demonstrates that low-frequency $Lg$ has significant signal strength relative to the preceding $Sn$ and $Sn$ coda even for long paths traversing the plateau. More examples were shown in Fan and Lay (2002). The 0.2 to 1.0-Hz passband is actually that for the classical definition of $Lg$ (e.g., Press and Ewing, 1952; Ewing et al., 1957), so there is no question that this energy is the Rayleigh-wave overtone energy recognized to constitute $Lg$ over all frequencies (e.g., Kennett, 1989; Xie and Lay, 1994; Zhang and Lay, 1995).

We utilize $Lg$ observations in the passband 0.2–1.0 Hz from four Chinese Digital Seismic Network (CDSN) stations, WMQ, LZH, LSA, and KMI, which have locations in and around the TP, as shown in Figure 2. Station WMQ lies just north of the eastern Tarim Basin, about 650 km from the northern boundary of the TP. Station LSA is located within the TP, near the southern end of the Lhasa Terrane along the Indus–Tsangpo Suture. Data from WMQ and LSA were processed by Fan and Lay (2002). New results are presented for LZH and KMI, which are located northeast and southeast of the plateau, respectively. The crust surrounding the TP has high $Lg$ $Q_0$ values of 500–600 (e.g., Phillips et al., 2000; Fan and Lay, 2002), which allows $Lg$ to transmit efficiently, typically as the largest amplitude high-frequency regional phase. However, the relatively long path lengths and strong attenuation within the TP constrain our data (even on relatively short paths to LSA) to frequencies lower than 1 Hz. We only analyze vertical-component recordings of $Lg$, to avoid confusion with fundamental-mode Love-wave energy on the transverse components. Our signals are extracted for a standard $Lg$ group velocity window of 3.6–3.0 km/sec, which precedes short- and intermediate-period fundamental-mode Rayleigh-wave energy (Fig. 1). This window captures the interfering Rayleigh-wave overtone energy, which constitutes the $Lg$ phase at both high and low frequencies. The events range in magnitude, $4.4 \leq m_b \leq 6.4$, and occurred...
between 1987 and 1999 within the TP and around its margins. For events prior to 1998, we use source parameters taken from the International Seismological Centre, and we use U.S. Geological Survey Preliminary Determination of Epicenters parameters for more recent events. We include only events with catalog and Harvard Centroid Moment Tensor solution source depths of less than 50 km. There is substantial uncertainty in the event source depths and focal mechanisms for events in the TP, but this is not critical for our analysis. Our events tend to be larger, better located events, and any attendant uncertainties in precise location are of second-order nature to this analysis. Following Fan and Lay (2002), we only retain events for which the broadband $Lg$ energy has amplitudes at least twice that of the 15-sec-long pre-$Pn$ noise window.

The CDSN stations have broadband seismometers, so we can analyze the low-frequency content of the $Lg$ window even for paths on which high-frequency $Lg$ is reduced to the noise level. The broadband spectra of waveforms like those in Figure 1 display systematic variations with propagation distance, with good signal-to-noise ratios relative to pre-$Pn$ energy across the 0.02- to 2-Hz passband. Numerous examples of spectra representative of our entire data set were shown in Fan and Lay (2002). To parameterize these large spectral differences, we follow Fan and Lay (2002) in defining an apparent $Lg$ corner frequency as the intercept of low- and high-frequency asymptotes to the velocity spectra in the range 0.01–5 Hz. The corner frequency measures are somewhat subjective and are affected if we decrease the low group velocity boundary of the $Lg$ window, which allows fundamental-mode Rayleigh-wave energy into the window (see Fan and Lay, 2002), but this simple parameterization suffices to grossly characterize the shape of the $Lg$ spectrum given the very large shifts seen in the data. We first consider distance dependence of the $Lg$ corner frequency measures and then compute formal $Lg$ attenuation parameters, assessing the regional characteristics of $Lg$ attenuation within the TP.

$Lg$ Spectra Variations across the Plateau

We plot the $Lg$ corner frequency measurements just described as a function of distance from CDSN stations KMI and LZH in Figure 2. Similar plots for WMQ and LSA observations were shown in Fan and Lay (2002). The event populations differ for each station due to recording history and station position relative to the TP; the map in Figure 2 shows the combined distribution of sources used for KMI and LZH. The 37 LZH and 30 KMI measurements are all new. The KMI data are limited in azimuthal coverage to exclude paths traversing the eastern Himalayas and thus preferentially sample the eastern TP. All four CDSN stations record systematic distance dependence of the apparent corner frequency measurements, with about an order-of-magnitude shift toward lower frequency over a 1000-km increase in propagation distance. Observations of $Lg$ corner frequencies outside the TP shift from about 1.0–2.0 Hz at 500 km to 0.7–1.0 Hz at 1500 km (Fan and Lay, 2002), which is far less of a trend than found for our data. The correlation coefficients of a straight-line fit to the data are $-0.903$ for LZH and $-0.948$ for KMI, comparable to the $-0.914$ value for LSA (Fan and Lay, 2002). WMQ observations show more scatter (correlation coefficient $= -0.820$), but these also have the greatest variation in path length outside of the plateau (Fan and Lay, 2002). Various alternate parameters of the paths that emphasize the portion within the TP, such as average elevation, path length above the 4000-m elevation level, and topographic variance, can have even stronger correlations with the $Lg$ corner frequency measurements. Fan
and Lay (2002) presented some of these additional correlations for WMQ; here we simply note that there is compelling evidence that it is the systematic effect of propagation within the TP crust that causes these large spectral shifts. We have not detected any correlation with event magnitude or focal mechanism for these data.

The systematic evolution of the $L_g$ spectra with distance in the TP indicates that abrupt blockage effects on the margins of the TP are not the primary cause of $L_g$ variations at these stations. The new measurements for LZH and KMI support an interpretation that progressive attenuation losses are the cause of the spectra shifts, with these losses being more severe than encountered in other regions of Eurasian crust. While dipping Moho or other structural effects could contribute to some spectral variations, the fact that our paths sample many azimuths and different subregions clearly favors an interpretation in terms of intrinsic attenuation. The strong shift of frequency content implies a likely shift in overtone branch and associated depth sampling of the dominant energy in the $L_g$ window at each distance. Thus, it is difficult to quantify the strong trends in Figure 2 in terms of a specific attenuation model without extensive modeling. However, the relative trends between stations can be directly compared, and this is done in Figure 3. The baseline level of each trend appears to reflect the mixing of portions within the TP and outside the TP. For example, WMQ has the highest path percentage outside the plateau of all stations, while the paths to LSA are all within the TP. The slopes of the trends for WMQ and LSA are very similar, suggesting that the data sample comparable spatial patterns of strong attenuation. These two stations have the most uniform sampling of the TP. The slightly lower spectral decay rates with distance for LZH and KMI are suggestive of somewhat higher $Q_{L_g}$ values in eastern Tibet than the overall average across the TP.

While the corner frequency measure is not an easily interpreted parameter, the regional consistency of the low-frequency $L_g$ spectral measurements argues for a first-order distribution of strong attenuation across the TP, possibly with somewhat lesser attenuation levels in eastern Tibet. The data do not reveal a strong internal north–south gradient within the plateau, as has been found for upper mantle properties. The broad sampling of the plateau for our source distributions and the diverse azimuths to each station indicate that the trends in Figure 3 arise from a regional-scale low baseline $Q_{L_g}$ across the TP with a lower value than estimated by early attenuation studies. Formal estimation of the $L_g$ attenuation model for WMQ data has been performed by Fan and Lay (2002) and for limited two-station/two-event geometries for stations WMQ/LSA and WMQ/KMI by Fan and Lay (2003). We now extend these results with attenuation estimates for stations KMI and LZH.

**New $L_g$ Attenuation Estimates**

The procedure that we follow for single-station, multiple-event attenuation estimation of $L_g$ attenuation parameters is the same as used for WMQ data by Fan and Lay (2002). Essentially, we compare the $L_g$ spectra from two events at different distances along a great-circle path to a station, applying baseline corrections for the relative source moments and geometric spreading corrections and fitting the spectral ratio with a parameterization of the attenuation function. This method explicitly cancels out site effects for the backazimuth to the events (we limit departures from the great circle to $\pm 15^\circ$ in practice), and it constrains the attenuation on the path between the two events. We assume that the $L_g$ radiation pattern is isotropic (e.g., Sereno et al., 1990; Shih et al., 1994), and we do not make an explicit correction for the source spectrum shape given that the very strong regional attenuation overwhelms any small differences in source corner frequency between our events. The isotropic radiation assumption is reasonable for short-period $L_g$, but less clearly so for longer periods; therefore we stack multiple pairs of spectral ratios for suites of closer and further events on the great-circle path to average out possible biases due to this effect. Experiments with applying source model corrections for various source parameterizations and the available seismic moment estimates to our data (which range in seismic magnitude by less than 1 magnitude unit for the events used in our attenuation estimation) indicate that individual ratios may incur some bias for frequencies of 0.5 Hz and higher, with stacking likely to shift this to a higher frequency range. The geometric spreading model used is a simple $d^{-0.5}$ model, where $d$ is the path length. This has been shown to be appropriate for $L_g$ spectra by Campillo et al. (1984), Chun et al. (1987), and Shin and Herrmann (1987).

The resulting stacked spectral ratio for a given corridor is parameterized by an attenuation model, $\Gamma(f)$, given by

![Figure 3. Composite of the $L_g$ apparent corner frequency versus distance regression lines for each of the stations from Figure 2 and from Fan and Lay (2002), shown on a common scale. The similarity of the regressions suggest pervasive, plateau-wide strong $L_g$ attenuation that shifts the spectral content systematically to lower frequency with increasing distance. The relatively high $Q_{L_g}$ portions of the paths outside the plateau to WMQ, LZH, and KMI baseline shift the curves relative to LSA. The slopes of the curves increase in proportion to the relative path sampling of the eastern region of the plateau.](image)
\[ \Gamma(f) = e^{-\eta f}, \]  
(1)

where \( \gamma \) is the attenuation coefficient, which is related to the quality factor \( Q_{Lg} \) and the group velocity \( U \) as

\[ \gamma = (\pi f)(Q_{Lg}U). \]  
(2)

Both intrinsic and scattering attenuation are folded into this loss parameter. We assume a constant group velocity of 3.5 km/sec, as this is consistent with the primary energy arriving in the \( Lg \) group velocity window and we do not isolate individual modes for which distinct group velocities can be measured. The attenuation coefficient is obtained as a function of frequency from the stacked, corrected spectral ratios for a given corridor. Then we assume a power-law frequency-dependent model of \( Lg \) attenuation given in terms of quality factor \( Q_{Lg} \), expressed as

\[ Q_{Lg}(f) = Q_0 f^\eta \]  
(3)

where \( Q_0 \) is the value of \( Q_{Lg} \) at 1 Hz, and \( \eta \) is the power-law frequency dependence. Based on equations (2) and (3), we fit a \( Q_{Lg}(f) \) model to observed logarithmic \( \gamma(f) \) by least-squares regression over a given bandwidth to estimate the parameters of the \( Lg \) attenuation model. The details of this procedure and its caveats were discussed in Fan and Lay (2002).

As in previous analyses of the broadband \( Lg \) spectra for paths around the TP, we find that the shape of spectral ratios over nearby paths tends to be very stable, but there is some scatter in baseline due to uncertainties in moment estimates and/or influence of radiation pattern effects that are not negligible. By stacking all of the combinations of spectral ratios available for sets of events at the shorter and larger distances in a given corridor, we obtain a robust average attenuation curve that has the overall common shape of the spectra, but with a more stable baseline. Our corridors are defined by azimuthal sectors that intersect the linear trends of seismicity across the TP (see Fan and Lay, 2003). Examples of the azimuthal sectors that intersect the linear trends of seismicity with a more stable baseline. Our corridors are defined by azimuthal sectors that intersect the linear trends of seismicity across the TP (see Fan and Lay, 2002).  

The estimated \( Lg \) attenuation coefficients for the corridors sampled by the LZH and KMI data are shown in Figure 4, along with the regression curves that yield attenuation parameters for passbands of 0.2–0.5 and 0.2–1.0 Hz. Table 1 lists the attenuation parameters obtained in each case. The attenuation coefficient estimates tend to have stable linear behavior below 0.5 Hz and then flatten at higher frequencies, with the flattened curve extending beyond 1 Hz (not shown). Flattening of the curve appears to be the result of the lack of signal-to-noise ratio due to propagation over long, highly attenuating paths to the station and is observed for all of the stations, including WMQ (Fan and Lay, 2002). What little high-frequency energy is present in the waveforms for the more distant sources, while often above the pre-\( Pn \) signal noise level out to frequencies of 2 Hz or more, appears to be from extended coda of high-frequency \( P \) and possibly some high-frequency \( Sn \) coda. Regressions that extend the bandwidth into the flattening portion of the attenuation coefficient estimate result in higher values of \( Q_{Lg} \) and we prefer the values obtained from the smooth lower frequency portion of the spectrum below 0.5 Hz where we know the signal-to-noise ratio is good. This does mean that our results are based on quite limited bandwidth; our estimate of the frequency dependence of attenuation is correspondingly uncertain, and some extrapolation to a 1-Hz value of \( Q_{Lg} \) is required. We believe that we do have reliable estimates of the attenuation function for relatively low frequency \( Lg \) in the corridors sampled, which can be compared to estimates from other procedures as long as differences in bandwidth and methodology are kept in mind.

Ten spectral ratios are stacked to give the result for southern central TP from LZH observations (Fig. 4a). The 10 pairs are formed for five events at closer distances and two events at larger distances (Table 1 identifies the corresponding information for each case). A nearly constant \( Q_{Lg} \) model, with \( Q_0 = 103 \pm 4 \), is estimated from the 0.2 to 0.5-Hz passband (Table 1). The region for which this value is valid is shown in Figure 5b, in south-central Tibet. Twenty spectral ratios were stacked to give the result for whole-plateau paths in eastern Tibet from KMI observations (Fig. 4b). A nearly constant \( Q_{Lg} \) model, with \( Q_0 = 106 \pm 18 \), is found for the lower frequency band. The area for which this is valid (Fig. 5b) was subdivided into eastern and western subregions with smaller numbers of event pairs. The eastern subregion has four stacked spectra at KMI with the result (Fig. 4c) yielding \( Q_0 = 147 \pm 22 \), and the western subregion’s six stacked spectra (Fig. 4d) yield \( Q_0 = 83 \pm 19 \). In each case, fitting the attenuation model over the range of 0.2–1.0 Hz leads to higher values of \( Q_{Lg} \) and stronger frequency dependence (Table 1), but as noted earlier, the flattening of the spectra casts doubts on the latter models. Using a precise limit of 0.5 Hz is, of course, uncertain as well; however, this is very close to the onset of flattening of the spectra and for many traces the lower bound for having a signal-to-pre-\( Lg \)-noise ratio of at least 1, as well as the cutoff for effects of our limited source spectrum corrections.
Figure 4. Estimates of the $L_g$ attenuation coefficients, $\gamma(f)$, obtained by single-station/multiple-event analysis of data from (a) station LZH for 10 pairs of events in southern central Tibet, (b) station KMI for 20 pairs of events in eastern Tibet, (c) station KMI for an eastern subregion of eastern Tibet with 4 pairs of events, and (d) station KMI for a western subregion of eastern Tibet with 6 pairs of events. The pluses indicate the attenuation coefficients, with standard deviations being shown for every other estimate. The solid lines indicate the $Q_{L_g}$ models estimated from the 0.2 to 0.5-Hz spectra, and the dotted lines indicate the $Q_{L_g}$ model estimated from the 0.2 to 1.0-Hz spectra. The resulting $Q_{L_g}$ models are listed in Table 1. The flattening of the spectra above 0.5 Hz results in a higher $Q_{L_g}$ estimate when 1.0-Hz energy is included, but this is likely to represent contamination of the $L_g$ window by high-frequency scattered $P$-wave and $S_n$ coda energy, so the lower frequency model is preferred, even though it involves some extrapolation to 1 Hz.

### Table 1

Lg Attenuation Coefficient in South-Central and Eastern Tibet

<table>
<thead>
<tr>
<th></th>
<th>LZH* (South-Central TP)</th>
<th>Eastern TP†</th>
<th>Eastern Subregion of Eastern TP§</th>
<th>Western Subregion of Eastern TP§</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_0$ 0.2–0.5 Hz</td>
<td>103 ± 4</td>
<td>106 ± 18</td>
<td>147 ± 22</td>
<td>83 ± 19</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.02 ± 0.15</td>
<td>0.03 ± 0.15</td>
<td>0.20 ± 0.13</td>
<td>−0.07 ± 0.19</td>
</tr>
<tr>
<td>$Q_0$ 0.2–1.0 Hz</td>
<td>187 ± 5</td>
<td>140 ± 7</td>
<td>210 ± 18</td>
<td>108 ± 5</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.57 ± 0.05</td>
<td>0.31 ± 0.08</td>
<td>0.57 ± 0.11</td>
<td>0.19 ± 0.06</td>
</tr>
</tbody>
</table>

*5 × 2 pairs.
†4 × 5 pairs.
‡2 × 2 pairs
§2 × 3 pairs.

First number indicates number of events at closer distances to receiver, second number indicates number at larger distances.

### Discussion and Conclusion

The regional consistency of $L_g$ spectral evolution over paths crisscrossing the TP in different directions (Fig. 3) is strong evidence for a regional low baseline for $Q_0$, and this must be significantly lower than the values around 350 indicated by estimates made in the last decade. Combining the $L_g$ spectral behavior with more recent, quantitative estimates of $Q_0$ from this article and the work of Xie (2002) and Fan and Lay (2002, 2003) indicates that the correct baseline is around 125. This is supported by recent work by S. Phillips (personal comm., 2002), who finds systematically lower values across the TP than had been estimated in an initial study (Phillips et al., 2000). While much additional work is
needed, it appears that a new consensus on very strong \( Lg \) attenuation across the TP is emerging. The baseline found is comparable to that in other tectonically active areas such as California (Herrmann, 1980; Nuttli, 1986), Iran (Nuttli, 1980), and the Bolivian Altiplano (Baumont et al., 1999). On a regional basis, seismic discriminants that utilize \( P/S \) type ratios, such as \( Pn/Lg \), will suffer from lack of high-frequency \( Lg \) energy, and thus high-frequency regional phase discriminants (e.g., Walter et al., 1995; Hartse et al., 1997) will not be diagnostic of the source type for paths in the TP.

Recent determinations of low \( Q_0 \) values in the TP are summarized in Figure 5a. Xie’s (2002) estimate of \( Q_0 = 126 \pm 9 \) in eastern Tibet corresponds to our corridor in the western portion of eastern Tibet, for which we obtain \( Q_0 = 83 \pm 19 \), and where Fan and Lay (2002) estimated \( Q_0 = 100 \pm 20 \). Xie’s data are broader band and likely yield a more stable estimate of frequency dependence and \( Q_0 \) in the immediate vicinity of the stations that he used. Our data indicate that this low value holds over a broader region. Our regional estimate for eastern Tibet (\( Q_0 = 106 \pm 18 \)) is in good agreement with the values estimated from WMQ data (\( Q_0 = 122 \pm 20 \)) by Fan and Lay (2002) and for WMQ/KMI two-station analysis (\( Q_0 = 119 \pm 17 \)) by Fan and Lay (2003). Our KMI observations suggest an increase in \( Q_0 \) toward the eastern edge of the TP (Fig. 5b), which agrees with the increase suggested by Fan and Lay (2002) (Fig. 5a).

The corridor in southern central Tibet that we sample (Fig. 5b) overlaps with localized International Deep Profiling of Tibet and the Himalaya (INDEPTH) II and INDEPTH III station \( Lg \) attenuation estimates by Xie et al. (2002). Our low-frequency estimate of \( Q_0 = 103 \pm 4 \) is at the upper bound of the broader band estimates in the range 60–100 given in Xie et al. (2002). We view this consistency as encouraging, recognizing that our path lengths are much longer and the high-frequency energy has been lost. Fan and Lay (2002) estimated, over the southern half of the central TP using WMQ data, a higher value of \( Q_0 = 316 \) (Fig. 5a), which is at odds with these results. We believe that it is likely that there are localized portions of southern central TP that do have higher \( Q_0 \) values; the very data used by Xie et al. (2002) suggest that high-frequency \( Lg \) waves manage to transit across the central plateau before encountering the very strong attenuation found along the INDEPTH profiles. However, it is also possible that the low-frequency estimates are biased or subject to much higher uncertainties than the formal estimates give. Reinspection of the spectral observations in Fan and Lay (2002) does not give any clear resolution of this issue; the data are well behaved, albeit certainly depleted in high-frequency energy. Further mapping out of the spatial pattern in attenuation is needed to bound the spatial extent of regions with particularly acute attenuation and to address the stability of the low-frequency estimates on paths with lateral variations.

The sparse station and path distributions within the TP thus far preclude a detailed analysis of \( Lg \) spectra to assess the separate contributions from scattering and intrinsic attenuation. Baumont et al. (1999) interpreted the frequency-dependent attenuation of \( Lg \) in the Altiplano as being predominantly caused by scattering from small-scale heterogeneity rather than partial melting. The regions in northern and southern central Tibet where particularly strong attenuation has been found do have independent evidence of the presence of partial melt. North-central Tibet is the most volcanically active area of the plateau (e.g., Molnar, 1988; Arnaud et al., 1992; Turner et al., 1993, 1996). Owens and Zandt (1997) presented evidence for a lower crustal low-velocity zone they inferred to involve partial melt in northern Tibet.
Tibet. This region has inefficient Sn propagation (Ni and Barazangi, 1983; McNamara et al., 1995), low Pn velocity (McNamara et al., 1997), and high Poisson’s ratios of 0.34–0.35 over a 30-km thickness (Owens and Zandt, 1997). Rodgers and Schwartz (1998) found very low \( Q \) values of 44–89 in the Qiangtang Terrane of central Tibet, along with a high Poisson’s ratio, which they attribute to partial melting of the crust. There is also evidence for partial melt and crustal low-velocity zones existing north of the Tsangpo Suture in southern Tibet (Kind et al., 1996; Nelson et al., 1996; Cotte et al., 1999). These observations suggest that strong \( Lg \) attenuation in Tibet may be a manifestation of widespread partial melting of the crust; however, there is no question that there is also strong small-scale heterogeneity within the plateau that will contribute to scattering losses as well. Localized sedimentary basins can efficiently scatter high-frequency \( Lg \) as well (e.g., Baumgardt, 1990). Ongoing deployments of additional Chinese permanent broadband stations around the plateau should improve coverage and enable detailed analysis of scattering versus intrinsic attenuation.

Constraining the depth distribution of attenuation in the crust will also require much additional work. \( Q_{Lg} \) involves complex sampling of the crustal wave guide, and shallow crustal attenuation needs to be constrained by fundamental-mode attenuation in order to establish the \( Q \) structure of the upper and lower crust (e.g., Mitchell and Xie, 1994). Preliminary estimates of fundamental-mode attenuation in Tibet (Jemberie and Mitchell, 2002) have indicated values of \( Q_n \) in the upper 10 km of the crust of 40–60 under the central TP and 60–120 in the eastern TP; at depths of 10–30 km in the crust, they found values of 60–120 under the central TP and 110–120 under the eastern TP; and from 30 km to the Moho, they found values of about 100–120 across the region. These values are close to what is needed to match the broadband \( Lg \) attenuation estimates. There is a suggestion of a south to north decrease in midcrustal \( Q_n \), with lowest values in north-central Tibet, but as yet, the spatial resolution is poor. With relatively low overall crustal velocities likely to exist in the northern and central TP (e.g., Owens and Zandt, 1997; Rodgers and Schwartz, 1998), low-frequency \( Lg \) waves may provide overall sampling of the thick crust, averaging the entire attenuation structure. Detailed modeling of \( Lg \) and surface wave observations on the same path will be required to assess whether the lower crust has strong attenuation and partial melt or not. At this time, it appears that the TP crust does not have a bimodal south–north contrast in properties similar to that in the upper mantle; the crust is strongly attenuating throughout large regions of the plateau.

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