Short Note

Frequency-Dependent *Lg* Attenuation in the Indian Platform

by S. Mitra,* K. Priestley, V. K. Gaur, and S. S. Rai

Abstract   We use seismograms from regional earthquakes recorded on digital seismographs in peninsular India to determine the frequency-dependent Q of *Lg* for the Indian platform. We measure *Lg* attenuation by determining the decay of spectral amplitudes with distance. The available data suggest some spatial variation in attenuation but a much denser ray-path coverage would be required to validate such observations. We, therefore, combine all the measurements of overlapping regions that span both the shield and intervening terranes to obtain an average value of attenuation for the Indian platform: $Lg - Q = 665 \pm 10$ with the frequency exponent $n = 0.67 \pm 0.03$. This average value of *Lg* attenuation for the Indian platform is similar to the average for other stable regions of the globe.

Introduction

Lg waves are short-period, higher-mode surface waves that propagate in the continental crust as a coherent package of energy with typical group velocities of 3.5 km sec^{-1} (Press and Ewing, 1952; Båth, 1954). For continental earthquakes at regional distances the *Lg* phase is often a large-amplitude arrival typically constituting the main portion of the wave-train energy. High-frequency, higher-mode Rayleigh waves combine to produce the vertical component *Lg* phase (Knopoff *et al.*, 1973). *Lg* can also be considered to arise from the interference of multiple reflected *S* waves propagating in the crustal wave guide (Bouchon, 1982; Kennett, 1985). Because virtually all the energy contributing to the *Lg* wave is in the form of shear-wave energy trapped in the crust, the *Lg* amplitude is strongly dependent on the crustal structure and therefore provides discriminating information about the average crustal shear-wave velocity and attenuation between the source and receiver. The *Lg* wave train formed by the superposition of the different *S* multiples not only builds to a clear amplitude maximum but often has a relatively long coda that may persist for several minutes after the onset of *Lg*. *Lg* coda measured over a long part of the seismogram results in a rather effective averaging of the scattered field, thereby acquiring a remarkably stable envelope magnitude that proves quite attractive for the estimation of earthquake magnitude (Mayeda and Walter, 1996) from fewer station data. Because of their well-constrained domain of propagation and strong stable amplitudes over a large epicentral distance, both *Lg* and *Lg* coda wave trains are well suited for attenuation measurements. In addition, spatial decay rates of their spectral amplitudes provide insights in the assessment of earthquake hazards.

In this work we determine the frequency-dependent Q of the Indian platform from the spatial decay of the spectral amplitudes of *Lg* wave trains since they were stronger on our records than the *Lg* coda. Little is known about the propagation characteristics of *Lg* in India. Because the Indian shield has low seismicity and until recently digital broadband seismic data were only available for the GEOSCOPE station at Hyderabad (HYB) (Fig. 1), few attempts at measuring *Lg* attenuation of the various Indian regions have been made. Singh *et al.* (2004) used data for four earthquakes to measure the frequency-dependent Q of *Lg* waves for the Indian shield region. Mandal and Rastogi (1998) measured the frequency dependence of coda Q_c (i.e., the total quality factor of the medium) for the Koyna–Warna seismic zone close to the west-central coast of India. Our study covers most of the Indian platform and is based on better ray-path coverage than that used in previous studies. The Indian shield is a stable region composed of three distinct Archean cratons: the Dharwar craton, the Singhbhum craton, and the Aravali craton (Fig. 1), which have remained a coherent unit since the Late Archean or early Proterozoic (Naqvi and Rogers, 1987). This coherence of the Indian Shield and its near-uniform crustal thickness of 35–40 km (Gaur and Priestley, 1997; Rai *et al.*, 2003; Gupta *et al.*, 2003) provide the rationale for seeking an average characteristic $Lg - Q$-value for the entire Indian platform.

Data and Analysis

Data for this study consist of regional, digital seismograms of three earthquakes: (1) Jabalpur in central India,

---

*Present address: Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur 721302, India.
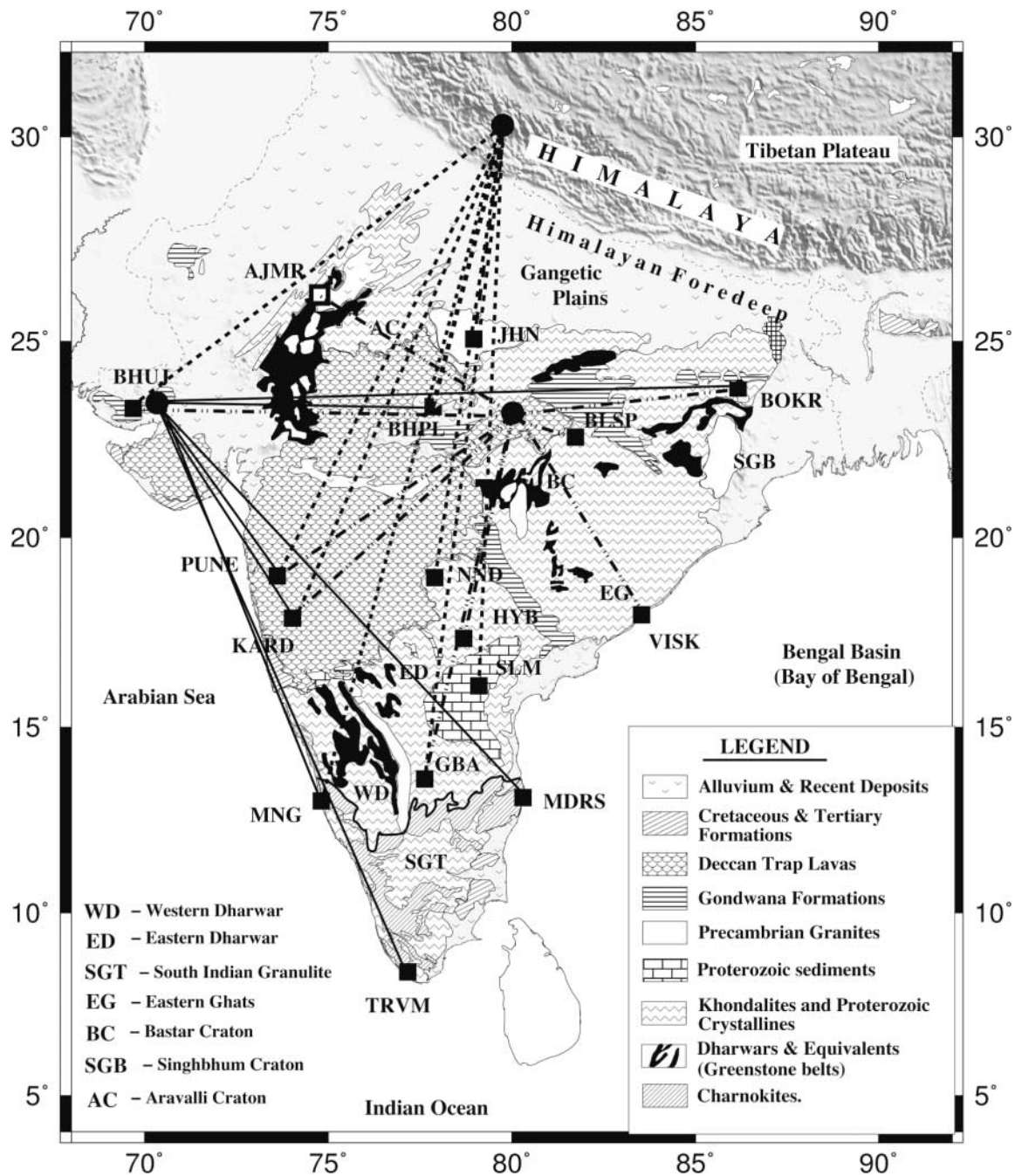
Figure 1.   Geological map of the Indian subcontinent, taken from Naqvi and Rogers (1987), showing the location of earthquakes (denoted by the filled circles), the broadband seismic stations (denoted by the filled squares) that recorded data for this study and the ray paths between them.

(2) Chamoli in the Himalaya in northern India, and (3) Bhuj in western India. Source information for these earthquakes taken from the Preliminary Determination of Epicenter (PDE) catalog is given in Table 1. Seismograms were recorded at 17 broadband seismograph stations in peninsular India (Table 2), operated by the Cambridge University, Indian Institute of Astrophysics (CU-IIA), the National Geophysical Research Institute (NGRI), and the Indian Meteorological Department (IMD). Figure 1 shows the location of the three earthquakes and the seismic stations. The source–receiver travel paths used in this study provided a good sampling of the crust of the central and south Indian Shield (Fig. 1).

We measure Lg attenuation by determining the decay of spectral amplitudes with distance. For shallow earthquakes, the S wave is the dominant phase on seismograms at distances less than about 100 km, whereas Lg dominates at dis-

Table 1
Source Information (PDE Catalog) of the Three Earthquakes Used in the $Lg - Q$ Measurements

No.	Origin Date	Time (hh:mm:ss)	Latitude	Longitude	Depth (km)	Magnitude
1	21 May 1997	22:51:30	23.104	80.118	39	6.0
2	28 March 1999	19:05:11	30.512	79.403	15	6.4
3	26 January 2001	03:16:42	23.400	70.280	20	7.5

Table 2
Location and Seismometer Type of NGRI, IMD, and CU-IIA Stations That Recorded Data Used in This Study

Network	Station	Latitude (°N)	Longitude (°E)	Elevation (m)	Seismometer Type
NG	BGL	13.021	77.570	791	CMG-3ESP
NG	GBA	13.564	77.357	681	CMG-3ESP
NG	SLM	16.101	78.894	368	CMG-3ESP
SE	TRV	8.510	76.960	64	STS-2
SE	MNG	12.941	74.822	11	CMG-40T
SE	MDR	13.070	80.250	15	STS-2
SE	PUNE	18.530	73.850	560	STS-2
SE	NGP	21.101	79.062	304	CMG-40T
SE	JHN	25.465	78.539	250	CMG-40T
SE	KARD	17.307	74.183	561	STS-2
SE	VISK	17.721	83.328	10	STS-2
SE	BLSP	22.129	82.131	271	STS-2
SE	BHPL	23.241	77.424	502	STS-2
SE	BHUJ	23.254	69.654	101	STS-2
SE	BOKR	23.794	85.885	307	STS-2
SE	AJMR	26.479	74.643	492	STS-2
CU	NND	19.107	77.287	314	CMG-3T

Table 3
Number of Stations That Recorded Each Earthquake, the Total Distance Range Covered for the $Lg - Q$ Measurements, Q_0, and Frequency Dependence (n) for the Three Earthquakes

Earthquake No.	No. of Stations	Distance Range (km)	Q_0 Value	Frequency Dependence (n)
1	9	233–1071	521 ± 21	0.74 ± 0.10
2	10	565–2001	663 ± 10	0.74 ± 0.03
3	7	654–1795	869 ± 45	0.64 ± 0.11

tances greater than about 100 km (Singh and Herrmann, 1983). The distance range used in this analysis (Table 3) has a minimum of 233 km, providing clearly observed Lg phases. Lg on the vertical component is extracted using a velocity window of 3.6–2.8 km sec^{-1}. Record sections of vertical-component seismograms for the three events are shown in Figure 2, with Lg windows used for analysis marked on each seismogram.

To determine the Lg attenuation, instrument-corrected, displacement-amplitude spectra were computed for the vertical component Lg phase. Noise levels in the data were determined by processing in a similar manner an equal length time window before the initial P-wave arrival time. In an attempt to eliminate random errors in the amplitude spectra, only those frequencies that had a signal-to-noise ratio greater than two were considered in the analysis. The Lg spectra were inverted for $Q(f)$ using

$$A(R, f) = \frac{S(f)}{G(R)} e^{-\pi f R / v Q(f)} \quad (1)$$

where, $A(R, f)$ is the spectral amplitude observed at a distance R and frequency f, $S(f)$ is the source term, $G(R)$ is the geometrical spreading term, v is the average group velocity,

taken as 3.5 km/sec for Lg. This model does not take into account scattering or radiation pattern effects and may therefore yield an apparent rather than the intrinsic Q. The effect of the source radiation pattern is minimized because the Lg phase is constructed as a superposition of many higher-mode surface waves (Knopoff *et al.*, 1973; Panza and Calcagnille, 1975) sampling a major portion of the focal sphere. Lg is modeled accordingly as constructively interfering higher-mode surface waves (Knopoff *et al.*, 1973; Nuttli, 1973; Panza and Calcagnille, 1975) and it is therefore assumed that the frequency-domain geometrical spreading scales with the square root of distance ($\sqrt{R}$).

Taking $\log_{10}$ of equation (1) gives

$$\log_{10} A + 0.5 \log_{10} R = \log_{10} S - \frac{\pi f \log_{10} e}{v Q} R \quad (2)$$

This is the equation of a straight line, whose intercept is given by the source term and slope by the Q term. For each earthquake, we plot ($\log_{10} A + 0.5 \log_{10} R$) versus R and perform a linear regression to determine Q at each frequency. Since Lg is an Airy phase (Nuttli, 1973), we are justified in using a frequency-independent travel time and hence a speed (v) of 3.5 km sec^{-1} in (2).

Writing the frequency-dependent Q in the form

$$Q(f) = Q_o f^n, \quad (3)$$

where Q_o is the Q at $f = 1$ Hz, and n gives the frequency dependence of the quality factor, we can rewrite (3) as

$$\log_{10} Q = \log_{10} Q_o + n \log_{10} f. \quad (4)$$

This again is the equation of a straight line and a linear regression is accordingly performed over $\log_{10} Q$ versus $\log_{10} f$, to determine values of Q_o and n, from the intercept and slope of the regressed line, respectively.

In Figure 3 we plot $\log_{10} (A) + 0.5 \log_{10} R$ versus R for all earthquakes at frequencies 0.6, 0.75, 1, 1.2, 1.5, 2, 3, 4, 5, and 6 Hz. The slope of the regression line in Figure 3 when substituted in (2) yields the Q-value at these frequencies. A comparison of these plots shows that for the lower frequencies, Q is systematically higher for the paths sampled by the Bhuj earthquake. Figure 4 shows the path coverage
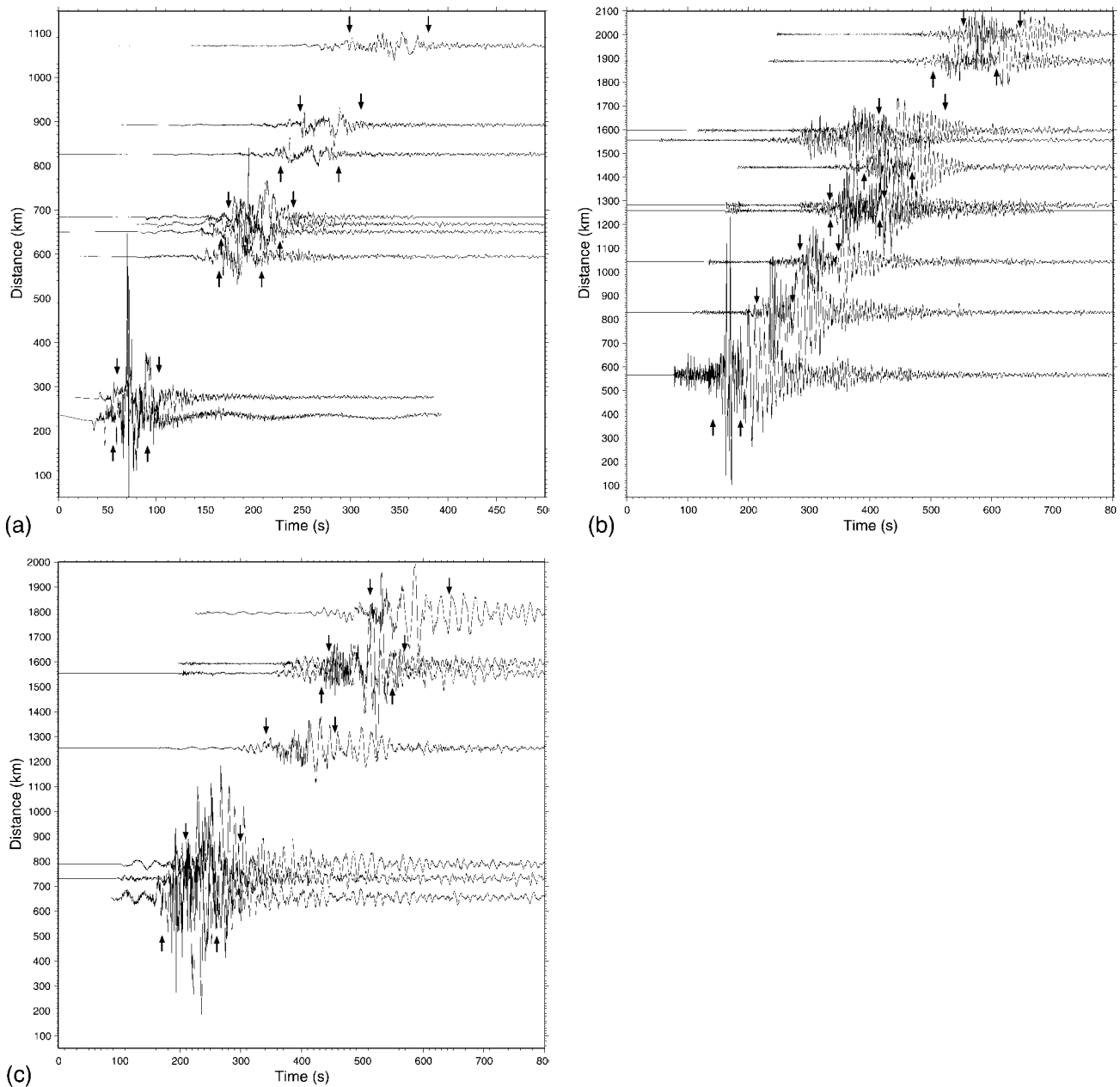
(a)

(b)

(c)

Figure 2.   Record section plot of the vertical component seismograms of the three earthquakes used for the *Lg* analysis: (a) 21 May 1997 (Jabalpur); (b) 28 March 1999 (Chamoli); and (c) 26 January 2001 (Bhuj). The velocity window from 3.6 to 2.8 km/sec is denoted by the pair of arrows above or below the seismograms.

for the individual earthquakes and plots of $\log_{10} Q$ versus $\log_{10} f$. The regression line through each dataset gives a value for Q_0 and n in Table 3 and Figure 4. Finally, we perform a weighted fit of the data from all three earthquakes to obtain an average value of Q_0 and n for the Indian Shield region (Fig. 5)

$$Q_0 = 655(\pm 10) f^{0.67(\pm 0.03)} \quad 0.6 \leq f \leq 6.0 \text{ Hz.} \quad (5)$$

This is obtained by fitting the average of the earthquake-

derived *Q*-functions, weighted by the standard deviation at each frequency.

Results and Discussion

We determine *Lg* attenuation, using digital records at 17 broadband seismic stations, of three regional earthquakes: one in the central Himalayan belt and the other two in the western and central part of the Indian shield. We selectively used only the high signal-to-noise (S/N) records which is
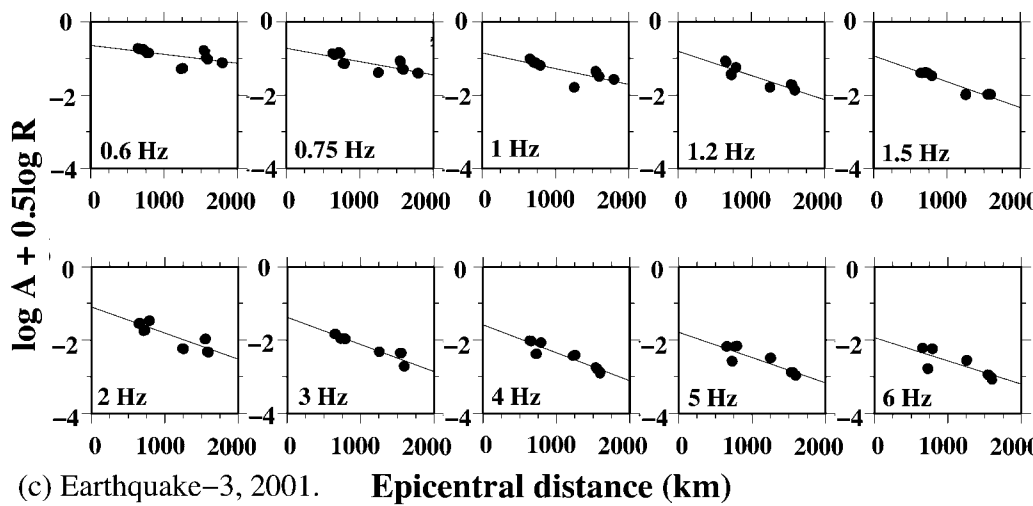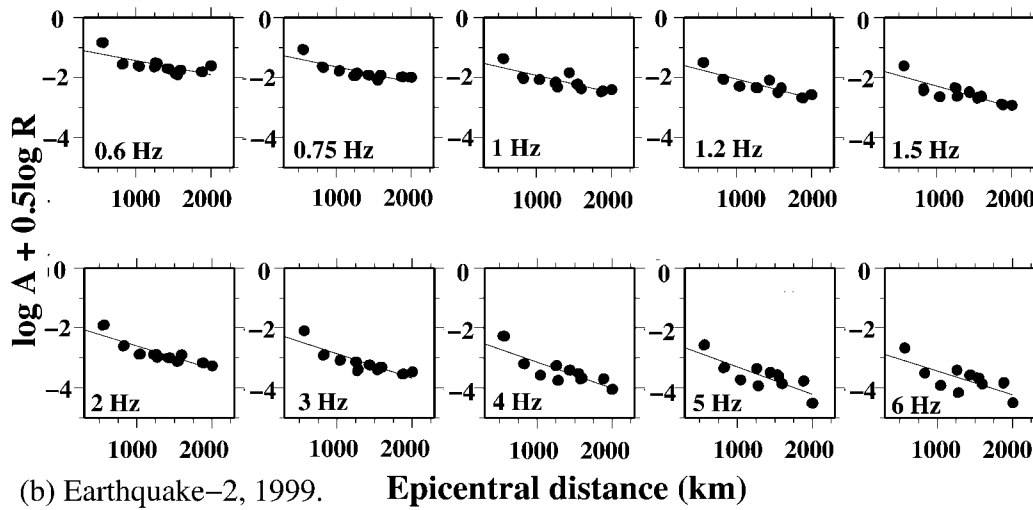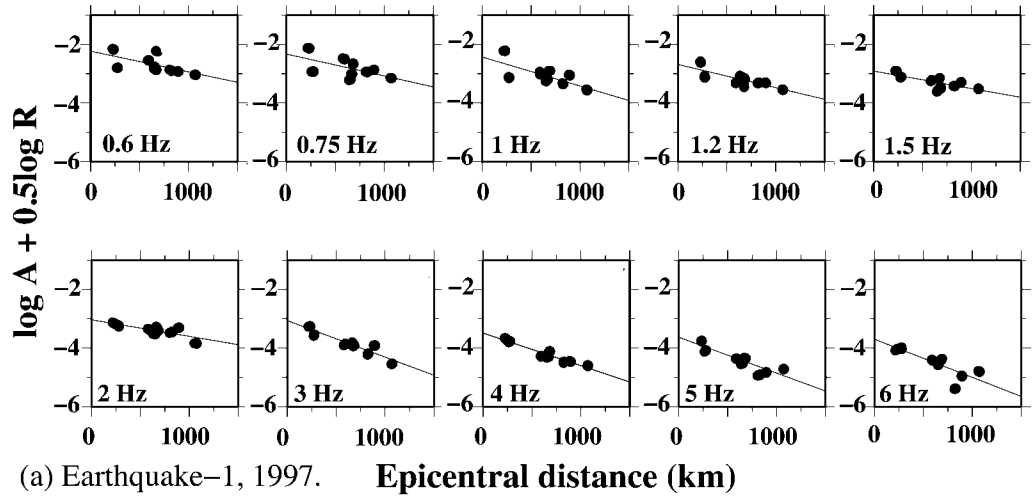
(a) Earthquake–1, 1997.   **Epicentral distance (km)**

(b) Earthquake–2, 1999.   **Epicentral distance (km)**

(c) Earthquake–3, 2001.   **Epicentral distance (km)**

Figure 3.   Plot of the $\log_{10} A + 0.5 \log_{10} R$ versus (R) for frequencies between 0.6 and 6 Hz for the three earthquakes.
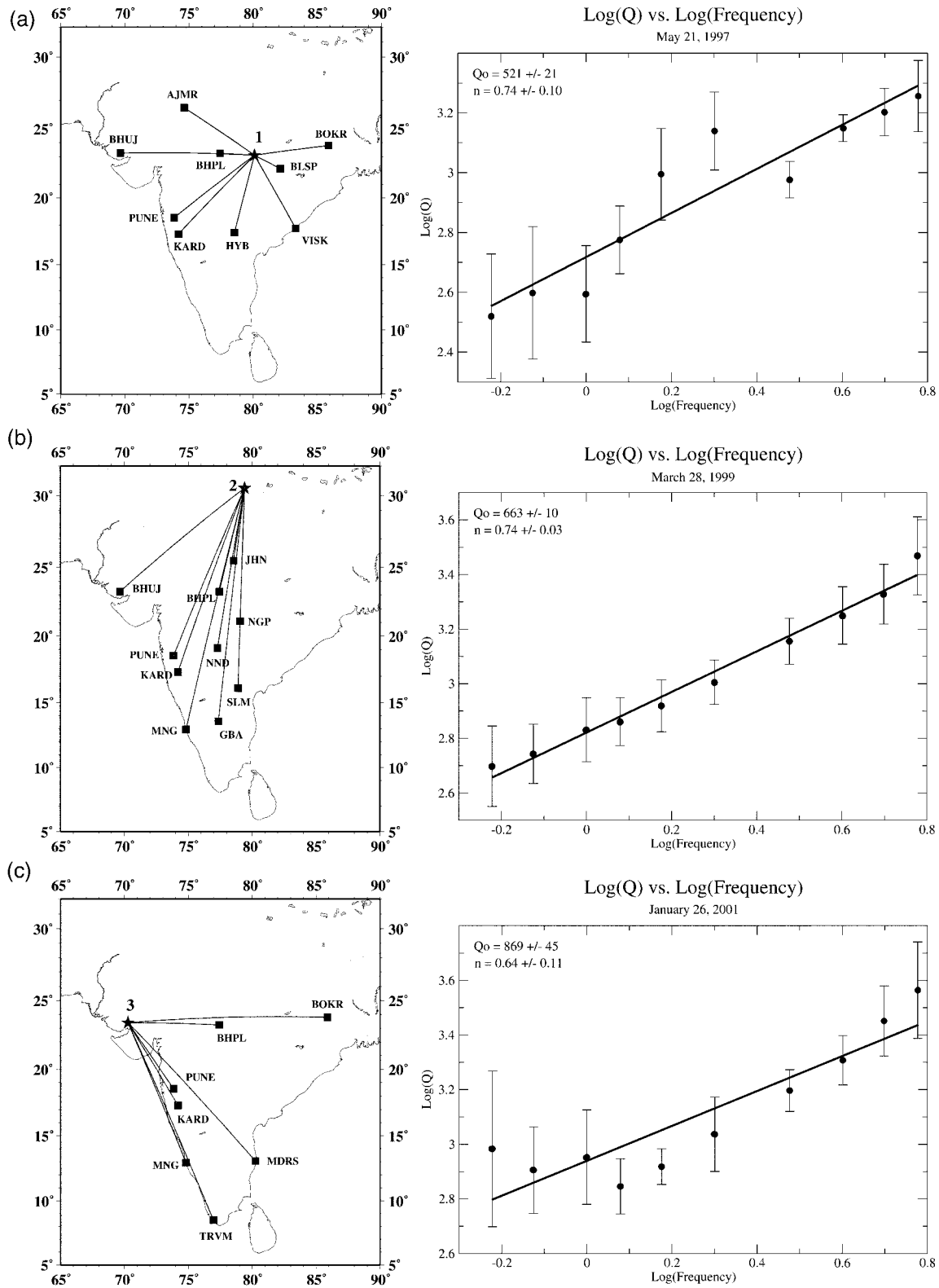
Figure 4.   (a) Result for the 21 May 1997 Jabalpur earthquake in central India. (Left) Ray-path coverage map. (Right) Plot of Log(Q) versus Log(f). The error bars are plotted over each data point. (b) Result for the 28 March 1999 Chamoli earthquake in the Himalaya. (c) Result for the 26 January 2001 Bhuj earthquake in western India.
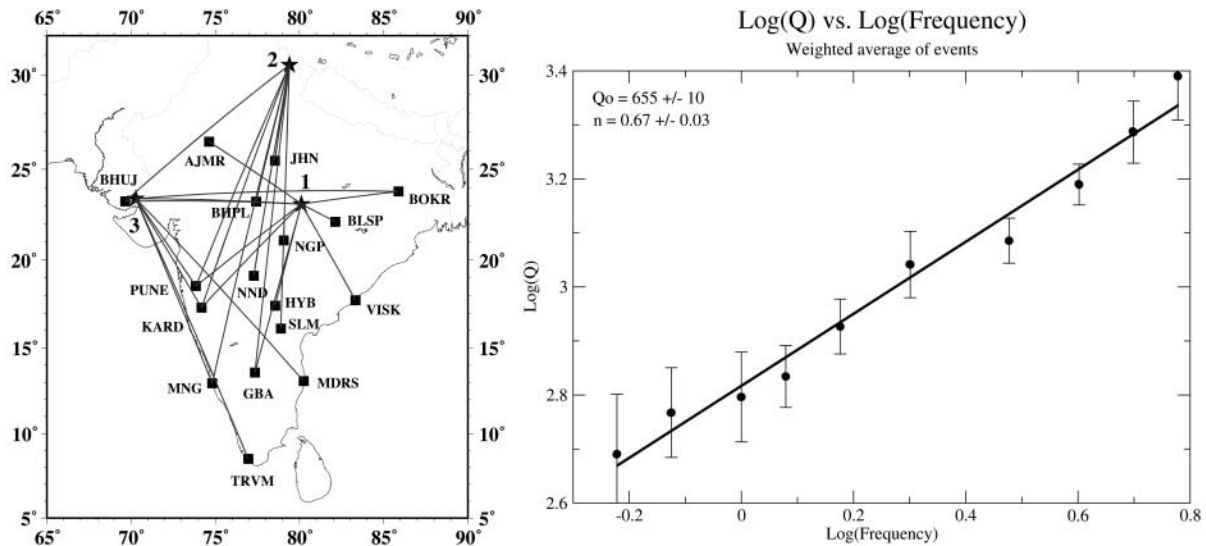
Figure 5. Combined result for the three earthquakes. (Left) Ray-path coverage for the Indian Shield. (Right) Plot of the weighted average of the Log(Q) versus Log(f) values.

reflected in the fairly well-resolved log(A) plots shown in Figure 3. We find that within the Indian platform region, the $Lg - Q$ is clearly frequency dependent with the frequency exponent $n = 0.67 \pm 0.03$.

Our results for $Lg - Q$ are better constrained for paths joining the Himalaya and sites in the south Indian shield (Fig. 4b) that include a substantial part of the stable cratons. These yield the expected high $Lg - Q$ value of 663 ± 10, and $n = 0.74 \pm 0.03$. For paths spanning central India (Fig. 4a), which include both cratons and intervening terranes of more variable ages, the values are somewhat lower: $Lg - Q = 521 \pm 21$ and $n = 0.74 \pm 0.1$. However, the Q-value is substantially higher and has larger scatter for paths (Fig. 4c) that include the west coast of India: $Lg - Q = 869 \pm 45$, and $n = 0.64 \pm 0.11$. The latter high $Lg - Q$-value is therefore largely weighted by the Western Ghats that constitute a narrow (~50 km) moderate relief (~1500 m) ridge which hugs the western coast most of the way and could possibly be the result of preferential energy channeling along the Ghats. This value is also higher than that determined by Mandal and Rastogi (1998) for a small region of ~50-km diameter array around Koyna on the west coast. But this can be explained because their results are valid only for a near-surface laterally limited volume of rocks subject to frequent reservoir-induced seismicity (Langston, 1976), and are therefore not directly comparable with our results corresponding to continental scale paths. The north-central Indian shield and the south Indian shield are characterized by significantly different values of Q. From a knowledge of recent earthquakes in India we know that the south Indian Shield region is relatively more stable and shows low seismic activity compared with north and central India where there have been several recent, moderately large earthquakes: Uttar-Kashi (1992), Latur (1993), Jabalpur

(1997), Chamoli (1999), and Bhuj (2001). However, available data allow only a coarse regionalization and a much denser ray-path coverage would be required to validate such observations. We, therefore, combine all the previous three measurements of overlapping regions that span both the shield and intervening terranes to obtain an average value of attenuation for the Indian platform: $Lg - Q = 665 \pm 10$ and $n = 0.67 \pm 0.03$.

Our average $Lg - Q$ values for the Indian platform are lower than the value of 800 determined by Singh *et al.* (2004) for the Indian shield using four regional events, three of which were common to our study. Their frequency exponent of 0.42 is also more than 50% lower than our average value of ~0.67. Shi *et al.* (1996) found $Lg - Q$-values for several subregions of northeastern United States to vary from 905 for the Adirondack Mountains with exposed Precambrian Grenville basement, which could be an analog of the Indian shield, to 561 for the Appalachian plateau and folded zone and a frequency exponent of 0.4 to 0.47. Baqer and Mitchell (1998) studied a larger region of the eastern United States extending from the Rocky Mountains to the Atlantic coast and obtained $Lg - Q$-values of 450–750. However, our average Q-value for the Indian platform is similar to the average for other stable regions of the globe: southern Africa (Congo and Kalahari) cratons, the West African craton (Xie and Mitchell, 1990), and the Siberian craton ($Q = 400$–600) (Mitchell, 1995). Most notably our $Lg - Q$ as well as frequency dependence are quite similar to the new continent wide maps of Lg coda Q and frequency dependence in Eurasia (Brian Mitchell, pers. comm., 2005). In particular, the similarity between our $Lg - Q$ and Lg coda values underline the implication that attenuation across India is dominated by intrinsic, rather than scattering mechanisms.

Acknowledgments

References

Baqer, S., and B. J. Mitchell (1998). Regional variation of Lg coda Q in the continental United States and its relation to crustal structure and evolution, *Pure Appl. Geophys.* **153,** 613–638.

Båth, M., (1954). The elastic waves *Lg* and *R$_g$* along Euroasiatic paths, *Arkiv. Geofysik.* **2,** 295–342.

Bouchon, M. (1982). The complete synthesis of seismic crustal phases at regional distances, *J. Geophys. Res.* **87,** 1735–1741.

Gaur, V. K., and K. F. Priestley (1997). Shear wave velocity structure beneath the Archaean granites around Hyderabad, inferred from receiver function analysis, in *Proceedings of the Indian Academy of Sciences, Earth Planet. Sci.* **106,** 1–8.

Gupta, S., S. S. Rai, K. S. Prakasham, D. Srinagesh, B. K. Bansal, R. K. Chadha, K. Priestley, and V. G. Gaur (2003). The nature of South Indian crust: Implications for Precambrian crustal evolution, *Geophys. Res. Lett.* **30,** no. 1, 1–4.

Kennett, B. L. N. (1985). On regional-S, *Bull. Seism. Soc. Am.* **75,** 1077–1086.

Knopoff, L., F. Schwab, and E. Kausel (1973). Interpretation of *Lg*, *Geophys. J. R. Astr. Soc.* **33,** 389–404.

Langston, C. A. (1976). A body wave inversion of the Koyna, India, earthquake of December 10, 1967, and some implications for body wave focal mechanisms, *J. Geophys. Res.* **81,** 2517–2529.

Mandal, P., and B. K. Rastogi (1998). A frequency-dependent relation of coda Q for Koyna-Warna region, India, *Pure Appl. Geophys.* **153,** 163–177.

Mayeda, K., and W. Walter (1996). Moment energy, stress drop, and source spectra of western United States earthquakes from regional coda envelope, *J. Geophys. Res.* **101,** 11,195–11,208.

Mitchell, B. J. (1995). Anelastic structure and evolution of the continental crust and upper mantle from seismic surface wave attenuation, *Rev. Geophys.* **33,** no. 4, 441–462.

Naqvi, S. M., and J. J. W. Rogers (1987). *The Precambrian Geology of India*, Oxford University Press, New York.

Nuttli, O. W. (1973). Seismic wave attenuation and magnitude relations for eastern North America, *J. Geophys. Res.* **78,** 876–885.

Panza, G. F., and G. Calcagnille (1975). *Lg, Li* and *R$_g$* from Rayleigh modes, *Geophys. J. R. Astr. Soc.* **40,** 475–487.

Press, F., and M. Ewing (1952). Two slow surface waves across North America, *Bull. Seism. Soc. Am.* **42,** 219–228.

Rai, S. S., K. Priestley, K. Suryaprakasam, D. Srinagesh, V. K. Gaur, and Z. Du (2003). Crustal shear velocity structure of the south Indian shield, *J. Geophys. Res.* **108,** no. B2, doi 10.1029/2002JB001776.

Shi, J. K., W-Y. Kim, and P. G. Richards (1996). Variability of crustal attenuation in the northern United States from Lg waves, *J. Geophys. Res.* **101,** 25,231–25,242.

Singh, S. K., and R. B. Herrmann (1983). Regionalization of crustal coda Q in the continental United States, *J. Geophys. Res.* **88,** 527–538.

Singh, S. K., D. Garcia, J. F. Pacheco, R. Valenzuela, B. K. Bansal, and R. S. Dattatrayam (2004). Q of the indian shield, *Bull. Seism. Soc. Am.* **94,** 1564–1570.

Wessel, P., and W. H. F. Smith (1995). New version of the generic mapping tool release, *EOS Trans. AGU* **76,** 329.

Xie, J. K., and B. J. Mitchell (1990). A back-projection method for imaging large-scale lateral variation of *Lg* coda *Q* with application to continental Africa, *Geophys. J. Int.* **100,** 161–181.

Bullard Laboratories
University of Cambridge
Cambridge CB3 0EZ, United Kingdom
  (S.M., K.P.)

Indian Institute of Astrophysics
Bangalore 560034, India
  (V.K.G.)

Center for Mathematical Modelling and Computer Simulations
Bangalore 560034, India
  (V.K.G.)

National Geophysical Research Institute
Hyderabad 500007, India
  (S.S.R.)