# SOURCE AND PATH EFFECTS ON REGIONAL PHASES IN INDIA FROM AFTERSHOCKS OF THE JANUARY 26, 2001, BHUJ EARTHQUAKE

Arthur Rodgers [1], Paul Bodin[2], Luca Malagnini[3], Kevin Mayeda[1], and Aybige Akinci[3]

Lawrence Livermore National Laboratory[1], University of Memphis[2], and
Istituto Nazionale di Geofisica e Vulcanologia[3]

Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract Nos. DE-FC52-03NA99512[2] and W-7405-ENG-48[1]

## ABSTRACT

The January 26, 2001, Bhuj, India, $M_W$ 7.6 earthquake was followed by an extensive aftershock sequence, including more than ten events with $M_W \geq 5.0$. Aftershocks were precisely located using available waveform data from temporary deployments and have been reported by Bodin and Horton (2004). As part of our previous research, we determined seismic moments and source spectra for nearly 900 events occurring during the aftershock deployment led by the University of Memphis and the United States Geological Survey (USGS). In the last year we have studied the attenuation of regional Lg phases from broadband waveforms for a small set of the largest aftershocks. The data were obtained from the Indian Meteorology Department (IMD), and the paths sample the subcontinent. Observed Lg spectra were modeled using the Magnitude Distance Amplitude Correction (MDAC) methodology of Walter and Taylor (2002). This method represents an observed regional phase Fourier amplitude spectrum in terms of a source and path correction. The theoretical source spectrum is based on the Brune (1970) model with modifications for non-constant stress-drop. The path effects include geometric spreading and attenuation for a frequency-dependent quality factor, $Q(f) = Q_0 f^g$, where f is frequency, $Q_0$ is the quality factor at 1 Hz, and g is the frequency exponent. For the available data we were able to compare theoretical source spectra, based on the estimated seismic moment and scaling parameters, with the estimated source spectra from local data, which is only slightly impacted by path propagation effects. Preliminary estimates of Lg attenuation indicate a frequency dependent quality factor model for the Indian sub-continent of $Q(f) = Q_0 f^{0.4}$, where $Q_0$ = 800-1000. The low attenuation for these paths is consistent with results from other stable continental regions. We will measure a complete set of amplitudes for all phases and estimate attenuation for the available paths.

## OBJECTIVES

Discrimination of small, possibly decoupled, seismic events depends critically on high-frequency (0.5–16 Hz) phase amplitudes at regional distances (200–2000 km). We have determined ground truth seismic moments and source parameters from local recordings of aftershocks of the January 26, 2001, Bhuj, India, earthquake. The objective of this study is to use these data to estimate regional phase attenuation models for the Indian subcontinent and test methodologies for calibrating seismic moments and regional phase amplitudes.

## RESEARCH ACCOMPLISHED

At last year's Seismic Research Symposium, we presented analysis of aftershocks of the January 26, 2001, Bhuj earthquake. These events, located in the state of Gujarat in western India, are shown in Figure 1. Using waveform data for aftershocks recorded by temporary deployments in the affected region, we reported locations, depths, focal mechanisms, seismic moments, and source spectra for a large event set spanning the time of our deployment (Bodin et al., 2004b). Our original plan was to use these ground truth source parameters to investigate the effect of source depth and focal mechanism on high-frequency regional phase amplitudes and discriminants. Unfortunately, there were no appropriate waveform data from openly available stations at regional distances (e.g., NIL, Nilore, Pakistan).

We were fortunate to obtain broadband three-component waveform data for 11 events from the nation-wide seismic network operated by the IMD. The IMD stations recorded broadband ground motions at 20 samples/second. These data include the mainshock and 10 aftershocks with $M_W \geq 5.0$. Unfortunately, we only have a source spectrum estimated from local data for one of the earthquakes. Several of these events were large enough to have centroid moment tensors (CMTs) from the Harvard CMT Project. Figure 2 shows the events, stations and paths for which we obtained IMD broadband waveforms.

Inspection of the high-frequency (0.5–8 Hz) regional waveforms showed that Lg propagates very strongly. Figure 3 shows a record section of the high-frequency vertical component data for one event.

We measured regional Lg Fourier amplitude spectra from the instrument corrected displacement waveforms, using a simple group velocity window (3.6–3.0 km/s) to isolate the phase. In order to quantitatively understand regional phase excitation and propagation in our study area, we model regional phase amplitude spectra with the MDAC (Taylor and Walter, 2002).

This methodology uses moment magnitudes, models of earthquake source spectra, geometric spreading, and attenuation to represent regional phase amplitude spectra. The MDAC equations represent an observed regional phase displacement spectrum, A(f), as a function of frequency, f, at distance, D, as a product of source, S(f), geometric spreading, G(D), apparent attenuation, q(D,f), site response, P(f), terms:

$$A(f) = S(f)\ G(D) q(D,f))\ P(f)\ . \qquad (1)$$

The source spectrum is based on the Brune (1970) model with modifications for non-constant stress-drop. The low-frequency level is directly proportional to the seismic moment. We use independent (and absolute) constraints on event size, from calibrated S-wave coda amplitude measurements (Mayeda et al., 2003; Bodin et al., 2004a, 2004b) or waveform modeling (e.g., Harvard CMT catalog). The source spectrum is then computed using a number of parameters, including the source and receiver elastic parameters and parameters controlling the scaling of corner frequency with moment. Geometric spreading is fixed to standard expressions. We typically use $D^{-1}$ for Pn and Sn and $D^{-1/2}$ for Pg and Lg. Apparent attenuation is represented as:

$$q(D,f) = \exp\left[ - D\ p\ f / [\ Q(f)\ U\ ]\ \right], \qquad (2)$$

where U is the velocity of the phase and attenuation is represented by the quality factor $Q(f) = Q_0\ f^g$ .

For the present application we wish to model Lg amplitude spectra. We begin by using the seismic moment and reasonable values for the elastic parameters and source corner frequency scaling to compute the source spectrum. We fix the geometric spreading to $D^{-1/2}$ Lg. We then compare the observed spectra to the predictions from a suite of attenuation models. Figure 4 shows the observed spectra for the $M_W$ 5.7 aftershock of January 28, 2001, and predictions from several attenuation models. The observed spectrum is best fit by a model with $Q_0$ = 800–1000 and g = 0.4. This is in close agreement with a recent estimate of $Q(f) = 800f^{0.42}$ by Singh et al. (2004) from the Indian shield. And our estimate is also consistent with low attenuation within other stable continental regions.

## CONCLUSIONS AND RECCOMMENDATIONS

The recently available broadband waveform data from the IMD allows us to estimate regional phase attenuation for paths crossing the Indian subcontinent. Preliminary estimates of Lg attenuation indicate a frequency dependent quality factor model of $Q(f) = Q_0f^{0.4}$, where $Q_0$ = 800–1000. Attenuation is low for these paths, consistent with stable continental regions. We will measure a complete set of amplitudes for all phases and estimate attenuation for the available paths.

## REFERENCES

Bodin, P. and S. Horton (2004). Source Parameters and Tectonic Implications of Aftershocks of the $M_W$ 7.6 Bhuj Earthquake of January 26, 2001, *Bull. Seism. Soc. Am.* 94: 818, 827.

Bodin, P., A. Akinci, L. Malagnini, K. Mayeda, and A. Rodgers (2004a), Seismic Sources and Wave Propagation in Western India, in *Proceedings of the 26th Seismic Research Review: Trends in Nuclear Explosion Monitoring*, LA-UR-04-5801, 1: pp. 221–226.

Bodin, P., L. Malagnini, and A. Akinci (2004b), Ground Motion Scaling in the Kachchh basin, India, Deduced from Aftershocks of the 2001 $M_W$ 7.6 Bhuj Earthquake, *Bull. Seism. Soc. Am.* 94: 1658–1669.

Brune, J. (1970), Tectonic Stress and the Spectra of Seismic Shear Waves from Earthquakes, *J. Geophys. Res.* 75: 4997–5009.

Mayeda, K., A. Hofstetter, J. O'Boyle, and W. Walter (2003), Stable and Transportable Regional Magnitudes Based on Coda-Derived Moment-Rate Spectra, *Bull. Seism. Soc. Am*. 93: 224–239.

Singh, S. K., D. García, 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.

Walter, W. and S. Taylor (2002), A Revised Magnitude Distance Amplitude Correction (MDAC2) Procedure for Regional Seismic Discriminants, Lawrence Livermore National Laboratory UCRL-ID-146882.

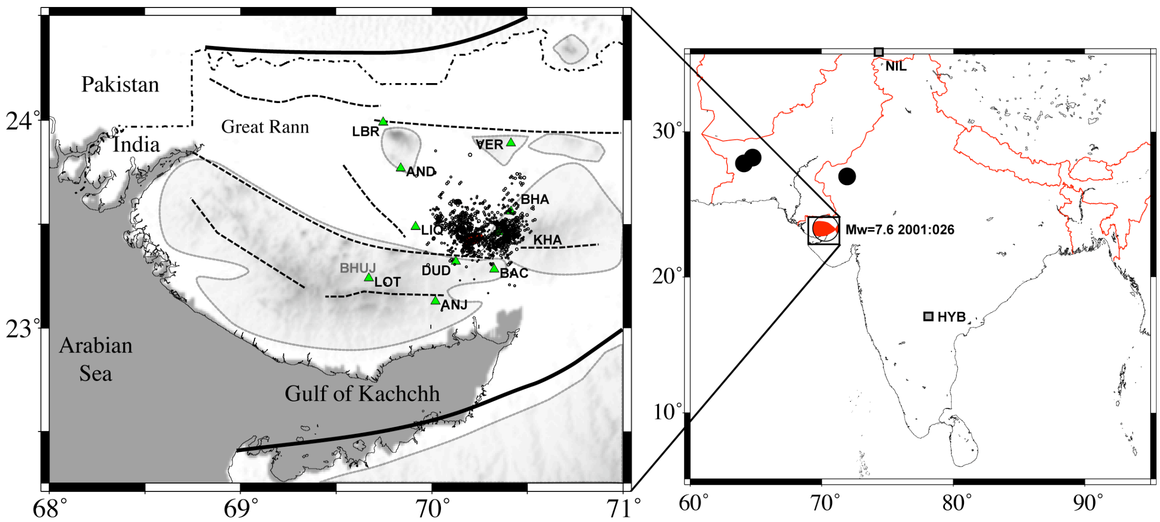


**Figure 1. Map showing the January 26, 2001, Bhuj, India earthquake and aftershocks. On the right side is the USGS fault plane solution for the main shock, ground station network (GSL) seismic station NIL, and Geoscope station HYB and known nuclear test sites in Pakistan and India (black dots). The left side shows epicenters (circles) of aftershocks and the University of Memphis temporary network stations (green triangles) that were used to locate them precisely. Also shown are the locations of faults (dashed lines and bold solid lines) and uplifts (enclosed shaded regions).**

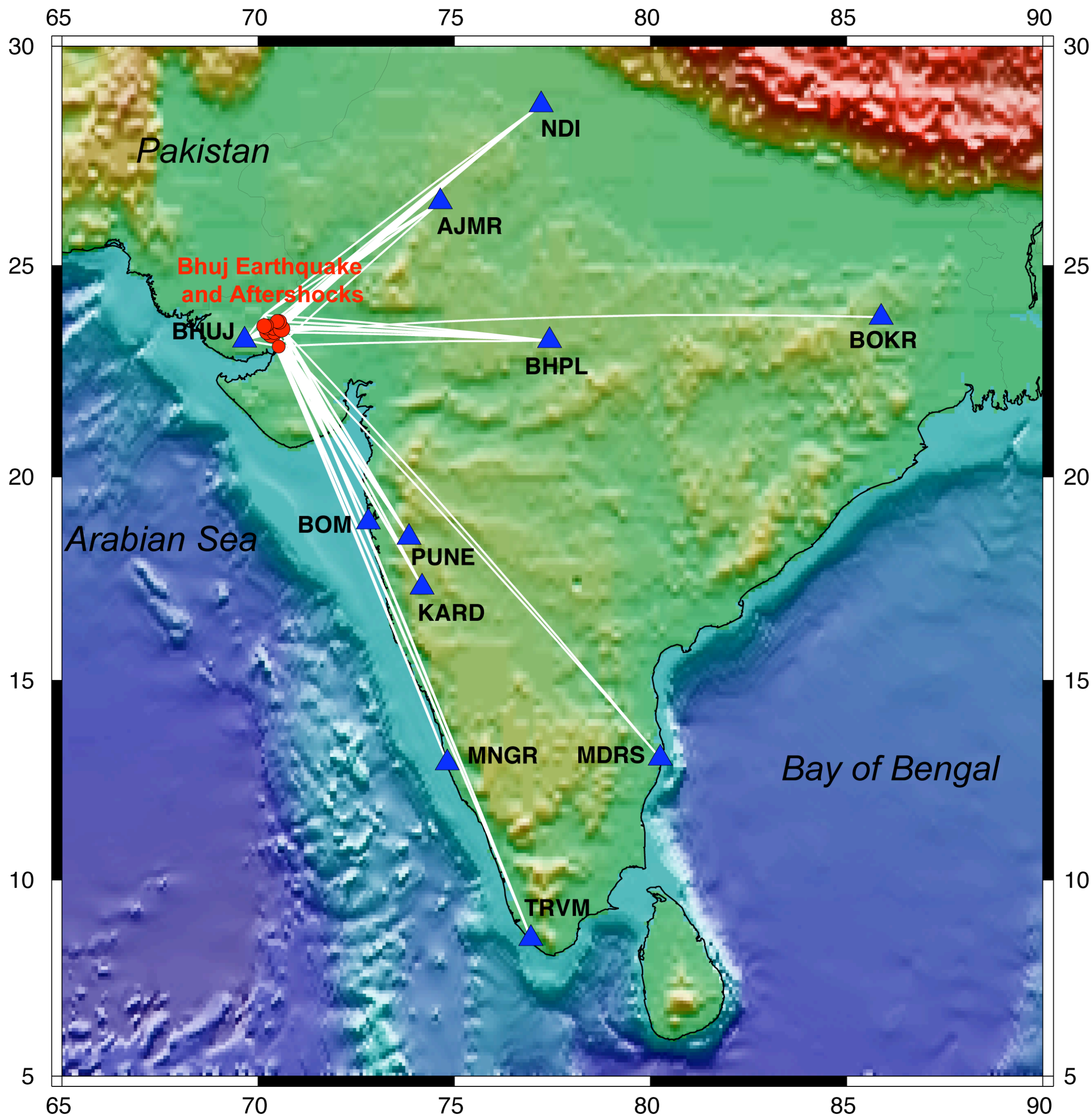


**Figure 2. Map showing the 11 events (red circles, size is proportional to magnitude) for which we have broadband IMD waveforms. IMD stations are indicated by triangles and are labeled.**

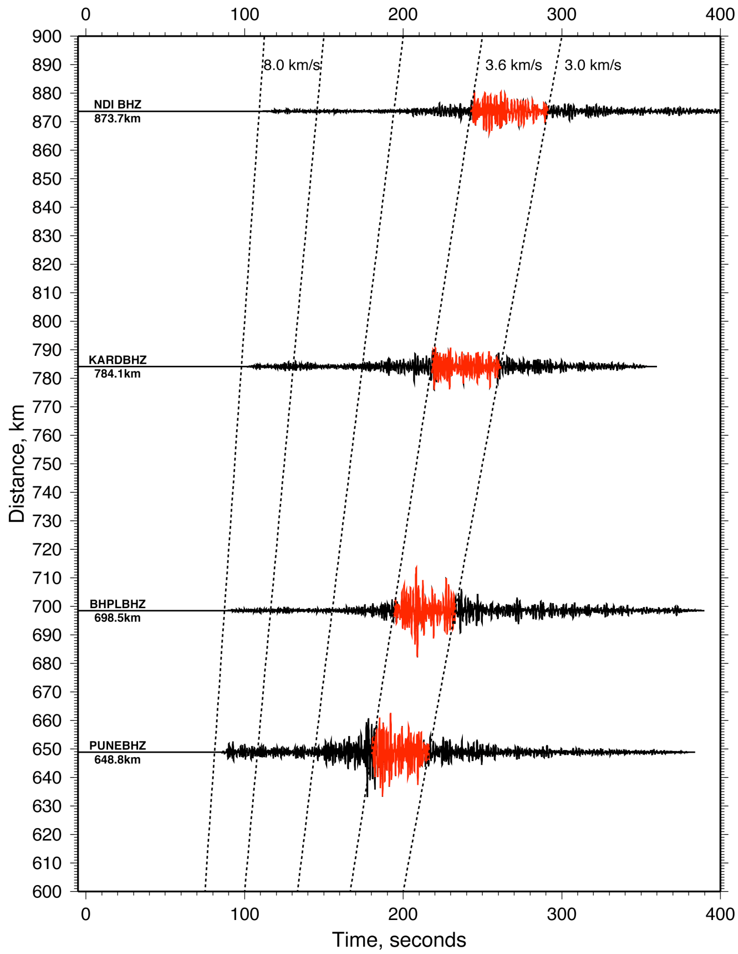


**Figure 3. Record section of vertical component waveforms observed at the IMD stations. The Lg window (group velocities 3.6–3.0 km/s) is indicated by the red portion of the waveforms.**

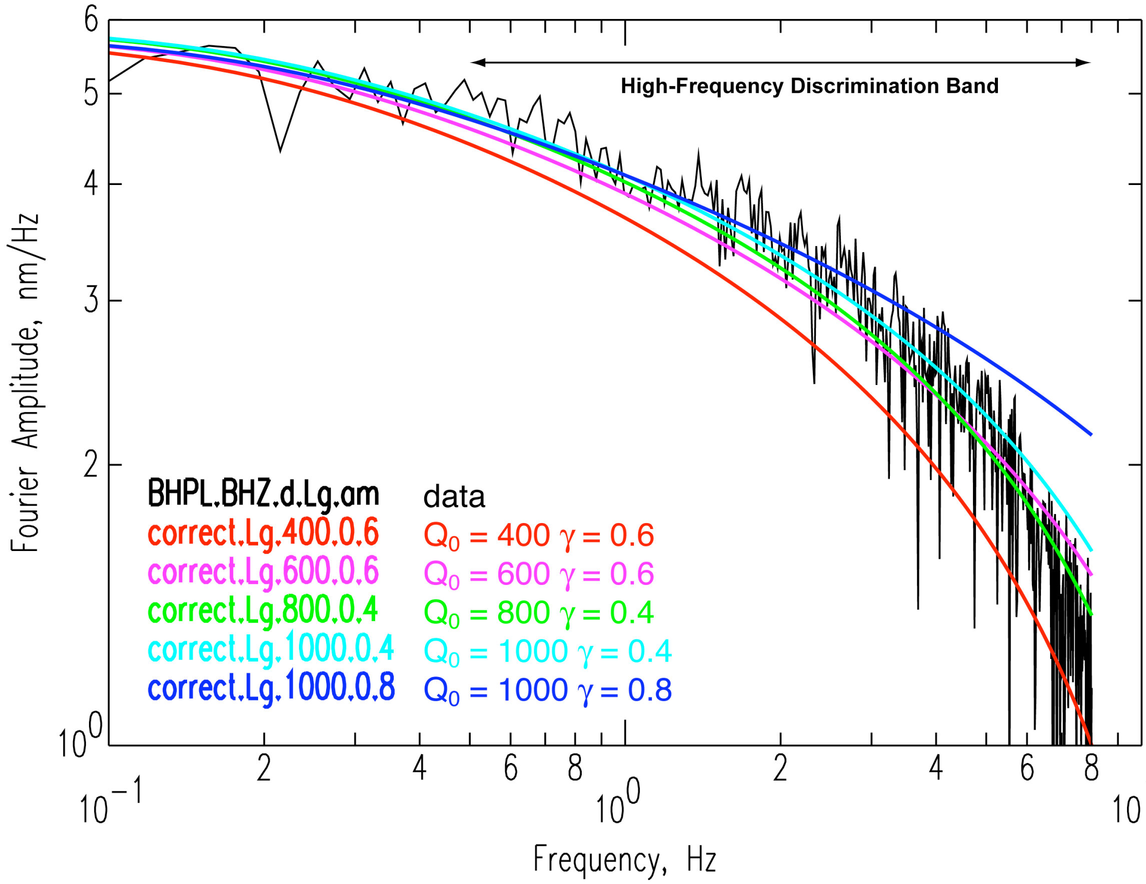


**Figure 4. Observed Lg spectrum (black) and predictions of several attenuation models (colors). The observed spectrum is for the vertical component of station BHPL for the January 28, 2001, $M_W$ 5.7 aftershock. Note that the observed spectrum is best fit in the discrimination band (0.5–8 Hz) with high quality factors of $Q_0$ = 800–1000 and g = 0.4.**