

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

### SEISMIC SOURCES AND WAVE PROPAGATION IN WESTERN INDIA

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#### **ABSTRACT**

We recorded more than 2500 aftershocks of the 2001 Mw7.6 Bhuj, India, earthquake on a network of 9 portable seismographs. We are augmenting this dataset with waveforms acquired by other temporary networks operated by other investigators, and that covers different times, propagation paths, and distance ranges than our data. Taken together, these data form excellent ground truth calibrations for regional and teleseismic determinations of locations and source amplitudes for seismic sources in the western India region. The uniqueness of these data derive from the fact that the region is relatively aseismic and that it has historically been difficult to obtain ground motion recordings from the earthquakes that do occur there. The Bhuj aftershock data would permit the testing of the effect of varying focal mechanisms, source depths, and magnitudes on commonly used teleseismic and regional seismic discriminants. The events (with magnitudes between ~2 and ~5.5) are being carefully relocated as precisely as possible. Using the re-located aftershock catalog derived from the local network(s), we are extracting waveforms for stations at region and upper mantle distances. Using methods developed at Lawrence Livermore National Laboratory (LLNL) these data are being analyzed to calibrate highly accurate coda moment magnitudes. We are measuring frequency dependent phase amplitudes to study the effect of depth and focal mechanism on P/S discriminants. Regional detection threshold curves will be computed for the regional phases in this region. Our preliminary results indicate that we will be able to provide several solid waveform-constrained focal-mechanisms, depths and moments. We have also constrained local frequency-dependent attenuation properties based on a subset of the dataset.

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### OBJECTIVE(S)

Our study of aftershocks of the Bhuj, India, earthquake of 26 January 2001 has several objectives, with the overall goals of improving our ability to locate and characterize seismic sources and to improve our understanding of wave propagation in western India. The first objective is to incorporate aftershock data that we have taken ourselves with that from colleagues at other institutions, and to use this combined dataset to improve our location quality. We also wish to calculate coda-derived seismic source spectra and include waveform modeling of the largest aftershocks. With these stable moment-rate spectra we further plan to achieve an absolutely calibrated dataset, from source, through attenuation/spreading to the near-site effects. Our final objective is to estimate regional structure/propagation from surface wave dispersion and waveform model regional broadband data.

### RESEARCH ACCOMPLISHED

Bodin and Horton (2004) located about 1200 events using a subset of the data we are assembling. Figure 1 shows the highest-quality locations (887 events), based on data from 8 University of Memphis temporarily-deployed (12-27 Feb., 2001) seismographs. The events shown on the figure all have rms values of 0.02 s or less. To date we have combined the University of Memphis data with recordings from the National Geophysical Research Institute (NGRI) in Hyderabad, India. We have used these combined data to relocate with the improved station coverage the 1200 earthquakes.

We have also used the ~800 events located well by the University of Memphis network to constrain the frequency-dependent attenuation in the region, and to model the scalar seismic moments of earthquakes in our dataset. Figure 2 illustrates our methods—showing the decay of peak amplitudes with distance for data in narrow passbands around a set of center frequencies. (Bodin et al., in press, 2004). Because the earthquakes that yielded the observations span a wide range of depths (from 5-35 km), we divided the data into 2 overlapping subsets, Shallow ( $H < 25$  km) and Deep ( $H > 20$  km). We interpreted the spatial decay of amplitudes observed in Figure 1 in terms of a frequency dependent attenuation operator,  $Q(f)$ , and a distance dependent spreading term ( $g(r)$ ), and assigned site amplification factors relative to an average of the stations. The results are summarized as.

Deep:

$$Q(f) = 790 \left( \frac{f}{f_{ref}} \right)^{0.22} ; \quad f_{ref} = 1.0 \text{ Hz} \quad (1)$$

$$g(r) = \begin{cases} r^{-1}; r \leq 40 \text{ km} \\ r^{-0.3}; 40 \leq r \leq 50 \text{ km} \\ r^{-0.9}; 50 \leq r \leq 60 \text{ km} \\ r^{-0.4}; 60 \leq r \leq 80 \text{ km} \\ r^{-0.55}; r \geq 80 \text{ km} \end{cases} \quad (2)$$

Shallow:

$$Q(f) = 790 \left( \frac{f}{f_{ref}} \right)^{0.35} ; \quad f_{ref} = 1.0 \text{ Hz} \quad (3)$$

$$g(r) = \begin{cases} r^{-1}; r \leq 40 \text{ km} \\ r^{-0.5}; 40 \leq r \leq 50 \text{ km} \\ r^{-1.0}; 50 \leq r \leq 60 \text{ km} \\ r^{-0.5}; 60 \leq r \leq 80 \text{ km} \\ r^{-0.55}; r \geq 80 \text{ km} \end{cases} \quad (4)$$

We are starting to perform a similar analysis on the dataset that includes the “new” NGRI sites, and on the additional earthquakes the combined dataset permits.

We have made a catalog of larger events ( $M \sim 4+$ ), which may have been recorded both locally and at regional and/or teleseismic distances. Our combined dataset extends the time for which we have useful local data (both earlier in

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time, to 7 Feb, 2001, and later in time, to 6 March), and thus represents a significant increase in earthquakes that might have been detected more remotely.

We have initiated waveform modeling to obtain well-constrained moment tensors for the largest events in our catalog. To date we have used only the University of Memphis data. We have applied both surface wave techniques (Herrmann), and a full-waveform technique (e.g. Zhao and Helmberger, 1994). An example of the surface waveform modeling is shown in Figure 3 and Figure 4. Waveform modeling revealed the earthquake to have been Mw 4.6, at a focal depth of 6 km. Figure 5 shows an example of a full waveform technique. Our preliminary work reveals that our earth model needs to be improved, and that additional constraints provided by the increased station density we will achieve from NGRI data will strengthen our results.

### **CONCLUSIONS AND RECOMMENDATIONS**

This study is still in its early stages. We are progressing on all objectives. Our work to date has demonstrated the capability of the data to provide very well determined locations for many events. The number of events recorded both locally and remotely remains unknown, but with the inclusion of the data from other sources, should be increased significantly from our earlier estimates. The moment tensors we derive from waveform modeling will “tie down” the proposed stable coda-derived moment-rate spectra, to facilitate comparison with global data.

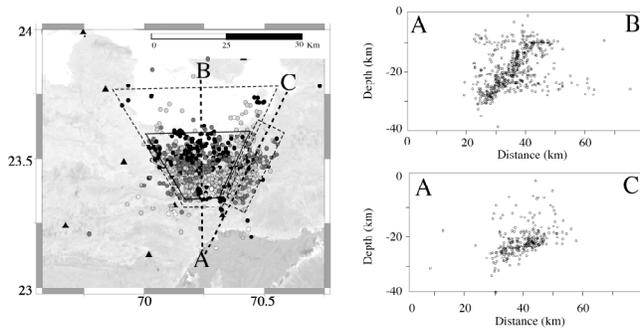
### **ACKNOWLEDGEMENTS**

We thank Bob Herrmann and Lupei Zhu, respectively, for help with the surface wave and full-waveform source inversions.

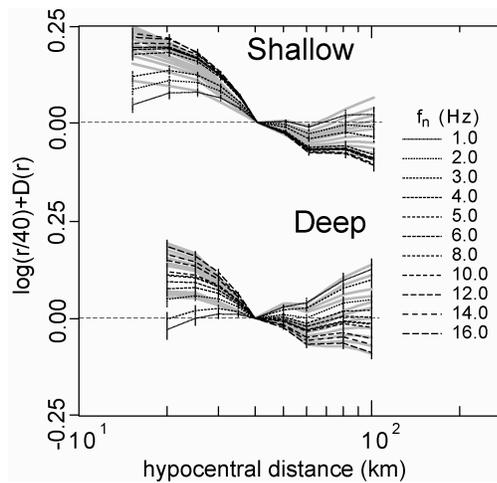
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**Figure 1. Bhuj aftershock locations.** On the map at the left we plot 887 aftershock epicenters over a satellite image. These locations represent events with depth errors less than  $\pm 3$  km, horizontal uncertainties less than  $\pm 2$  km. Mean RMS travel-time uncertainty for these data is 0.0036 s., and the greatest RMS uncertainty is .01 s. Epicenters are shaded by depth, with white =  $>30$  km, light grey = 20 to 30 km, dark grey = 10 to 20 km, and black =  $< 10$  km. Small black triangles are seismograph sites. Dashed quadrilaterals show spatial regions for events shown in cross-sections at right. Solid trapezoid is surface projection of rupture model discussed in text.



**Figure 2. Decay of peak amplitudes of ground motion as a function of distance and frequency for the Bhuj aftershock data.** Each dashed curve is the average peak amplitude, referred to the average peak amplitude of signals at 40 km, within a narrow passband with each dash pattern representing a particular central frequency, as shown on the right. Error bars are two standard deviations. Uncertainties for periods greater than 1 Hz were large, and these frequencies were not used in the modeling. The curves are plotted such that a horizontal line represents a spatial decay of  $r^{-1}$ , which is expected for body waves in a homogeneous crust. Equations (9-12) lead to models of the observed decay curves shown as family of grey curves underlying the brightly dashed curves..

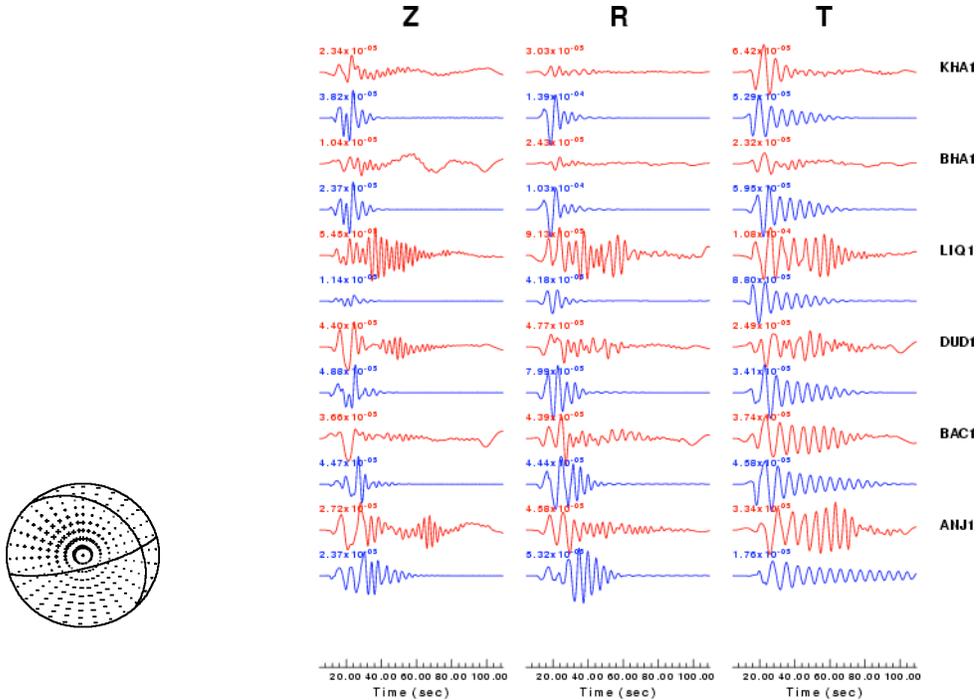


Figure 3. The focal mechanism shown at the left was produced by modeling surface waveforms. The waveform data (red) and synthetics (blue) are shown at the right.

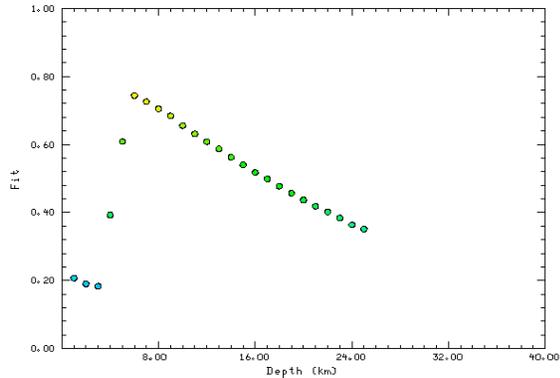
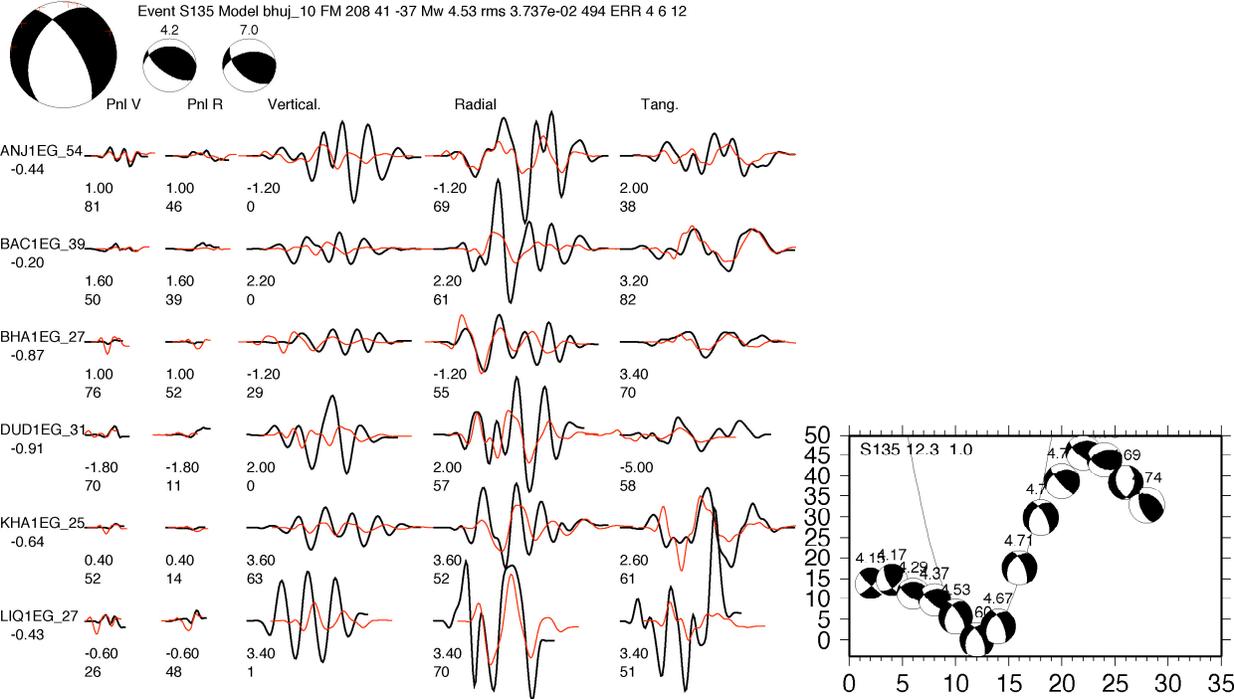


Figure 4. Depth sensitivity of the focal mechanism solution quality, for the event shown in Figure 3.

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**Figure 5. Preliminary modeling results for the earthquake of 2001:050:08:23. At right is depth sensitivity and variability of the focal mechanism. Station LIQ1, for example, exhibits clear site effects in the tangential component from many earthquakes, but have not yet been accounted for.**