

## COMPLETE REGIONAL WAVEFORM MODELING TO ESTIMATE SEISMIC VELOCITY STRUCTURE AND SOURCE PARAMETERS FOR CTBT MONITORING

Arthur J. Rodgers, William R. Walter and Todd M. Bredbeck  
Lawrence Livermore National Laboratory, Geophysics and Global Security Division  
Livermore, CA 94551 USA

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### **ABSTRACT**

Intermediate-period (10-100 s) regional seismic data contain information about the seismic source as well as the velocity structure along the propagation path. Using independently well constrained source parameters we determine averaged one-dimensional velocity models by matching reflectivity generated synthetic seismograms to the observed data. Once the velocity structure along the path is well known, then one can determine the nature of the source for new events (e.g. earthquake, explosion or collapse) as well as accurate estimates of event size and depth. We are modeling regional waveforms to infer velocity structure and source parameters in the Middle East and North Africa.

Complete regional waveforms (body and surface wave amplitudes and phase) are sensitive to the seismic P and S wave velocities in the crust and uppermost mantle. However, there are tradeoffs when using waveform matches to determine both the velocity structure and the depth and focal mechanism of earthquakes, especially when using data from a sparse network in a tectonically complex region. We make use of large ( $m_b > 5.5$ ) events with well-constrained mechanisms (e.g. when Harvard CMT and USGS NEIC are available and agree) and well-constrained depths (e.g. depth phases modeled teleseismically) to fix the source and determine the structure. Waveforms are fit using a grid search method where synthetic seismograms for many velocity models are computed and compared to the data. To limit the range of the grid search and speed up the process we often make use of an initial model evaluation by roughly matching the observed Love and Rayleigh wave group velocity dispersion. This narrows the number of models that then need to be compared against the complete waveforms. The resulting velocity models reveal the great geologic and tectonic complexity of our study region. Ideally we model paths that are completely contained within a single tectonic province. We have found this technique is particularly useful for estimating structure in large aseismic, sparsely instrumented regions where structural information is limited, such as North Africa, Arabia and India. We show waveform fits and associated velocity models from each of these regions.

Once velocity structures are determined, we then estimate the source parameters of events with unknown or poorly constrained mechanisms and depths. We sometimes find that smaller Harvard CMT events require significant changes in depth and/or mechanisms to match the regional waveforms. Events of particular CTBT interest are the smaller earthquakes ( $M_w < 4.5$ ), and explosion and collapse events. An excellent example of the utility of this research is the May 11, 1998 Indian nuclear test. At the regional distance station NIL (Nilore, Pakistan) this nuclear explosion showed a strong Love wave and reversed Rayleigh waves. These observations indicate that there was a strong tectonic release associated with the explosion. We modeled the observed waveforms by adding contributions from both explosion and double-couple sources. Other examples of estimated source parameters and potential pitfalls of these methods are shown.

**Key Words:** Regional seismic data, seismic velocity models, earthquake parameters

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**OBJECTIVE**

Regional waveform modeling fulfills several needs of Comprehensive Nuclear-Test-Ban Treaty monitoring. On a fundamental level, waveform modeling helps us characterize tectonic regions by their seismic velocity and attenuation structure. This information guides regionalization by providing estimates of lithospheric structure such as sediment and crustal thickness. Once velocity models are determined for a given region, waveform modeling is used to estimate seismic moments, focal mechanisms and depths of earthquakes. Seismic moments are used to calibrate the robust *Lgcoda* magnitude scale (Mayeda and Walter, 1996; Mayeda et al., *this volume*). These magnitudes can be estimated from a single regional broadband seismogram. Accurate measurements of event size are crucial for seismic discrimination, particularly small events. Lastly, waveform modeling can be used to characterize the seismic source as an earthquake, explosion or collapse. We modeled regional waveforms to estimate the velocity structure of the crust and upper mantle and the moments, focal depths and mechanisms of earthquakes in the Middle East, Africa and south Asia. Using estimated velocity structures we modeled the tectonic release of the May 11, 1998 Indian nuclear explosion.

**RESEARCH ACCOMPLISHED**

We worked on several waveform modeling projects during the previous year. These projects are divided into two parts: waveform modeling for earth structure and waveform modeling for source parameters. The following sections describe these efforts.

*Structure of the Arabian Peninsula*

We estimated seismic velocity structure of the lithosphere (crust and uppermost mantle) from waveform data recorded by the 1995-1997 Saudi Arabian Broadband Deployment (Vernon and Berger, 1998). Whereas the interior of the Arabian Plate is aseismic, the lithosphere of this region can be sampled by earthquakes along the plate boundaries recorded at stations within the interior. Results of waveform analysis for Arabia are presented in Rodgers et al. (1999) and are briefly summarized here.

The temporary stations recorded two moderately large earthquakes (events 95327 and 96145 in Figure 1). The paths for these events provide excellent sampling of the Arabian shield and the Arabian platform. Analysis of the group velocity dispersion reveals significant differences between the structure of these two regions (Figure 2). The group velocities for the shield paths are approximately 10% faster than those for the platform. We modeled the Love and Rayleigh wave group velocities for each path with a grid search scheme. The objective of this procedure is to estimate a suite of velocity models that fit the group velocities and use these models as starting models for waveform modeling. Surface wave group velocities provide constraints on average lithospheric velocities, but suffer from severe trade-offs between layer thicknesses and velocities. Observed waveforms contain surface wave group and phase velocity information as well as body and surface wave amplitude information.

The instrument corrected displacement seismograms were fit using a grid search scheme similar to previous studies (Rodgers and Schwartz, 1998). For this case we used the group velocity modeling results as starting models. Using the United States Geological Survey-Preliminary Determination of Epicenters (USGS-PDE) locations and origin times and the Harvard CMT focal mechanisms we computed reflectivity synthetic seismograms (Randall, 1994). The fits to the observed waveforms and the velocity models are shown in Figure 3. In Figure 2 we show that the group velocities are well fit by the models which we inferred from waveform modeling.

*Structure of the Northern Arabian Platform*

We estimated velocity structure of the Northern Arabian platform using waveforms recorded in Jordan. Two temporary stations deployed in Jordan by LLNL in conjunction with the Jordanian Natural Resources Authority and the USGS. Figure 1 shows the location of the stations and two earthquakes analyzed with these data (events 98277 and 98264). Using methods similar to those described above we estimated the velocity structure of the lithosphere. Because the temporary stations are band-limited instruments

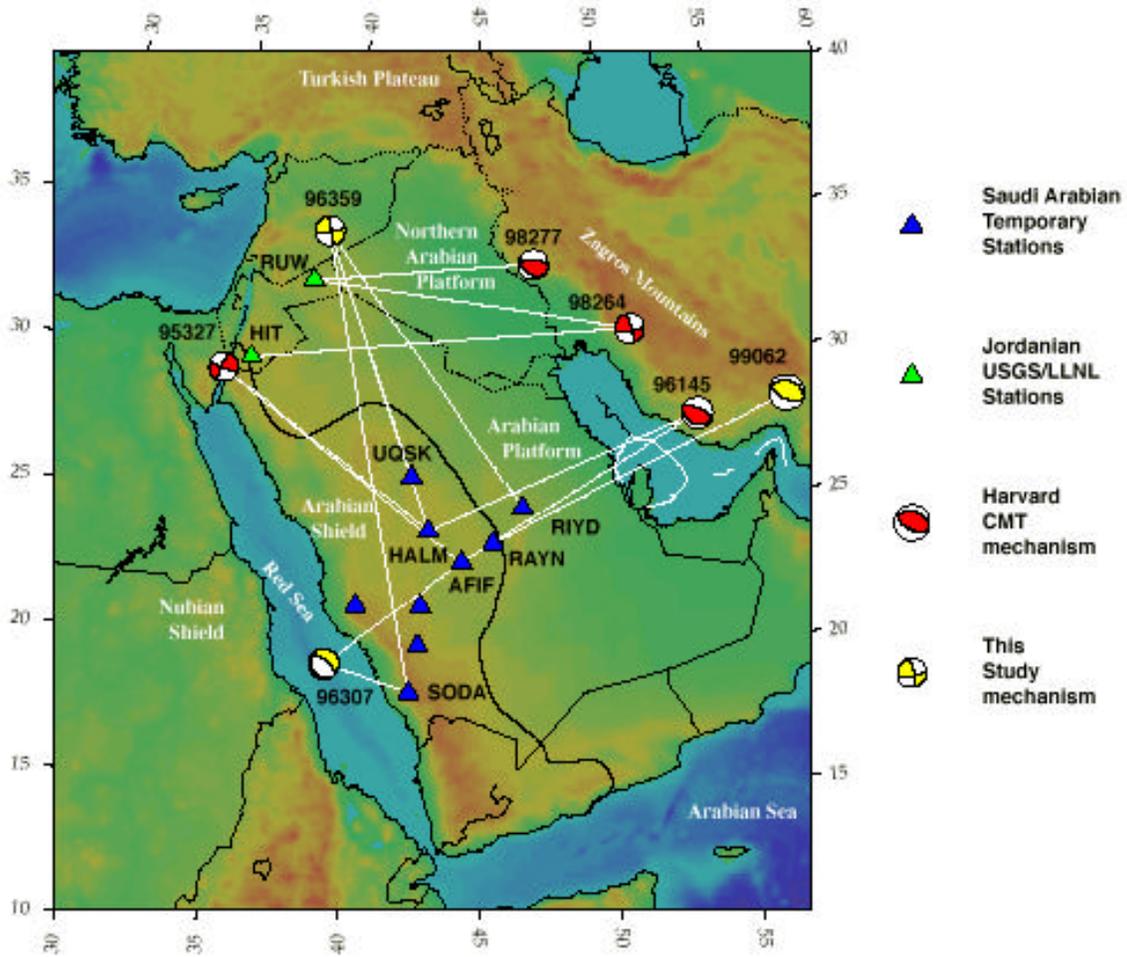


Figure 1. Map of the Arabian Peninsula, events, stations and paths analyzed.

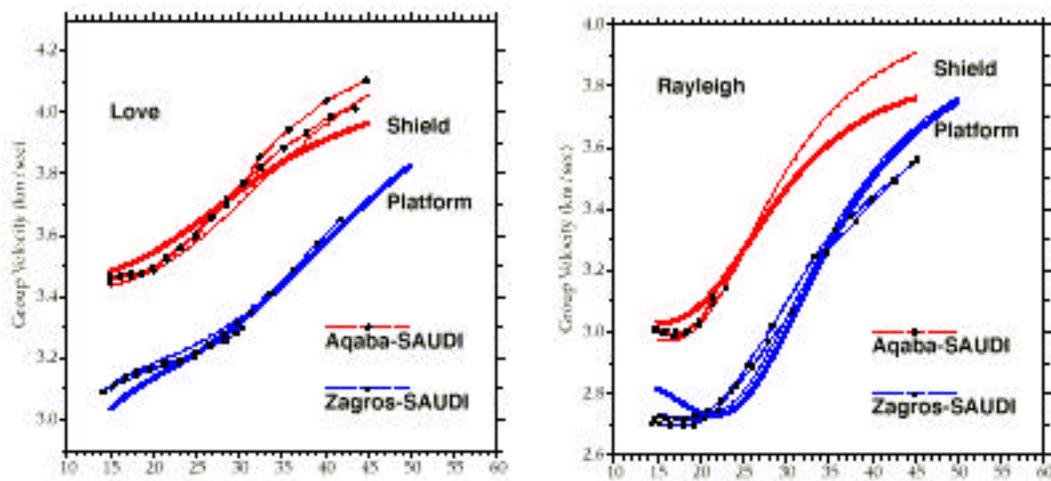
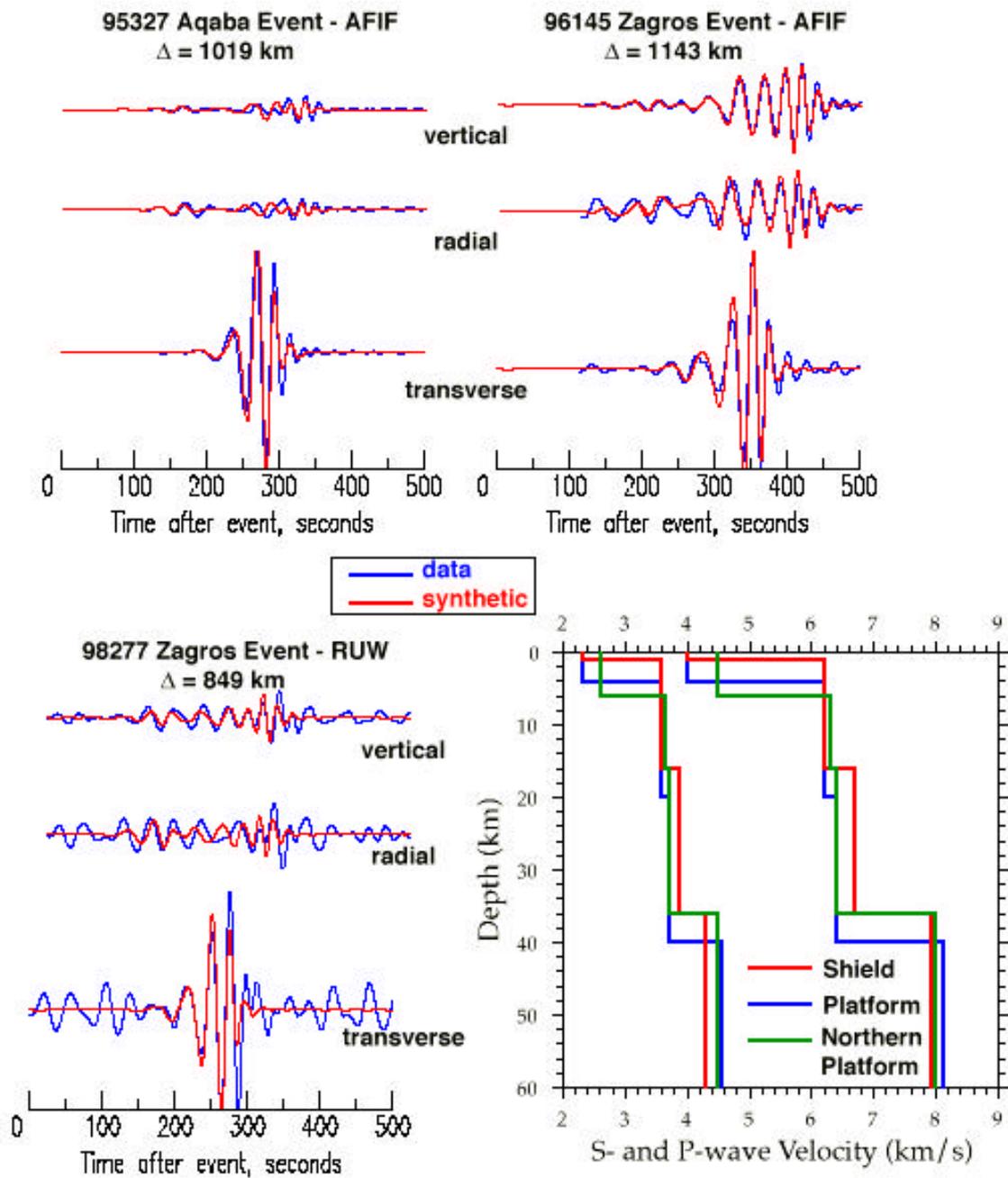


Figure 2. Group velocity dispersion for the 95327 and 96145 events as measured at stations AFIF and HALM. The dispersion curves for the velocity models that best fit the observed dispersion are shown as the light lines. The dispersion curves for the velocity models that best fit the observed waveforms (perferred model) are shown as the heavy lines.



**Figure 3.** Fits of the synthetic sesimograms for the preferred models to the observed waveforms for the Arabian shield (top left), the Arabian platform (top right) and the Northern Arabian platform (bottom left). Velocity models for the Arabian Peninsula are also shown (bottom right).

(Guralp CGM-3) we could not model periods greater than about 40 seconds. This resulted in limited resolution of the mantle by the surface waves, however the upper parts of the model are well determined. The resulting waveform fits and velocity models are shown in Figure 3. Notice that the model is similar to the Arabian platform model, except that the sediment layer is slightly thicker and the crust is thinner. This is consistent with the Cornell University crustal and sediment thickness models for the region (Seber et al., 1996).

#### *Source Parameters for the November 2, 1996 Red Sea Earthquake*

Effective seismic monitoring and discrimination requires accurate estimates of event magnitude. A magnitude scale tied to seismic moment is most useful because it does not saturate at large magnitudes. We estimated seismic moment, focal mechanism and depth for earthquakes in the Middle East by modeling intermediate-period (10-100 s) waveforms. When modeling focal parameters it is essential that the velocity model be well known because of trade-offs between the model and the inferred source parameters.

Using the velocity models obtained for the Arabian shield and platform, we estimated source parameters for the Red Sea (event 96307) and the Zagros (event 99062) earthquakes. Source parameters (seismic moment, depth, strike, dip and rake) were estimated by a grid search algorithm (Walter, 1993). These large events were globally observed and moment tensors were reported by the Harvard CMT project. We found excellent agreement between our regional waveform modeling estimates of source parameters and the Harvard CMT estimates. Figure 4 shows the waveform modeling results for the November 2, 1996 Red Sea event (96307).

We estimated source parameters for a number of events in the Middle East, north and central Africa and south Asia. Some of these focal mechanisms are shown in Figure 1. As we estimate and refine velocity for these regions we will infer seismic moments, focal depths and mechanisms. These results will be used to calibrate the *Lgcoda* magnitude scale (Mayeda et al., *this volume*) and advance efforts to regionalize our study areas.

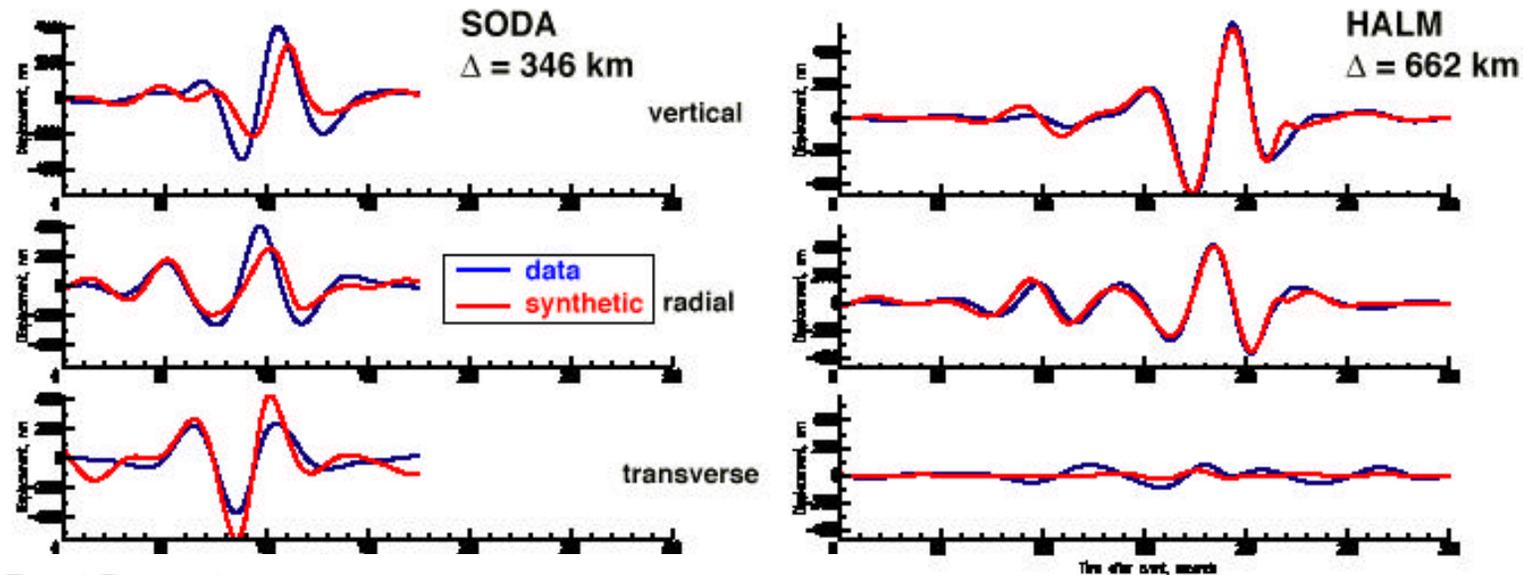
#### *Structure of the Indian Platform*

For waveform analysis of the May 11, 1998 Indian nuclear test it was necessary to estimate velocity structures for the region. Figure 5a shows the events, stations and paths analyzed in this region. We began by modeling the May 21, 1997 earthquake. This event has source parameters (moment, depth and focal mechanism) reported in both the Harvard-CMT and USGS-NEIC catalogs. The lower crustal depth is well constrained by depth phases. Because the source parameters agree and fit the long-period filtered data, we feel confident that the source is well modeled. By fixing the source parameters and adjusting the velocity model, we obtained good fits to the observed three-component seismograms (Figure 5b). The inferred velocity structures (Figure 5d) reveal some heterogeneity in the lithospheric structure of the Indian sub-continent. The mantle velocity gradient may not be resolved by the intermediate-period regional data.

#### *Source Parameters for the April 1, 1996 Pakistan Earthquake*

A moderately large earthquake occurred in the Thar Desert on April 1, 1996. This event was located by the USGS-PDE at a depth of 43 km. The Harvard CMT catalog reports this event at a depth of 92 km. We used the regional recordings of this event at stations NIL and HYB to estimate the source parameters. The velocity models used for this analysis were slightly modified from those shown in Figure 5d. Synthetics for the CMT solution at station NIL do not fit the data at relatively long-periods (Figure 5c). We solved for the source parameters using the shallower USGS-PDE depth of 43 km and recordings at both NIL and HYB. Our mechanism shows a much improved fit over the CMT solution.

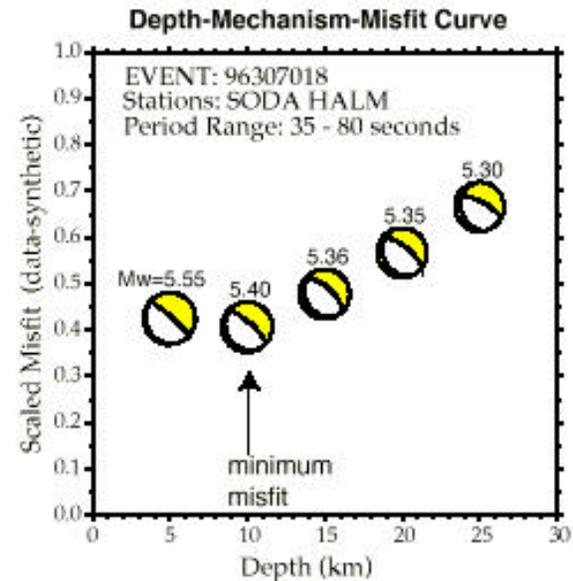
This event demonstrates that source parameters routinely estimated from long-period teleseismic waveform modeling may be in error. Errors in estimated source parameters are probably larger for smaller events because of poor signal-to-noise. Also errors may be larger in regions of heterogeneous or anomalous crustal structure, such as the Alpine-Himalayan Front. This event illustrates the importance of considering both the source and the velocity structure when trying to extract information from intermediate period waveforms.

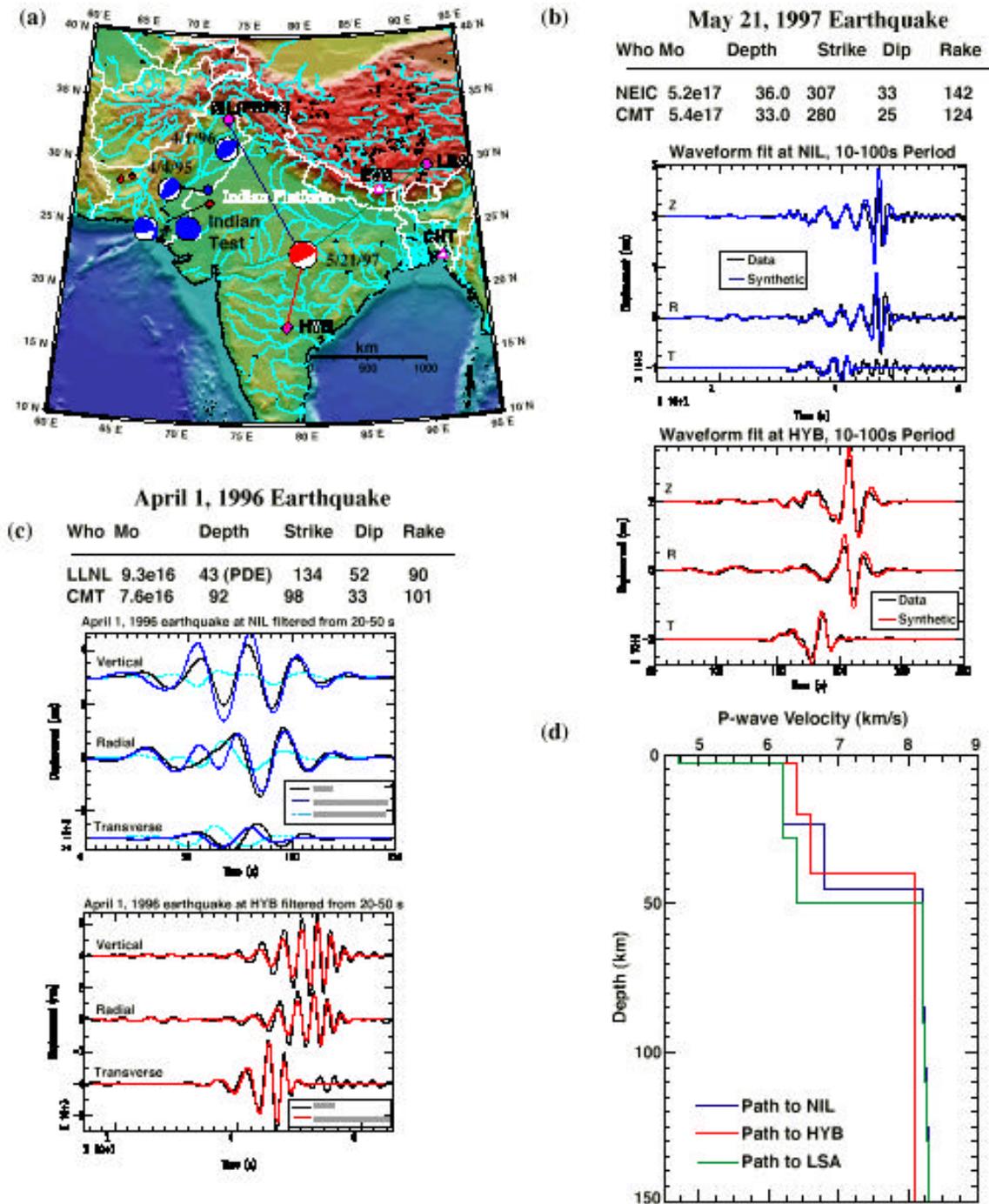


**Event Parameters**

strike (deg)	dip (deg)	rake (deg)	depth (km)	moment (dyne-cm)	Mw
150	16	-72	10	1.41e24	5.4 (LLNL solution)
153	20	-68	15	0.99e24	5.3 (Harvard CMT)

**Figure 4.** Waveform modeling to estimate earthquake moment, depth and best double-couple focal mechanism for the Red Sea event (96307). (top) Waveform fits to stations SODA and HALM. (right) Depth-mechanism-misfit curve showing the best-fitting depth is 10 km. Our estimated source parameters agree excellently with those reported by the Harvard CMT project. Synthetics were computed using our Arabian shield model (Figure 3) and filtered in the long-period band 35-80 seconds. The misfit of the Rayleigh wave at station SODA probably arises because this path is mostly oceanic while the velocity model is representative of the continental portion of the path.





**Figure 6.** (a) Fits to the April 4, 1995 earthquake at station NIL. The focal mechanism for this event is plotted on Figure 5a. (b) Intermediate-period (10-20 s) three-component waveforms for the May 11, 1998 Indian nuclear test at NIL. Note the strong Love that is not expected from an explosion source. (c) Vertical component Rayleigh wave of the Indian test and a synthetic seismogram for an explosion source. Notice that the synthetic Rayleigh wave (red) has the opposite polarity of the data. (d) Waveform modeling of tectonic release of the Indian nuclear test. The focal mechanism of the tectonic is plotted in Figure 5a.

Magnitude-Distance Amplitude Correction (MDAC; Taylor et al., 1999) to regional body-wave amplitudes for discrimination and calibrating the coda-based magnitude scales.

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