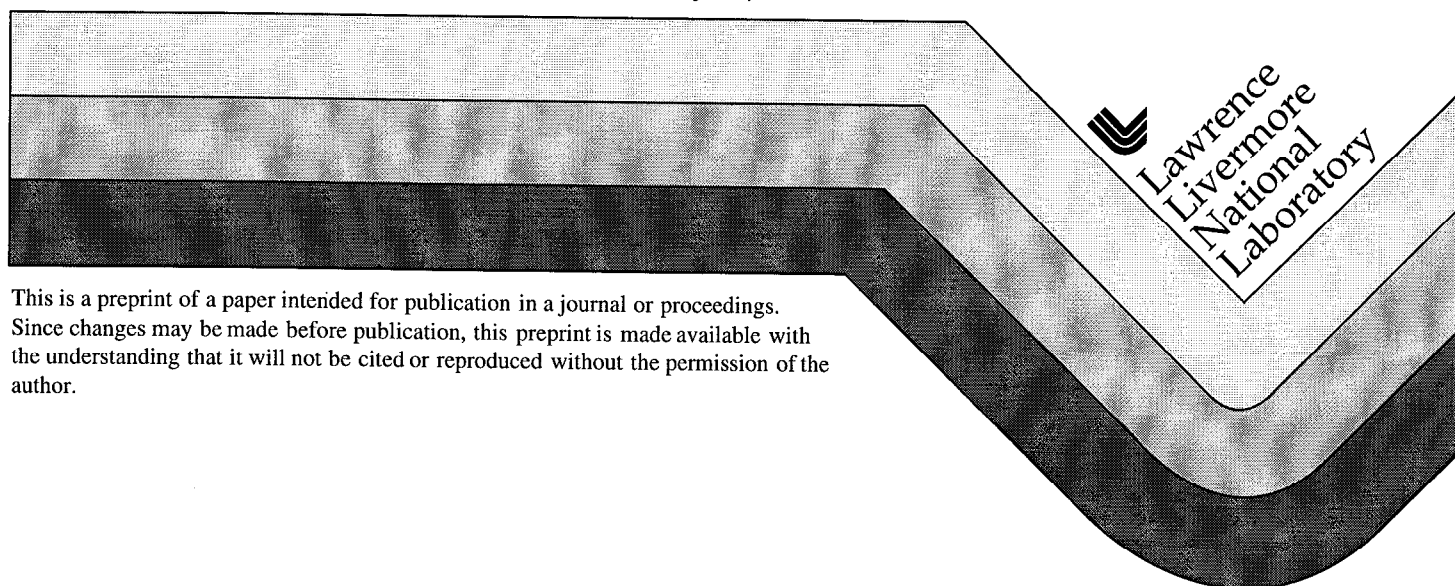# Complete Regional Waveform Modeling to Estimate Seismic Velocity Structure and Source Parameters for CTBT Monitoring

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DISCLAIMER

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

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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 (mb>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.

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 (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 by 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.

The April 4, 1995 Thar Desert Earthquake near the Indian Test

The April 4, 1995 earthquake is about 100 km north of the Indian nuclear test. We modeled the source parameters and the velocity structure for this earthquake. The depth was constrained to the ISC P-pP depth of 15 km. Short-period synthetic seismograms confirmed this depth. We estimated an initial mechanism using the velocity models for the May 21, 1997 event to NIL and HYB. Using a bootstrap technique we iteratively modified the velocity model and focal mechanism to achieve the best-fit.

The focal mechanism is shown in Figure 5a and the waveform fit is shown in Figure 6a. The reverse mechanism of this event is consistent with the mechanism of the April 1, 1996 earthquake (Figure 5a). Because we are able to model this event reasonably well, we can use the inferred velocity structure to model the source parameters of the May 11, 1998 Indian nuclear test.

Tectonic Release of the May 11, 1998 Indian Nuclear Test

The Indian Nuclear Test of May 11, 1998 was observed at regional distances by station NIL (740 km, Figure 5a). Short-period discriminants clearly identify this event as an explosion (Rodgers and Walter, 1999). However at intermediate periods (10-50 seconds) the NIL recordings of this event show evidence of tectonic release. The rotated three-component waveforms show a strong Love wave (Figure 6b). For a plane-layered earth model in the far-field explosions should not generate any energy on the transverse component. Furthermore, the Rayleigh wave for this event is reversed when compared to a synthetic seismogram for an explosion source (Figure 6c).

Although there is some uncertainty in the location, depth and origin time of this event and the velocity structures used to model the waveforms, the data at station NIL suggest that there is a tectonic release. Unfortunately, we have had difficulty modeling the waveforms at other stations. Station AAK (Ala Arch, Kyrgyzstan) is along the same azimuth as NIL and does not provide more information about the source. Station LSA (Lhasa, Tibet, PRC) recorded this event, but the path crosses the Himalaya Mountains obliquely and samples severe crustal thickness variations. Thus it is difficult to represent the path with a one-dimensional model.

We estimated the tectonic release using the NIL data by modeling the waveforms. We assumed an isotropic moment from the body-wave magnitude, mb, and fit the remainder of the waveform with a double couple mechanism. This procedure results in a reasonably good fit to the intermediate period waveforms and an estimate of the tectonic release (Figure 6d). A mechanism of tectonic release consistent with the regional stress appears to fit the data.

CONCLUSIONS AND RECOMMENDATIONS

The velocity structures and source parameters estimated by waveform modeling provide valuable information for CTBT monitoring. The inferred crustal and uppermost mantle structures advance understanding of tectonics and guides regionalization for event location and identification efforts. Estimation of source parameters such as seismic moment, depth and mechanism (whether earthquake, explosion or collapse) is crucial to event identification.

In this paper we briefly outline some of the waveform modeling research for CTBT monitoring performed in the last year. In the future we will estimate structure for new regions by modeling waveforms of large well-observed events along additional paths. Of particular interest will be the estimation of velocity structure in aseismic regions such as most of Africa and the Former Soviet Union. Our previous work on aseismic regions in the Middle East, north Africa and south Asia give us confidence to proceed with our current methods. Using the inferred velocity models we plan to estimate source parameters for smaller events. It is especially important to obtain seismic moments of earthquakes for use in applying the

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

ACKNOWLEDGEMENTS

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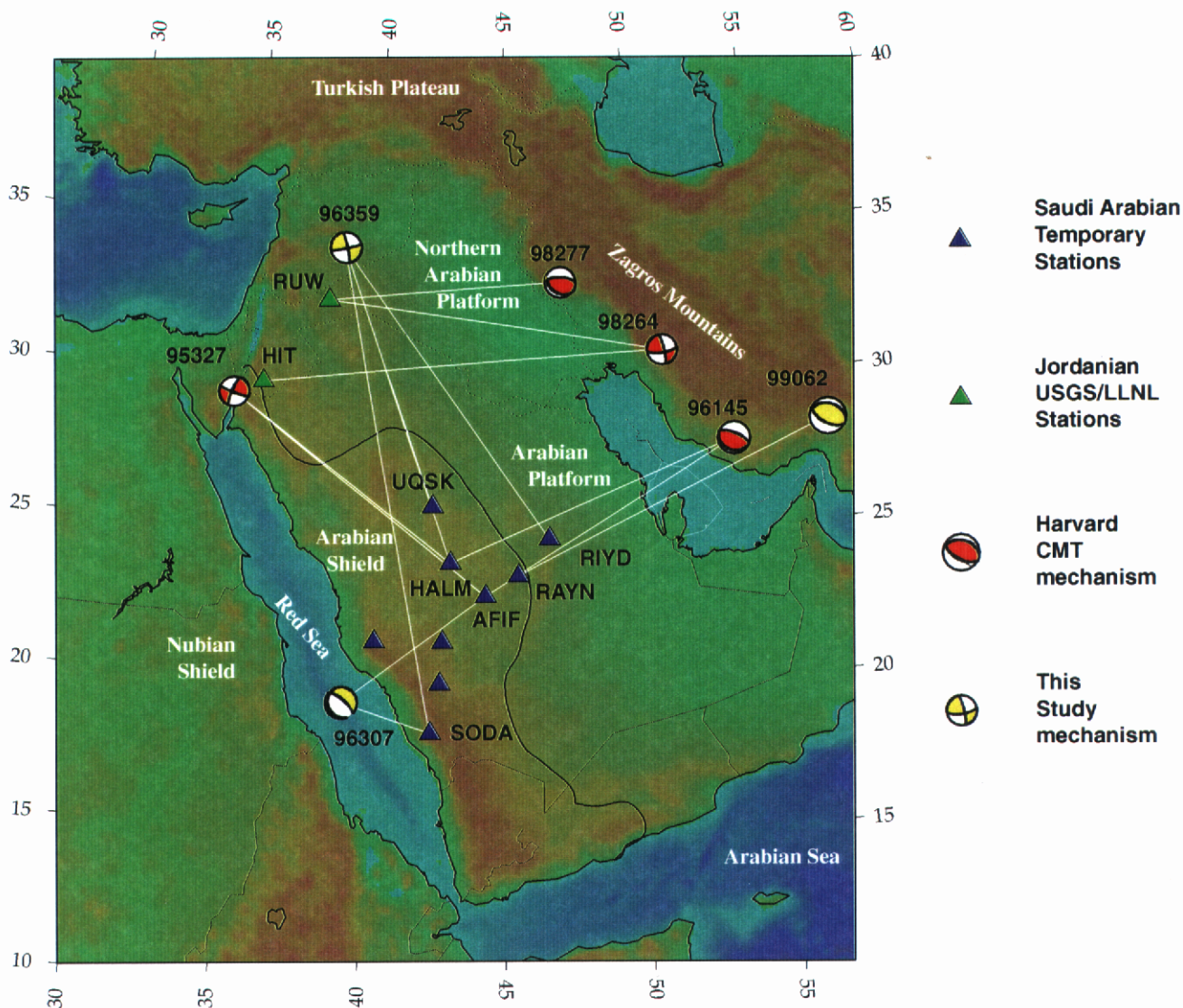
**Figure 1.** Map of the Arabian Peninsula, events, stations and paths analyzed.
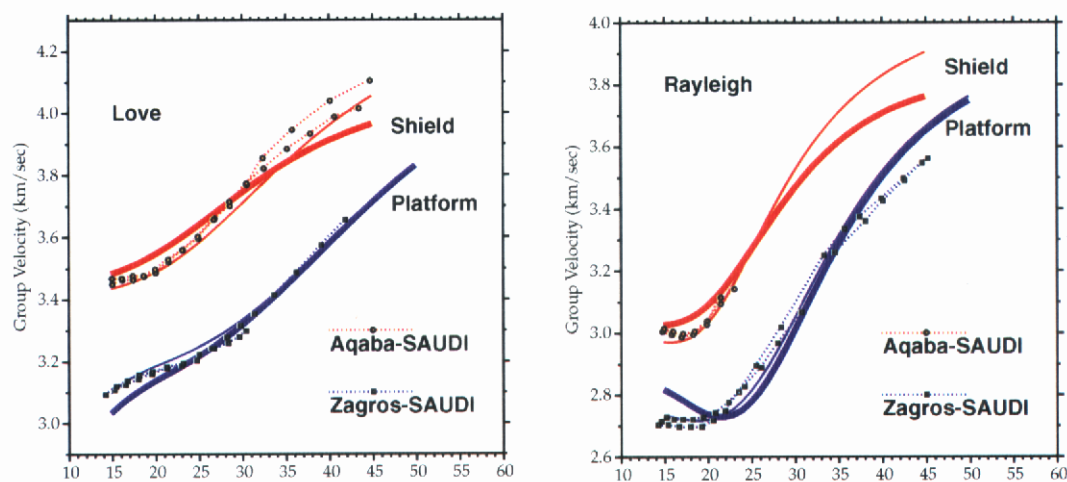
Figure 2. Group velocity dispersion for the 95327 and 96145 events as measured at stations AFIF and HALM. The dispersion curves for the velocity models that best fit the observed dispersion are shown as the light lines. The dispersion curves for the velocity models that best fit the observed waveforms (perfered model) are shown as the heavy lines.
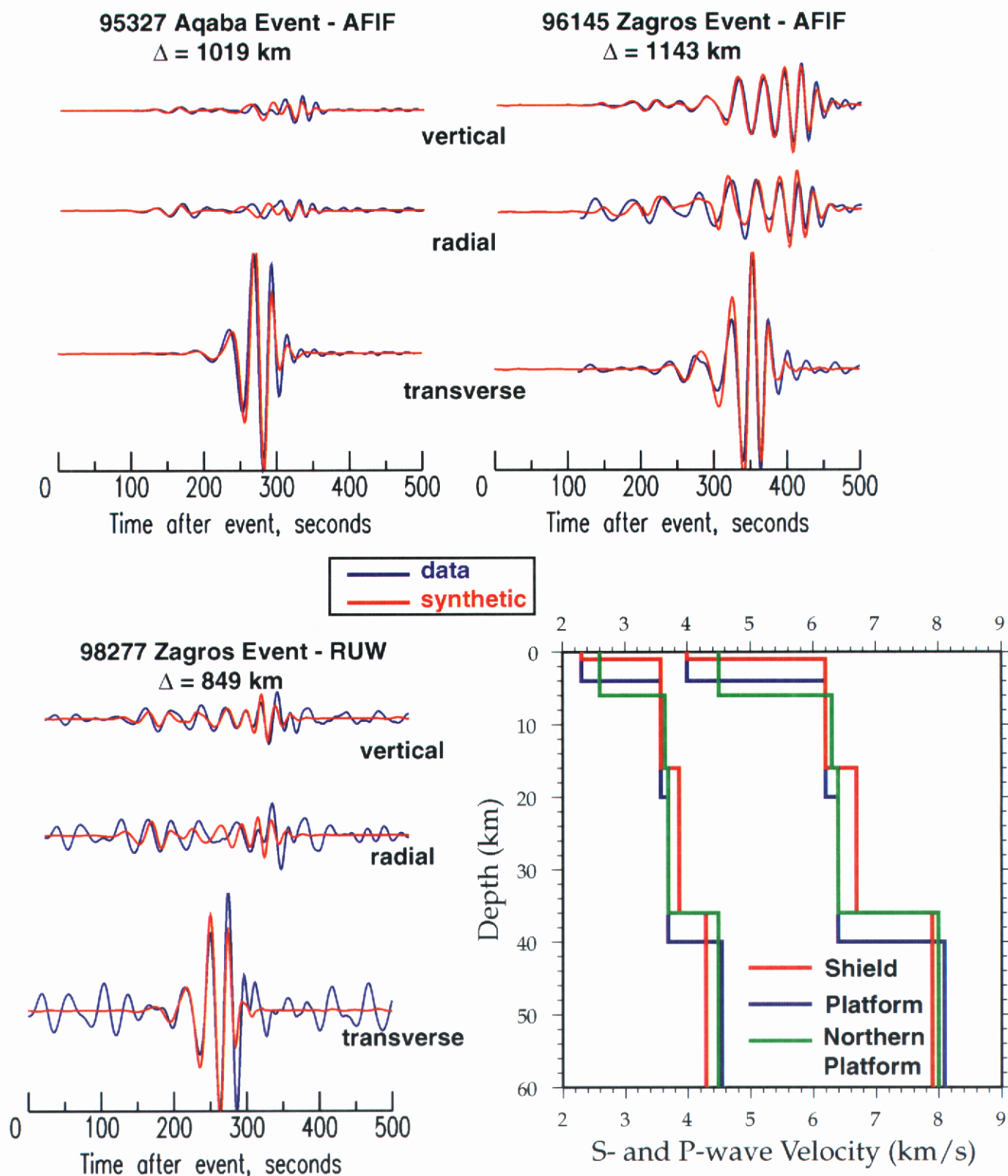
Figure 3. Fits of the synthetic sesimograms for the prefered models to the observed waveforms for the Arabian shield (top left), the Arabian platform (top right) and the Northern Arabian platform (bottom left). Velocity models for the Arabian Peninsula are also shown (bottom right).
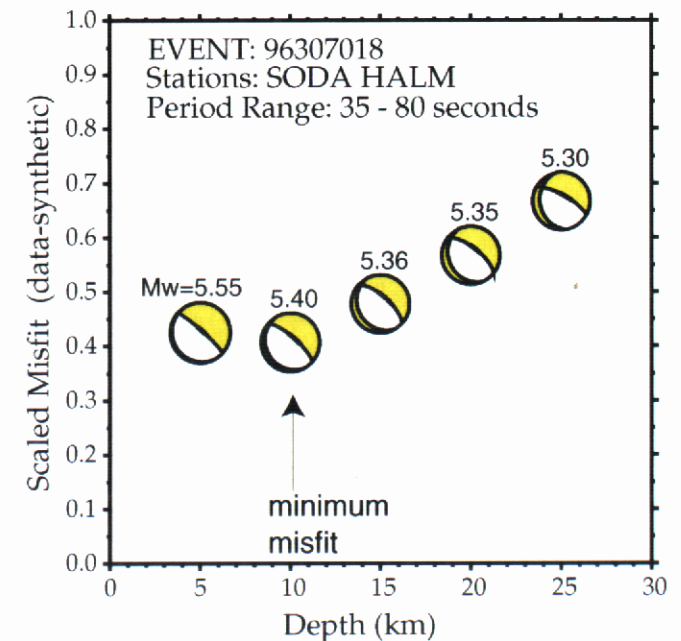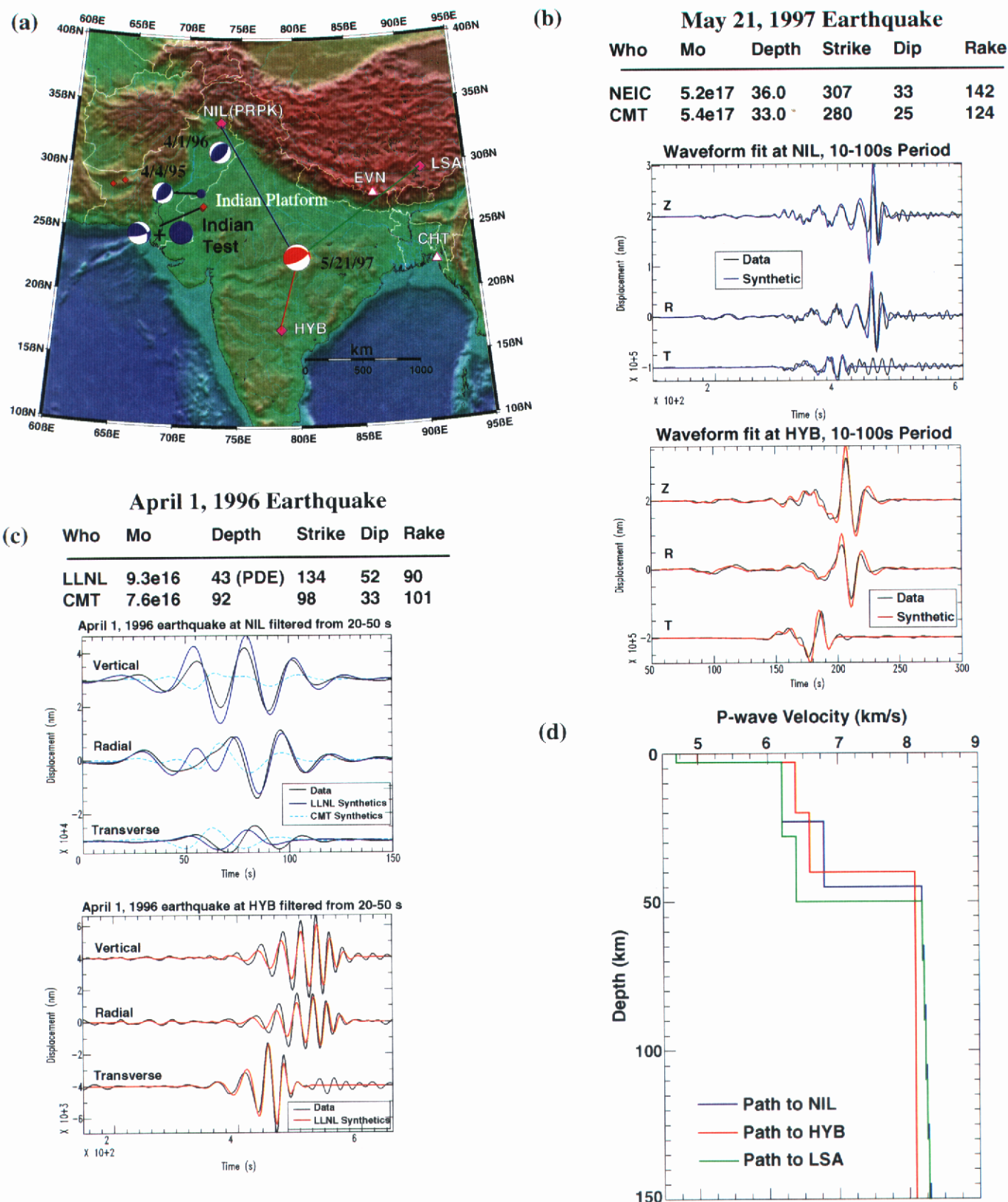
SODA
Δ = 346 km

HALM
Δ = 662 km

vertical

radial

transverse

Time after event, seconds
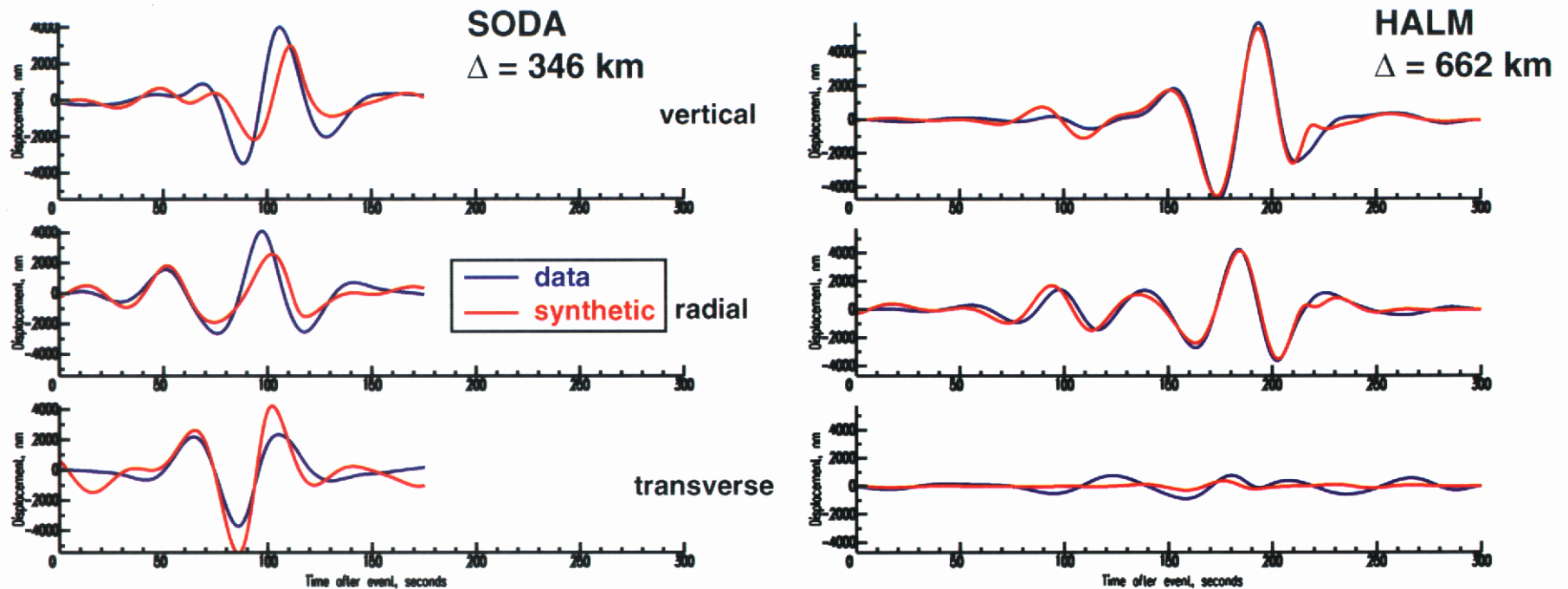
Event Parameters

| 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.

Depth-Mechanism-Misfit Curve

EVENT: 96307018
Stations: SODA HALM
Period Range: 35 - 80 seconds

(b) May 21, 1997 Earthquake

Who	Mo	Depth	Strike	Dip	Rake
NEIC	5.2e17	36.0	307	33	142
CMT	5.4e17	33.0	280	25	124

Waveform fit at NIL, 10-100s Period

Waveform fit at HYB, 10-100s Period

April 1, 1996 Earthquake

(c)

Who	Mo	Depth	Strike	Dip	Rake
LLNL	9.3e16	43 (PDE)	134	52	90
CMT	7.6e16	92	98	33	101

(d)

P-wave Velocity (km/s)

Figure 5. (a) Map of the Indian sub-continent, events, stations and paths analyzed. (b) Fits to the May 21, 1997 earthquake for stations HYB (Hyderabad, India) and NIL (Nilore, Pakistan). Note that the USGS-NEIC and CMT depths, moments and mechanisms agree for this event. (c) Fits to the April 1, 1996 earthquake. Note that the USGS-PDE and CMT depths do not agree and our source parameters (LLNL) fit the waveforms at NIL better than the CMT parameters. (d) Velocity models for the May 21, 1997 event.

(a) April 4, 1995 Earthquake   **(b)** May 11, 1998 Indian Test
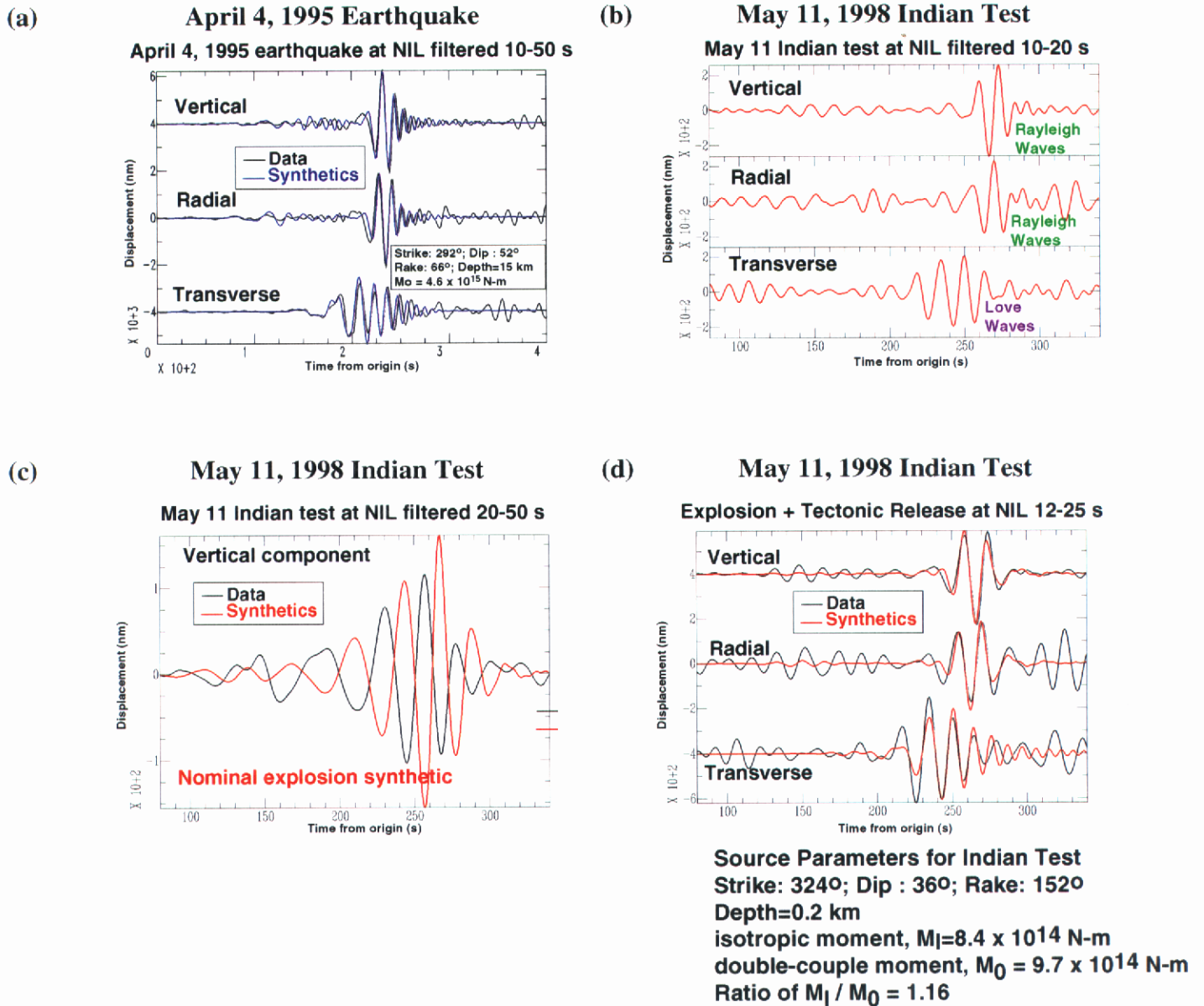
Figure 6. (a) Fits to the April 4, 1995 earthquake at station NIL. The focal mechanism for this event is plotted on Figue 5a. (b) Intermediate-period (10-20 s) three-component waveforms for the May 11, 1998 Indian nuclear test at NIL. Note the strong Love that is not expected from an explosion source. (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.