EXTENDING REGIONAL WAVE FORM MODELING TO SHORTER PERIODS TO IMPROVE THE LOCATION AND IDENTIFICATION OF SMALL SEISMIC SOURCES

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ABSTRACT

We are developing an interactive analysis system whereby the finer (short period) time-domain features of regional seismograms are modeled. The path calibration for this waveform analysis is being conducted in several steps. First, the best fitting 1-D structure is determined by modeling the broadband waveform features of large (Mw > 5) master events for which source parameters from teleseismic analysis are available. For these events we also determine depth from teleseismic P-wave depth phases. This depth estimate is critical to relocating the event and the relocation is integral to the determining regional velocity model as we have found that using the teleseismic ISC locations result in travel-time discrepancies on the order of 5 sec. in comparison to observations of near-regional distance (200 < R < 400 km) records. Such timing errors, over a 400 km distance, result in P-wave velocity errors on the order of 5% for typical crustal models. We relocate the event using the teleseismic depth in conjunction with the regional P and S travel times and a first-order velocity model. We have developed I-D models for the area surrounding the Lop Nor test site and the region encompassing S. W. Pakistan and N. W. India. With these models, regional source inversions and locations can be performed on smaller events that are still well recorded by 1 or more stations, but which are poorly observed teleseismically, thus lowering the monitoring threshold for the region. We are now refining these models for higher frequency (f > 0.25 Hz) observations. For this, we are applying the method of Pseudo Green's functions to calibrate the finer regional structure. This method has been applied successfully model S waves for events in the southern California and the Hindu Kush region of S. W. Asia. We are extending the method to P waves, which are more important in seismic monitoring practice. These refined Green's functions can then be used to generate realistic short-period seismograms to compare to observations -- particularly for smaller events (M < 4.5) -- for the purpose of characterizing the seismic source.

Key Words: Location, Source Characterization, and Regional Waveforms

OBJECTIVE

We are developing techniques to model the short-period character of regional waveforms in order to improve the analysis of small (mb< 4.5) seismic events which are not well-observed teleseismically for location purposes (Sweeney, 1996) or waveform analysis (Saikia, et al, 1996), as they may only have several usable regional observations. The procedure we use is to first obtain the best-fitting velocity model of the crustal waveguide for long-period waveforms and then refine the model(s) progressively to shorter periods, initially for broadband waveforms and then short-period ones. Particularly for the short-period case, the model is modified to predict the arrival times of prominent regional phases (Pn, Pg, S). For this short-period path calibration in particular, it is essential to have ground truth hypocentral locations for the master events which are large enough to be well recorded teleseismically, so that the P-wave depth phases can be analyzed. We are applying this methodology to regions centered about known test sites, where there is the greatest need and interest to locate and identify small seismic events. In particular our current effort is focused around the Lop Nor test site.

For areas with strong lateral variations, the crustal waveguide model may well have to be sub-regionalized for specific source-receiver paths. As we are only examining specific source regions, only paths for certain distance ranges and azimuths for which regional stations are situated need be modeled, thus limiting the scope of the path calibration. For the fine-timing of the short-period crustal waveguide, we are investigating the application of the pseudo Green's function method (Song and Helmberger, 1998) whereby the 1-D crustal model is broken-up into a 2-D block structure and a genetic algorithm is used to best fit the arrival time and amplitude of specific phases. Thus this modeling requires the identification of the various regional phases.

RESEARCH ACCOMPLISHED

Ground Truth Events

To calibrate the paths from the Lop Nor test site to the various regional stations (see Figure 1), we are modeling the waveforms of master events. Unfortunately, the only event recorded at WMQ, the closest station, with GIO (see Yang and Romney, 1999 for a definition of these criteria) or better location resolution is the 88273 explosion. There are good-sized earthquakes in the vicinity as shown on the map, but none is better than GT25. To develop regional velocity models which yield accurate travel times, event locations need to be well constrained. Therefore their teleseismic locations need to be confirmed or the events need to be relocated using a combination teleseismic depth-phase modeling and regional travel-time data.

Relocation results for 17 earthquakes throughout the Tien-Shan region, including those near Lop Nor, are given in Figure 2 (Velasco, personal communication). The upper box compares the ISC depths (circles) with ours (diamonds) determined from a combination of teleseismic P-wave modeling and regional waveform inversion (Woods et al., 1998) and are in close agreement with results from regional surface-wave spectra inversion (Patton, 1998). In some cases the change in depth is quite significant -- by as much as 50 km. The lower box compares the change in distance, r, between the ISC locations and the regional relocations using free depths (circles) and our constrained depths (diamonds); the events were relocated using a crustal model of central Asia (Mooney and Li, 1997). The constrained-depth relocations tend to move less than the free-depth ones on average, suggesting that the ISC epicentral locations are fairly accurate and that free-depth relocations are susceptible to errors. Thus constraining source depth helps to significantly improve regional event locations.

Figure 3 shows an example of the teleseismic depth-phase modeling for the earthquake 90165. In this case it was possible to model the SH component as well as the P waves; fitting the S waves helps to better constrain the event's seismic moment which, in turn, helps in the modeling of absolute amplitude of the regional phases, thus constraining the attenuation model. Once a reliable depth is determined, the event is relocated with respect to best available regional velocity model as described above.

Modeling Paths

With the best-constrained hypocentral relocations we model regional waveforms. Figure 4 compares observed and synthetic P-SV displacement waveforms, in absolute timing for the 88273 explosion. This model fits the P and S timing well. We are now using this velocity structure to relocate earthquakes near Lop Nor, so that paths from these events to the more distant regional stations (see Figure 1) can be accurately modeled. We also applied this velocity model to events recorded at WMQ from other azimuths. Figure 5 compares broadband (left column) and long-period (right column) observed and synthetic waveforms for the earthquake 90297, west of WMQ. The seismograms are again plotted with respect to absolute time; the synthetics are little slow, requiring a slightly faster model. Otherwise the waveform fits are quite good, suggesting that the model used only needs slight refinements to make it yield accurate travel times for the P and S phases. The large amplitude, ringing nature of the S-wave train, which is also produced in the synthetics, suggests the presence of a gradient in the upper crust at the base of the low-velocity sedimentary layers as was previously observed by Saikia and Burdick (1991) for some regional paths from NTS. Our current model for station WMQ, includes a similar gradient. The refined model for short-period waveforms should include this effect.

Refining Path Models for Short-Period Observations

To refine the regional model for specific azimuths and, in some cases, distances, we are applying the pseudo Green Function (PGF) technique (Song and Helmberger, 1998) whereby the I-D model is broken into blocks and the relative timing of the various regional phases are used to modify this 2-D block model in a fashion similar to waveform tomography. For this procedure the individual phases must be identified. Figure 6 is the anatomy of phases for a set of three-component regional seismograms which we used to identify the major phases recorded at WMQ. For each component the top trace is a generalized ray synthetic and the lower trace is the full waveform generated from F-K integration. The primary rays of interest are Pn, PmP, pPn, pPmP, sPmP, Sn and SmS. Identification of these rays is necessary for the next step in refining the model using pseudo Green's functions.

In the PGF method each ray $R_i(t)$ (determined generalized ray synthetics) is shifted by d_{ti} and amplified by a factor A_i:

$$S(t) = \sum_i A_i R_i(t) * d(t - d_{ti})$$

where i is the index of the ray, in order to best match the composite generalized ray synthetic to the observed waveform. Prior work using the pseudo Green Function method involved modeling only S waves. Figure 7 shows the applicability of the method in which a SH waveform recorded at the TERRAscope station GSC is successfully modeled. The upper left column shows individual rays with their path shown opposite in the right column; the solid trace is for the 1-D model and the dashed trace is the perturbed ray. In the lower left-hand comer are the SH wave displacements records; the top trace is the observed seismogram, the middle trace is the final iteration of the PGF synthetic, and the bottom trace is the 1-D synthetic. The PGF records fits the observed waveform significantly better.

We are currently working on extending the method to P-waves. The idea behind the PGF path calibration is to develop Green's functions for a particular source region using large, well recorded master events. These PGFs could then be used to model records from smaller events from the same vicinity in order to determine information regarding the seismic source, in particular mechanism.

CONCLUSIONS AND RECOMMENDATIONS

For regions with few GTIO (or better) events, locations and source depths, necessary for accurate path calibration, can be better constrained using teleseismic depth phase information. Regional locations with poor azimuthal coverage and no constraint on source depth leads to errors in relocations. A good-fitting regional model has been found for the path from Lop Nor to WMQ. It is now being refined to improve predictions of P and S arrival times.

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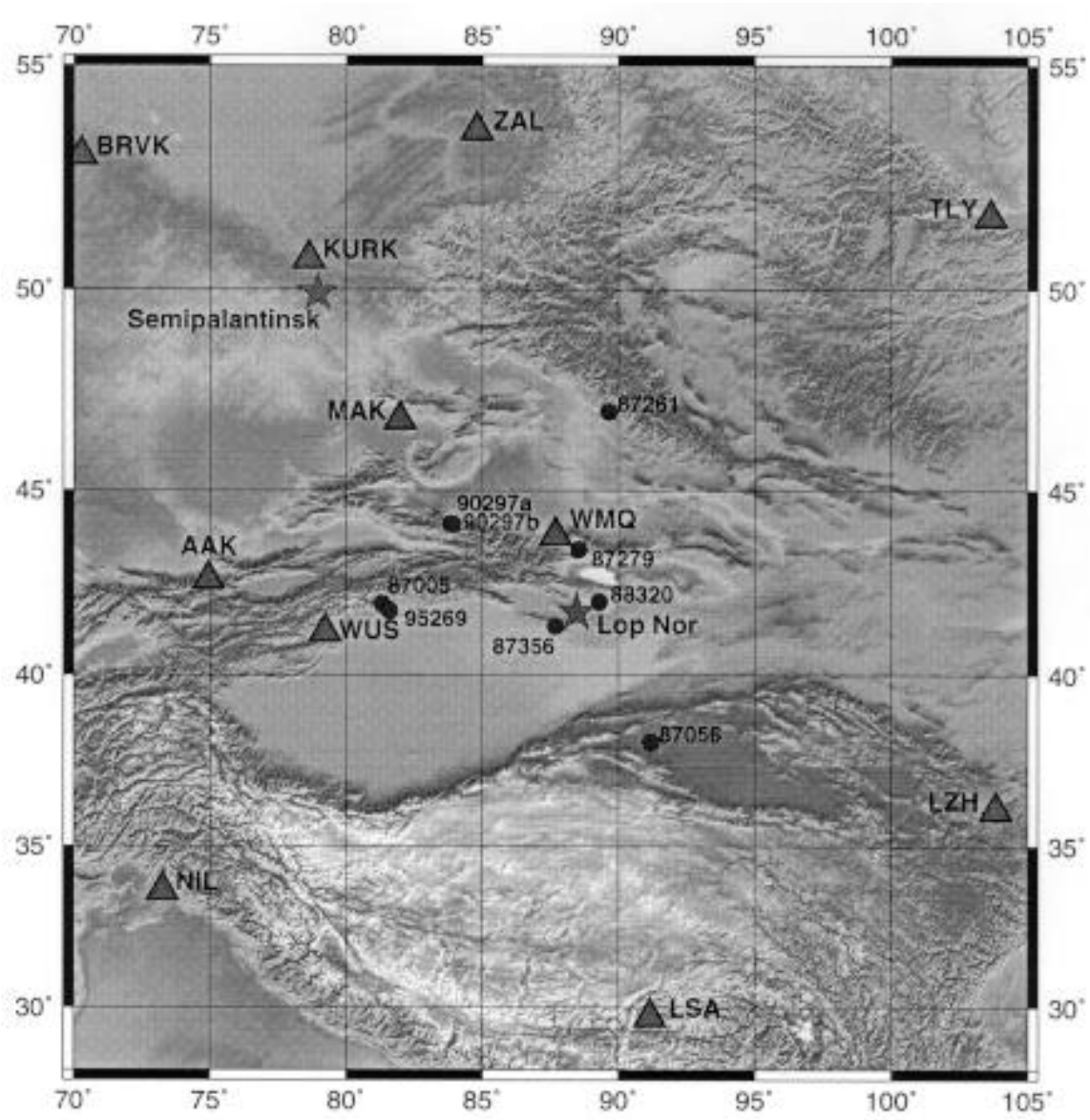

Figure 1. Topographic map of the northwestern border region of China showing the location of earthquakes (circles) and test sites (stars), for which better GT data are available, used to calibrate crustal path models to the regional stations (triangles).

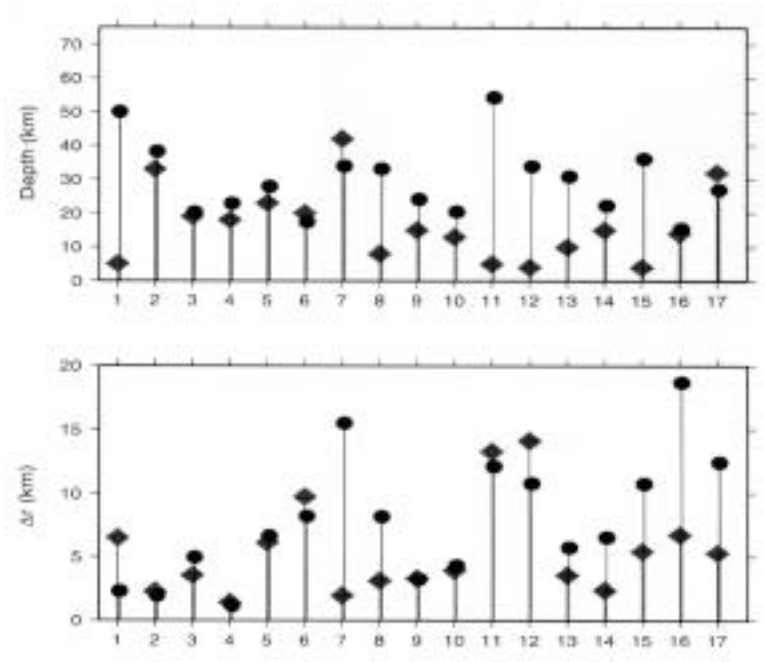

Figure 2. Upper panel: Comparison of ISC (circles) focal depths and those determined from a combination of teleseismic P-wave modeling and regional waveform inversion (diamonds). Lower panel: Change in epicentral location (relative to ISC) for relocations using regional travel times for free-depth (circles) and fixed-depth (diamonds) travel-time inversion; the fixed depth are those determined by Woods et al. (1998).

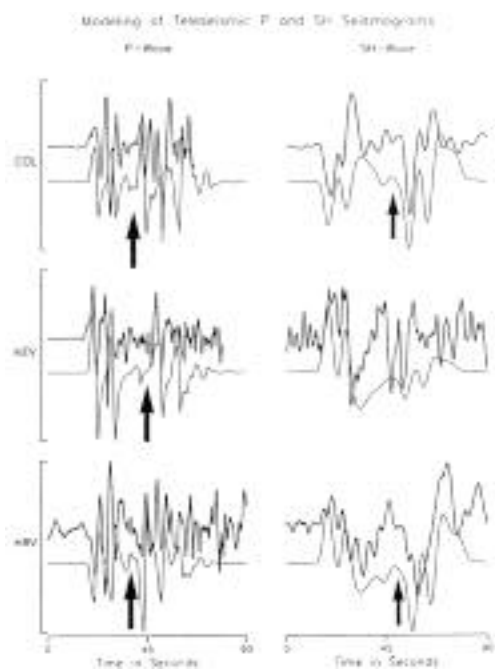

Figure 3. Teleseismic modeling of P and SH waveforms recorded at three stations for the 90165 earthquake. The observed seismograms are the upper (thicker line) trace. Focal mechanism is the Harvard CMT solution. The depth phases are shown by the arrows.

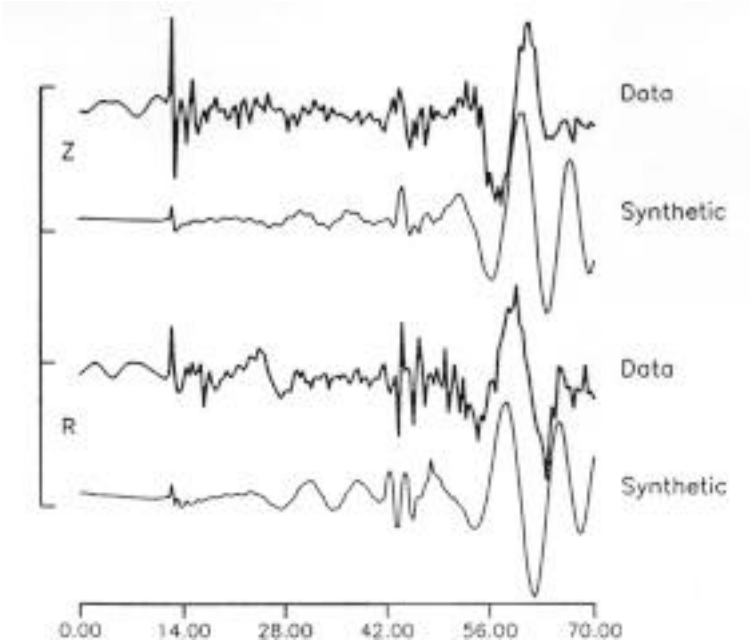

Figure 4. Comparison of observed (upper, thicker trace) and synthetic displacement seismograms for the 88273 Lop Nor explosion recorded at WMQ; both vertical and radial components are displayed.

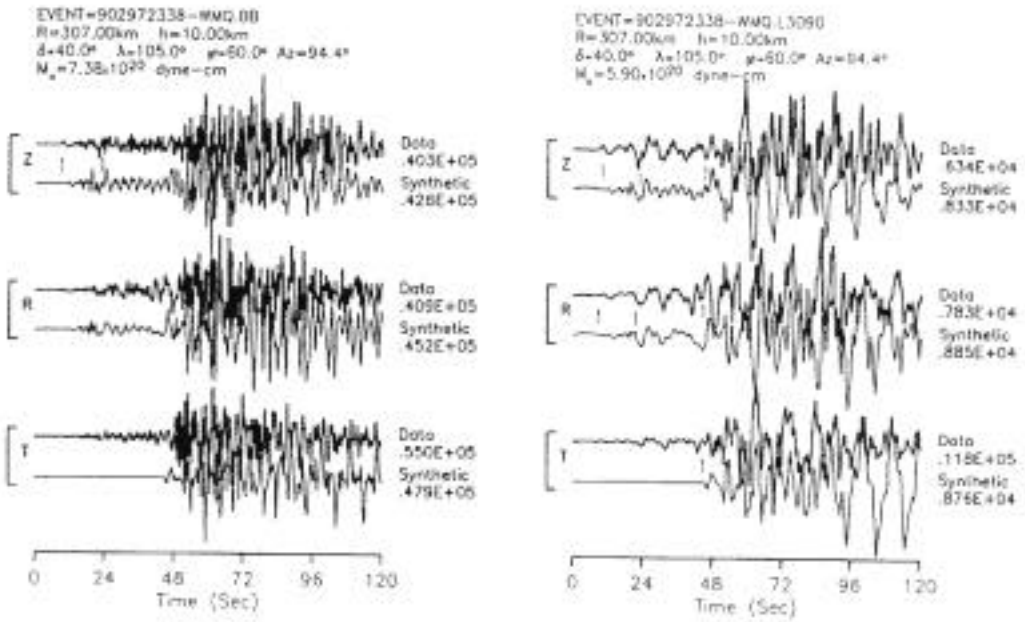

Figure 5. Comparison of observed (upper, darker trace in each pair) and synthetic regional seismograms for the event 90297 recorded at WMQ. The left-hand set of records are the broadband play-outs and the right-hand ones are convolved with a long-period 30-90 instrument.

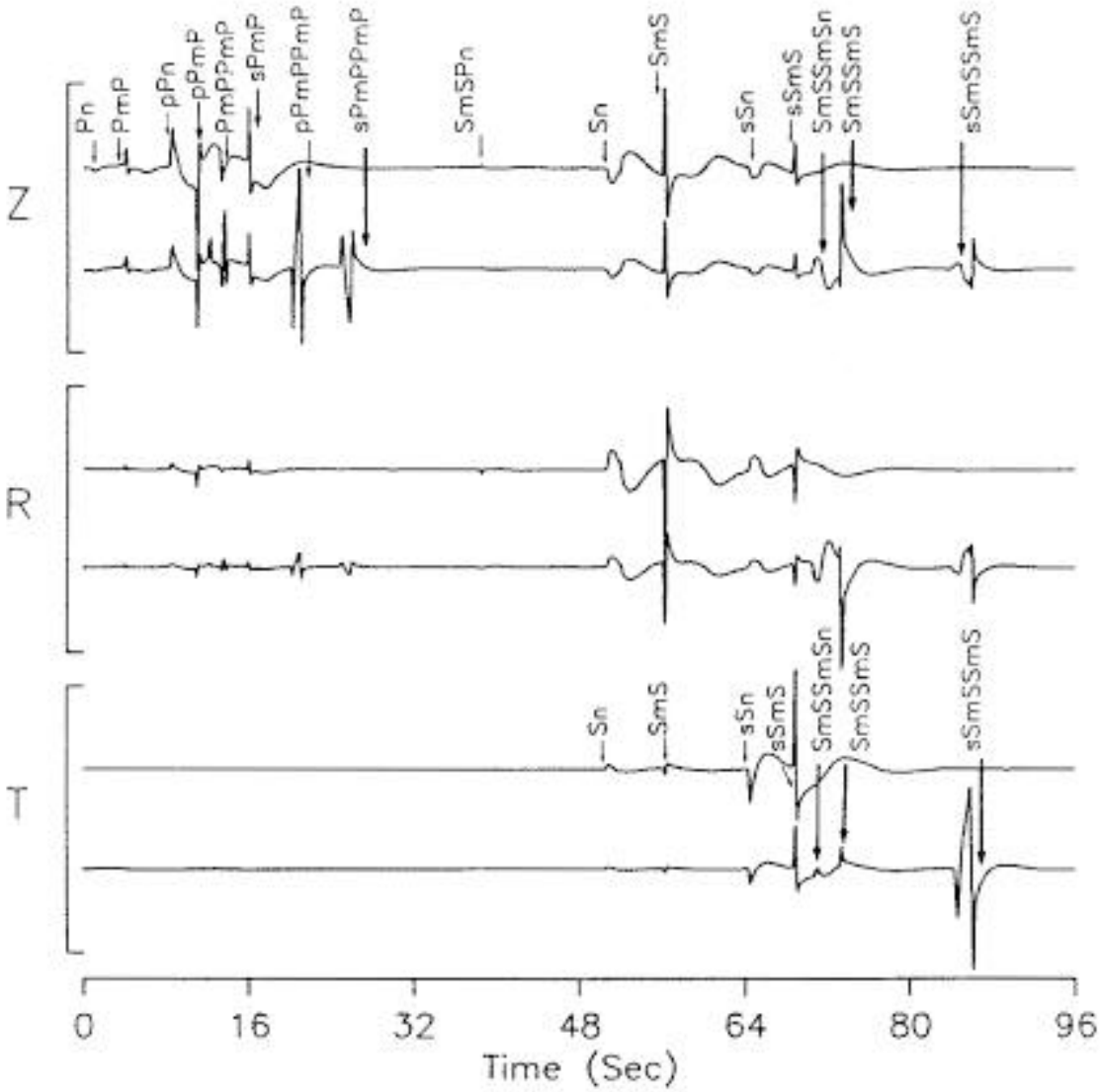

Figure 6. Anatomy of regional seismograms for vertical, radial and tangential components. The top trace in each pair of seismograms is generated with generalized rays, while the lower trace is the full wavefield generated from F-K integration.

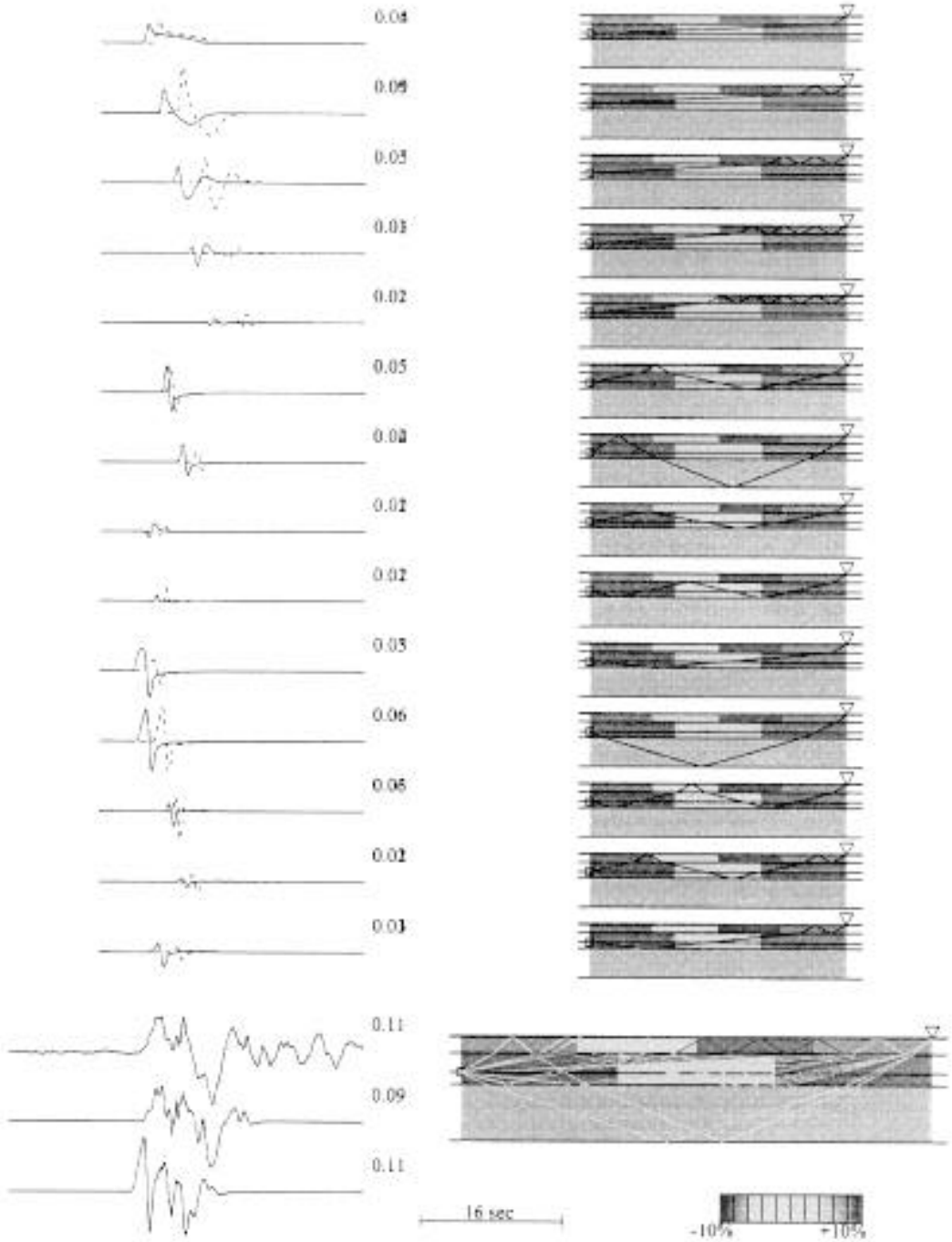

Figure 7. Example of the pseudo Green's function method applied to a tangential component regional record. Each pair of traces in the upper left column is the individual ray contribution corresponding to the ray diagram shown in the right column; the solid trace is for the 1-D model and the dashed-line trace is the perturbed ray in the 2-D block structure (shown in the right column). The number to the right of each pair of traces is the peak amplitude. The three seismograms in the lower left-hand corner are the observed record (top trace), the pseudo Green's function sum of the above rays (middle trace), and the full 1-D F-K synthetic (bottom trace). The full ray diagram in the final 2-2 block model is shown in the lower right-hand corner.