REFINING FAULTING PARAMETERS AND DEPTH ESTIMATES FOR EARTHQUAKES IN EASTERN ASIA

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ABSTRACT

Accurate and stable seismic source parameters for small-to-moderate size events are essential for many aspects of regional nuclear explosion monitoring. For example, magnitude and distance amplitude corrections (MDAC) have been developed for regional discrimination, but they rely on stable moment estimates. We develop a catalog of regional earthquakes in eastern Asia with estimated seismic moments, source mechanisms, and depths using regional seismic data. A catalog of regionally estimated seismic moments, source mechanisms, and depths is also a useful tool for magnitude calibration and regional characterization. We are particularly interested in constraining seismic moments, which are critical for calibrating regional magnitude scales with global catalogs, and in improving depth estimates for Asian events.

A significant challenge of modeling small-to-moderate-size seismic sources is the necessity of relying on short-period signals with long travel paths that have substantial sensitivity to earth structure along the path. When the path effects are unknown or difficult to account for, we must rely on components of seismic signals that are minimally dependent on the structure. Although regional surface-wave phases are strongly influenced by structure, surface-wave amplitude spectra can be modeled adequately with relatively simple earth models, and these spectra carry valuable information on source character. Our efforts build on existing seismic source analysis techniques. We directly model regional seismograms where possible but combine those with surface-wave amplitude spectra observed at more distant regional stations. The inversion is performed using a grid search for strike, dip, rake, moment, and depth. Choosing suitable weights for the different data sets remains a challenge that will only be overcome with experience. Initially, all data are weighted equally by normalizing seismograms and spectra by their uncertainty and the number of observations in each data set. For larger events ($M_W > 5$) we can also include long-period (approximately 40-s period) body-wave trains, which can be modeled reliably using simple stratified earth models. The use of spectra and long-period signals is ideal for estimating the moment and faulting geometry of signals but simple least-squares norms based on these signals do not often provide satisfactory resolution of source depth (when the source is shallow). However, in cases where the long-period mechanism is relatively stable as a function of depth, we can overcome this limitation by exploiting signals more diagnostic of source depth such as teleseismic body-waveforms, broad-band *Pn* waveforms, or select short-period Rayleigh wave spectra. For example, once the mechanism is relatively well known, we can refine depth estimates using short-period P-waveforms using a synthetic seismogram-matching procedure that provides source depth constraints that in some cases span a few kilometers.

KEY WORDS: seismic source characterization, magnitude calibration, regional characterization, regional wave propagation, seismic source depth

OBJECTIVE

Estimating the source type or faulting geometry of small seismic events located hundreds of kilometers from the nearest seismometer can be difficult. Typically one of two classes of modeling approaches is adopted: Spectral, or time-domain. Spectral techniques use the observed variation in surface-wave spectra as a function of azimuth to match the radiation pattern of the source (e.g. Patton, 1976, 1980, 1998; Herrmann, 1976, 1979; Romanowicz, 1982; Patton and Zandt, 1992; Herrmann and Ammon, 1997, and many others). Time-domain methods are straight-forward matches to the observed seismograms and include both amplitude and phase information (e.g. Langston, 1981; Dreger and Helmberger, 1991, 1992, 1993; Lay et al., 1994; Randall et al., 1995; Ghose et al, 1998; Ammon et al., 1998, and others). Spectral methods can be designed to include amplitude only, or amplitude and phase information, while time-domain methods include both. Phase information provides valuable constraints on the source mechanism and depth, but the observed phase is often sensitive to details in Earth structure along the propagation path. Time-domain source inversion methods are usually applied to large events with good long-period signals or short-period signals of small events that have minimal distortion from Earth structure (such as teleseismic P and SH waves) or local and close-regional (less than a few hundred *km*) signals. To use phase in surface-wave spectral analyses works best with a good estimate of the surface-wave phase velocity variations between the source and receiver.

If we consider the problem addressed in Comprehensive Nuclear-Test-Ban (CTBT) work, the best signals from a shallow small event are most likely to be short-period surface waves. But directly fitting the phase of short-period Rayleigh waves (probably the best regionally observed, deterministic signal from a small, shallow event) is challenging because these waves are sensitive to shallow, variable structure along the propagation path. Rayleigh-wave spectral amplitudes are less sensitive to structure variations than the corresponding signal phase, and contain valuable information on the source depth. Thus, it is desirable to combine the part of distant signals that is less sensitive to structure with the amplitude and phase information from the closer stations.

Simultaneous spectral and time-domain seismic source modeling

To achieve this, we combine surface-wave spectral amplitude modeling and time-domain waveform fitting in a grid-search algorithm to estimate the source mechanism (systematically check strike, dip, rake, and depth, & include an isotropic source for comparison). The procedure include surface-wave amplitude information for stations distant from the source and include both amplitude and phase information from the closer observations and teleseismic body waves if the event is large enough for these to be observed (Figure 1). Incorporating observations from more distant stations makes a significant contribution to seismic source studies in two important ways: First, the azimuthal coverage of radiation patterns is improved and second, Rayleigh wave amplitude spectra contain valuable information on the source depth. For shallow events, improved resolution of the depth requires short-period information because the information on shallow depths are contained in the short-period signals. Herrmann (1979) exploited information in intermediate-period surface waves to estimate the faulting geometry and depth of earthquakes in east and central North America from old analog records. He observed signals out to distances of thousands of kilometers and extracted spectral amplitudes suitable for constraining the earthquake parameters. We cannot be certain that observations from such large distances in central Asia will be as simple or robust as those in the stable part of North America. The signal amplitudes may be lower due to scattering and intrinsic attenuation. However, signals from small events may be isolated from background noise and extracted using phase-match filtering exploiting dispersion observations from larger events.

RESEARCH ACCOMPLISHED

The goal of estimating source depth with some precision will require a combination of observations. Particularly valuable in constraining earthquake depth are short-period Rayleigh waves, which may contain a spectral notch indicative of source depth (e.g. Herrmann, 1979). Short-period surface waves can be tricky and when analyzing the signals some form of mode isolation can help simplify their interpretation. Toward-

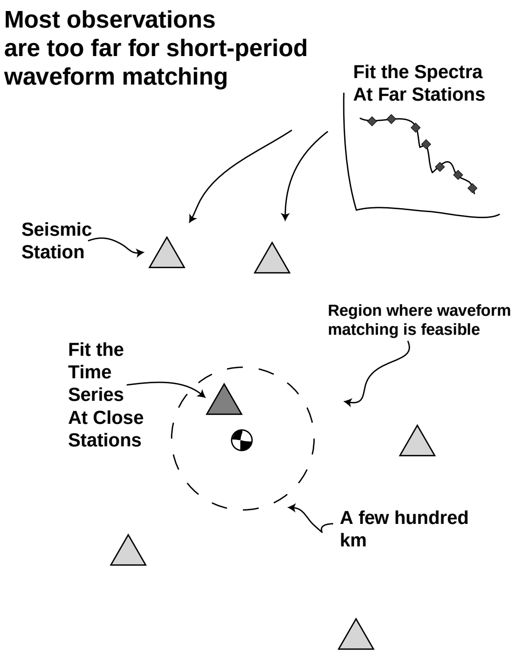

Figure 1. Schematic illustration of the joint source parameter inversion scheme. The triangles represent seismic stations, the focal mechanism represents the source location. The basic idea is to combine observations with a minimal sensitivity to earth structure to produce more accurate estimates of the event mechanism and depth. Since most observations are too far for direct short-period waveform modeling we sacrifice the phase information and use only the more robust spectral amplitudes at those sites. Phase information is included from seismograms recorded at nearby stations, teleseismic P-waves, or regional Pn arrivals.

this goal we have improved and extended software that can be used to analyze and isolate dispersed seismic waves.

Surface-Wave Mode Isolation Software Improvements

In the case of surface-wave analyses, the noise can be background earth noise or signal-generated noise such as body waves, higher modes, multi-pathed arrivals, etc. The dispersed character of surface waves is the key to their identification and extraction from other signals. The computational methods for surface-wave isolation are well established and have been employed for about thirty years (e.g. Dziewonski et al., 1969; Herrin and Goforth, 1977; Levshin et al., 1987, Ritzwoller and Levshin, 1998). An example analysis is shown in Figure 2. We have added a number of minor software improvements to an existing computer application written to perform the surface-wave isolation and group velocity estimation. These enhancements will help ease two aspects of small-event processing. First, we added an option to use pre-event ground motion to estimate the signal-to-noise ratio of the observations. Such information allows quick and easy identification of obviously unreliable observations saving valuable analysts' time for the more subtle observations that require expert knowledge in surface-wave analysis. We have also added the ability to use path-specific group velocities to construct mode-isolation filters (Herrin and Goforth, 1977). Also, higher-mode isolation is now an option. Such higher mode observations can provide valuable constraints on source mechanism and depth, as well as contribute to a better mapping of the regional structure.

Initial Joint Inversion Results

Our early applications of the technique suggest that, in addition to the surface-wave information at greater distance, it can provide better constraints on mechanisms for small events. For larger events, the approach

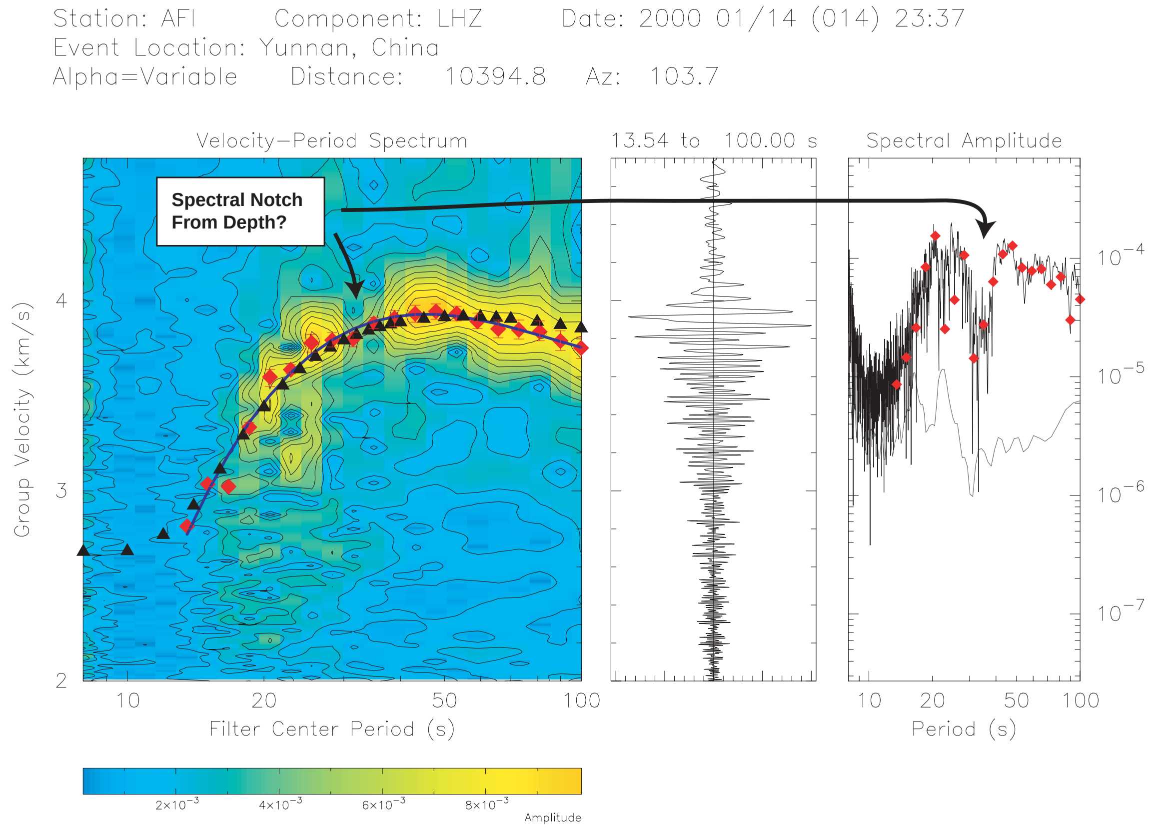

Figure 2. Group-velocity/Mode-Isolation software written for surface-wave analysis. For estimating source properties, the value of the analysis is isolation of fundamental mode surface waves to allow robust spectral amplitudes and to identify waveforms that contain depth relative notches. The above seismogram corresponds to a Rayleigh wave recorded at station AFI at a distance of 10,395 *km* from the *Mw* 5.9 source. The panel on the left shows the signal energy as a function of period and group velocity, the center shows the seismic signal as a function of group velocity, and the last panel shows the seismogram and pre-signal noise spectra.

of Harvard makes more sense since it requires less processing and piecing together of different parts of the seismic wave field. However, the cost of processing simplicity is the fact that the depth of even moderate-size events may be poorly constrained by long-period observations.Thus, we hope to add information even for these moderate-size events by analyzing broad-band or short-period body waveforms (e.g. Langston and Helmberger, 1975). Our initial efforts using waveform comparisons relying on the Harvard mechanisms have resulted in improved depths for a number of events. An example is presented in Figure 4. The Harvard and PDE depths for this event are 33 *km*, but the SH body waveforms observed at station MA2 suggest a slightly shallower depth of about 10 -20 km.

Waveform Collection Efforts

We have assembled long-period displacement seismograms for 50 earthquakes that occurred in the years from 1995-2000 in the Flinn-Engdahl seismic regions 26,27,28, and 41 and which have been modeled as part of the Harvard CMT project. Our plan is to begin modeling these calibrated events to assess the strengths and weaknesses of the joint spectral and time-domain inversion approach. In addition, we have gathered teleseismic P waveforms for the same events to use depth phases to refine depth estimates. Most of the catalog depths for these events are 15 *km* or 33 *km* for Harvard or the USGS respectively.

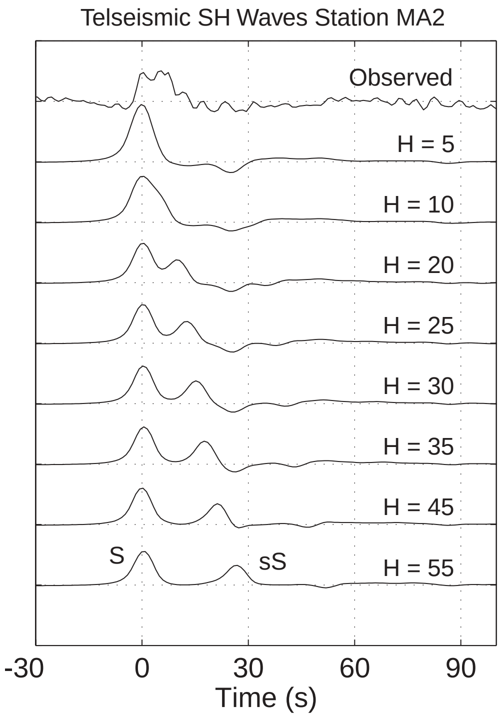

Figure 3. Teleseismic SH-wave comparison for station MA2 ($\Delta = 48$) for a range of source depths. The apparent source depth lies between 10 and 20 *km*. The predicted seismograms were computed using the reflection matrix method for a layered model with a crustal structure appropriate for Asia and a mantle based on PREM. A six-second long trapezoid was convolved with the synthetic seismogram. The signals were aligned on the first peak in the SH waveform.

CONCLUSIONS AND RECOMMENDATIONS

The idea of using teleseismic body waves, surface-wave spectra, or regional Pn waveforms to constrain source depth is not new. Our point is that to constrain the depths of seismic events will require an adaptive approach that utilizes the best data for a particular distribution of observations and a particular focal mechanism. Whenever possible, the combination of these data should be used to assess the reliability of a particular depth. While the approach seemingly lacks elegance or is not easy to implement routinely, the effort is rewarded with improved estimates of source depth, an important parameter for discrimination and for the additional use of the seismograms to estimate such quantities as moment and source mechanism.

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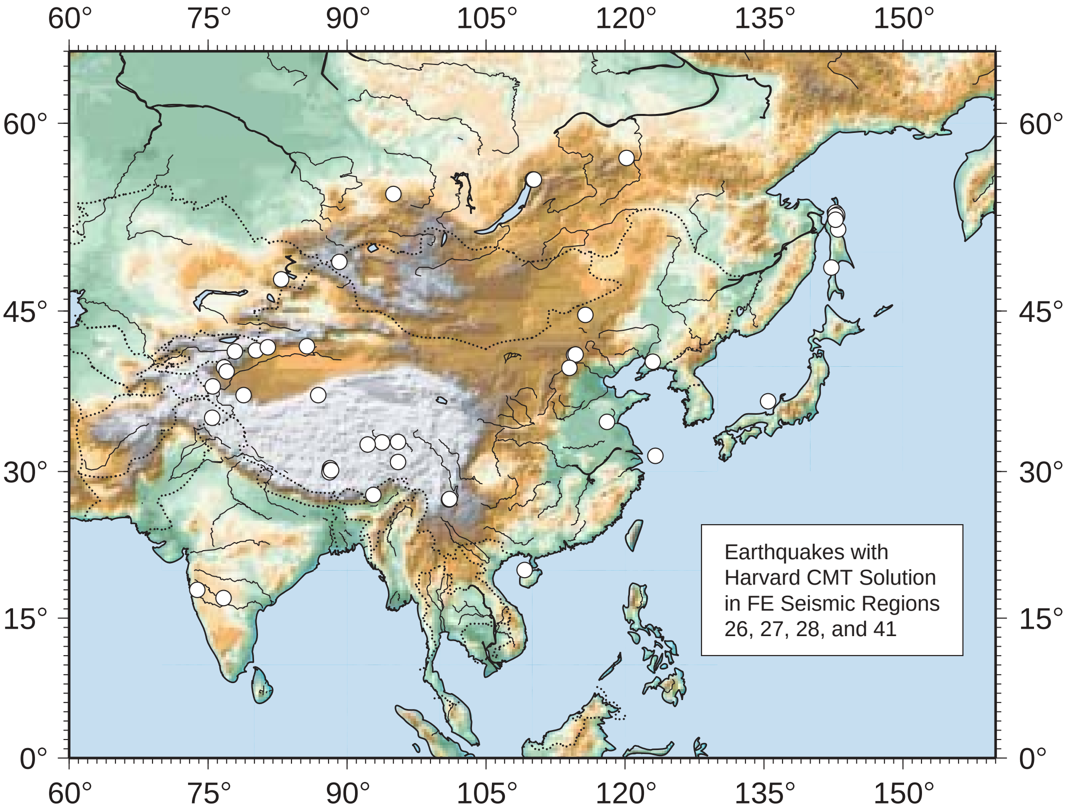

Figure 4. Although the eventual target application for the joint surface-wave spectrum seismogram source estimation procedure are smaller events, the calibration data set is comprised of events with Harvard CMT solutions (shown as circles in the map above). We have selected events within Flinn-Engdahl regions 26,27,28, and 41 for analysis.

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