LOCATING NUCLEAR EXPLOSIONS USING WAVEFORM CROSS-CORRELATION

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ABSTRACT

We apply waveform cross-correlation to seismograms from the global seismic networks to measure the differential times between P-wave arrivals from nuclear explosions-at both the Semipalatinsk (Soviet) and Lop Nor (Chinese) test sites. Waveform cross-correlation is ideally suited for this purpose, due to the high degree of waveform similarity observed at individual stations between closely spaced events. The differential times are more precise than could be obtained by picking the P arrival times on the seismograms separately. We use these times to compute relative event locations at both test sites, using a grid-search algorithm based on the LI norm. Our locations show reduced scatter compared to catalog locations for these events and better agreement with satellite observations. This is achieved using only a small number of global stations (8 to 15). However, the accuracy of the final locations is sometimes limited by small timinc, errors (several tenths of seconds) in the seismic data. The technique should be applicable to other areas of clustered seismicity.

Keywords: event location, nuclear explosions

OBJECTIVE

To test the effectiveness of waveform cross-correlation methods in measuring relative locations between nuclear explosions.

RESEARCH ACCOMPLISHED

Introduction

Locating earthquakes is one of the oldest problems in seismology and remains an area of active research. The problem is complicated by the nonlinear dependence of seismic travel times on location, the often incomplete knowledge of the full three-dimensional velocity structure along the source-receiver paths, and difficulties associated with inadequate station coverage and outliers in the observed travel-time picks. The advent of computers enabled routine event locations for large numbers of events, using one-dimensional reference velocity models and linearized, least-squares techniques [e.g., *Flinn*, 1965]. This made possible the production of both global and local earthquake catalogs listing thousands of events, each located in a standard way.

As computer capabilities improved, researchers began to develop new methods for earthquake location. These include joint-hypocenter-velocity (JHV) inversions to handle the effects of three-dimensional velocity structure [e.g., *Thurber*, 1983; *Dziewonski*, 1984; *Eberhart-Phillips*, 1990; *Lees and Malin*, 1990; *Magistrale et al.*, 1992; *Eberhart-Phillips and Michael*, 1993; *Vasco et al.*, 1994; *Magistrale and Sanders*, 1996], techniques to downweight the effect of data outliers [e.g., *Anderson*, 1982; *Buland*, 1986; *Kennett*, 1992; *Kijko*, 1994], station term and master event methods to improve relative location accuracy in clusters of events [e.g., *Douglas*, 1967; *Evernden*, 1969; *Frohlich*, 1979; *Jordan and Sverdrup*, 1981; *Smith*, 1982; *Pavlis and Booker*, 1983; *Pujol*, 1988], grid search, simulated annealing and evolutionary programming approaches to finding global misfit minima [e.g., *Sambridge and Kennett*, 1986; *Sambridge and Gallagher*, 1993; *Billings*, 1994; *Billings et al.*, 1994; *Minster et al.*, 1995].

When seismic waveforms are available, cross-correlation techniques can be used to achieve precise relative locations between closely spaced events with similar waveforms [e.g., *Poupinet et al.*, 1984; *Ito*, 1985, 1990; *Fremont and Malone*, 1987; *Xie et al.*, 1991; *Deichmann and Garcia-Fernandez*, 1992; *Nadeau et al.*, 1995; *Haase et al.*, 1995; *Dodge et al.*, 1995; *Got et al.*, 1994; *Gillard et al.*, 1996; *Shearer*, 1997]. This approach is illustrated in Figure 1. Two nearby events will often produce nearly identical waveforms at individual stations, despite the fact that the waveforms vary widely between stations. If the waveforms are similar enough, a time shift can be obtained from the cross-correlation function (or from the phase spectra in frequency domain methods). These differential times are typically much more accurate than can be measured by picking individual seismograms, and can be used to compute high-precision relative event locations. For local earthquakes, standard location errors of tens of meters or less have been achieved for closely spaced events.

Despite these successes the waveform cross-correlation approach has generally been used only to relocate small numbers of earthquakes in special areas of interest and has not been applied to large portions of earthquake catalogs. This stems in part from the storage and computational difficulties associated with computing cross-correlation functions for large numbers of events. It is also unclear how similar the earthquakes must be in location and focal mechanism for the method to produce useful results. Cross-correlation methods have most often been applied to local earthquake data and their applicability to teleseismic records from the global seismic networks is uncertain.

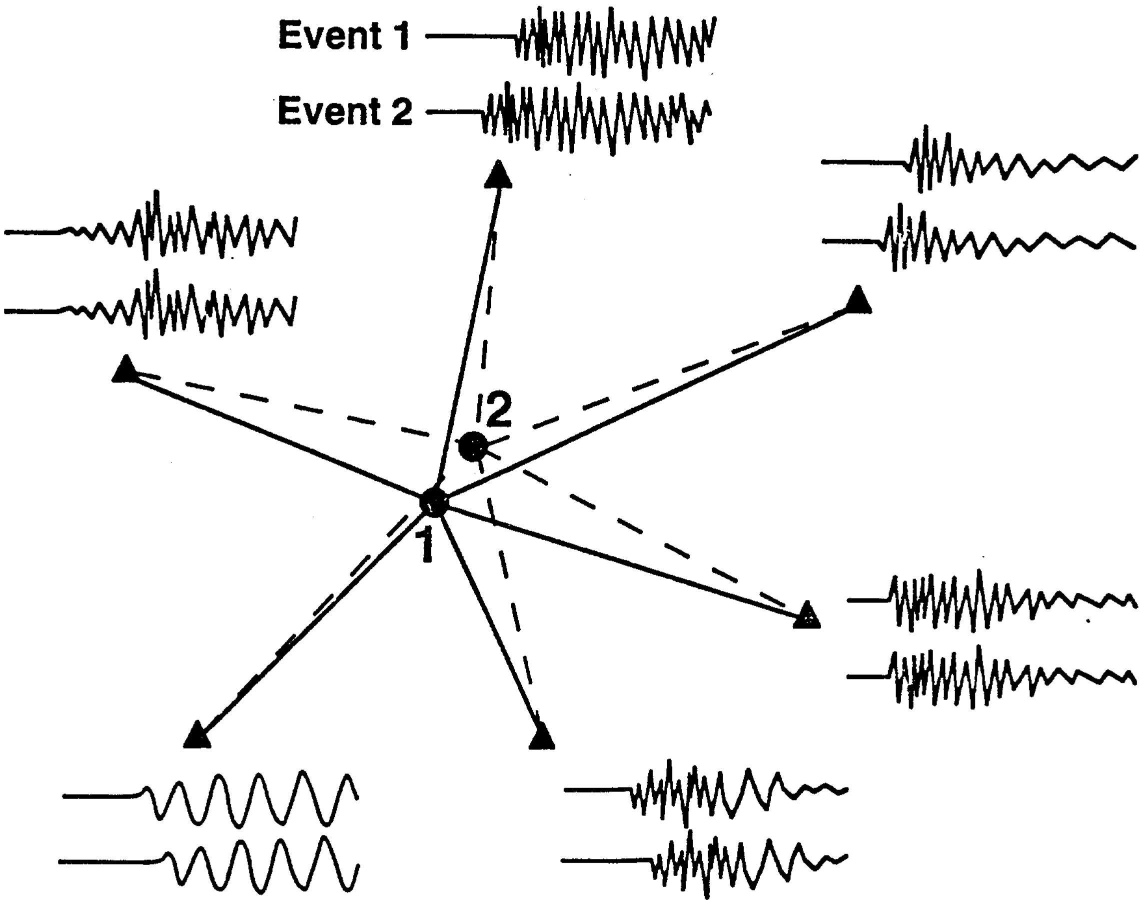

Figure 1. A cartoon showing how waveform cross-correlation has been used to improve relative event location. Two closely spaced earthquakes will often produce similar waveforms at individual seismic stations, even though the traces may vary widely between different stations due to propagation and site effects. If the waveforms are similar enough, cross-correlation can be used to measure differential times between the events; these times are more accurate than individual arrival times can be picked. These times can then be used to constrain the relative location between the two events.

Nuclear explosions at the major test sites are an ideal test case for cross-correlation methods because they provide a series of closely located events with similar source mechanisms. In addition, their locations are often precisely known so that the effectiveness of relocation methods can be directly tested. Here, we examine waveform data from two nuclear test sites—the Soviet Kazakhstan site and the Chinese Lop Nor site.

The Kazakhstan test site

For Kazakhstan, we extracted short-period, vertical component data for 30 events between 1980 and 1987 from GDSN stations as archived by the National Earthquake Information Center (NEIC) on CD-ROM. These data windows do not include the S arrivals, so our analysis is limited to P data. Figure 2 plots a comparison of seismograms recorded at 8 different stations for a pair of events, a m_b=6.1 event on 12 June 1983 and a m_b=5.9 event on 20 July 1985. The waveforms are very similar, and the cross-correlation functions show well defined peaks. Other event pairs exhibited comparable levels of correlation, and 22 events were sufficiently similar that their relative locations could be computed.

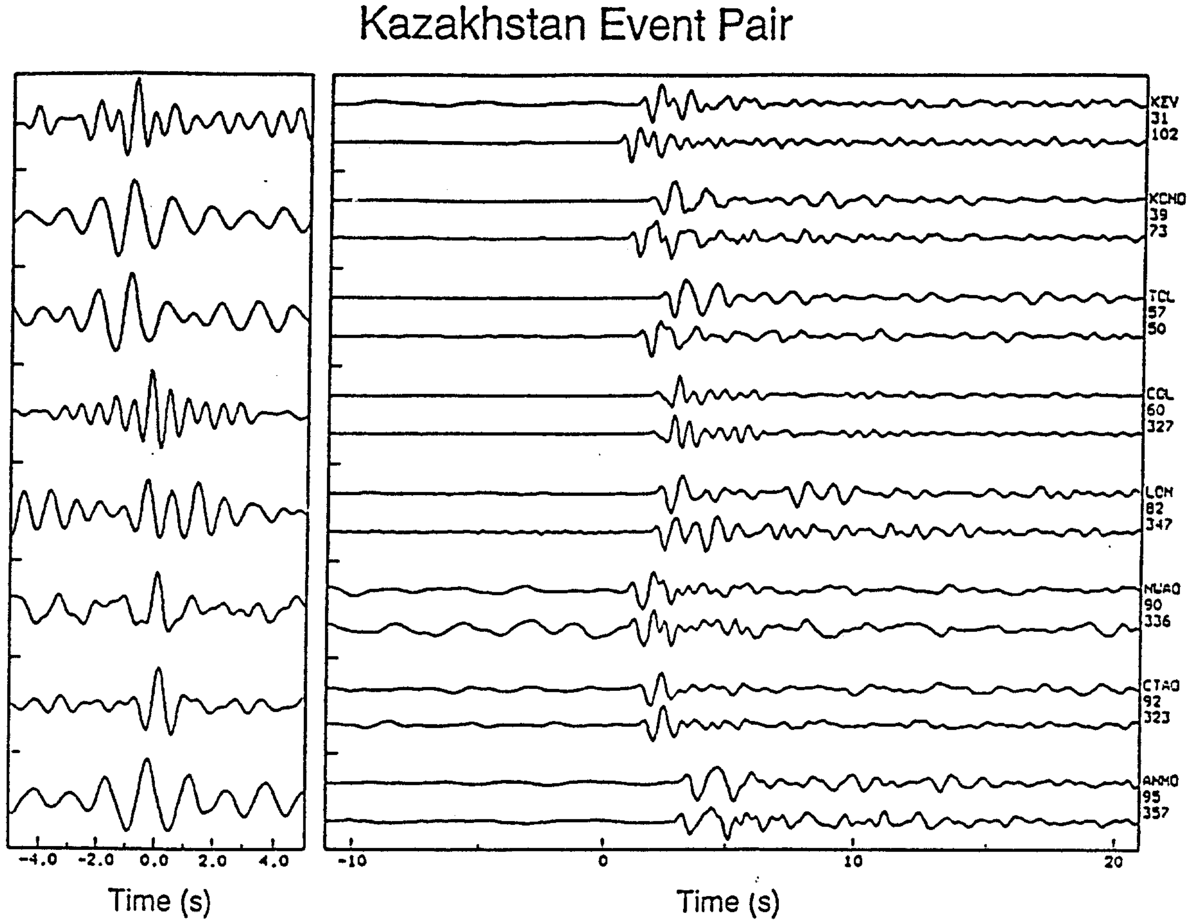

Figure 2. Short period GDSN records of the P wave from a pair of nuclear explosions at the Kazakhstan test site in the former Soviet Union. The top trace in each pair is from a m_b=6.1 event on 12 June 1983, the bottom trace is from a m_b=5.9 event on 20 July 1985. Station names, ranges, and azimuths are plotted on the right. Note the very similar waveforms produced by the two events. Cross-correlation functions for these traces are plotted on the left; the well-defined peaks can be used to define very accurate differential times at each station.

We compute cross-correlation functions between records for every pair of events. For n events, this results in a total of $n(n-1)/2$ possible pairs. From the peaks in the cross-correlation functions we estimate differential times between the waveforms. We then compute the relative location between the event pair using a grid-search, L1-norm approach [see *Shearer*, 1997, for details] for robustness with respect to data outliers. Finally we reconcile all of the differential locations from the different event pairs into a single best-fitting set of relative locations for all of the events. This is analogous to the method used by *Got et al.* [1994] for the local earthquake location problem, except that, for robustness, we use the L1-norm measure of misfit and we apply a grid-search approach to computing the differential locations, avoiding the need to linearize this step.

The resulting relocations show less scatter than the NEIC locations for the same events

(Figure 3). Estimated standard location errors for most of the events are less than 1 km. For comparison, locations obtained from analysis of satellite images by *Thurber et al.* [1994] are also plotted. These locations agree much more closely to our relocated events than to the original catalog locations. However, there are still some discrepancies, which may be caused by absolute timing errors in the waveform data (see below).

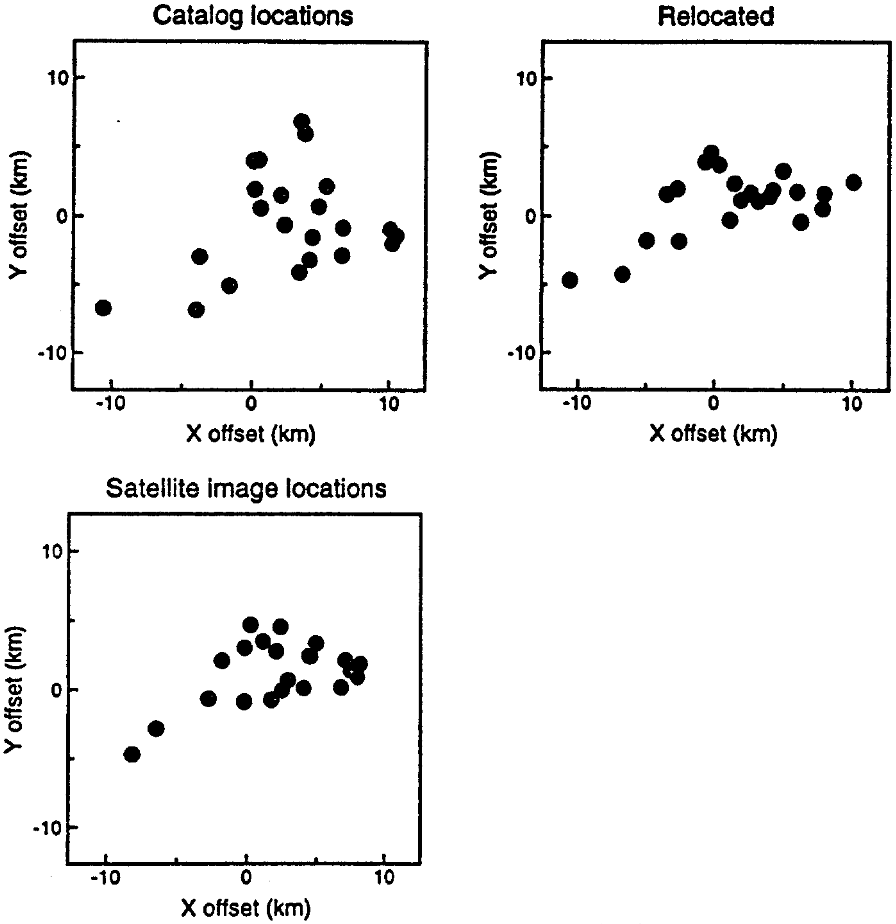

Figure 3. Relative locations for 22 events at the Balapan test site in Kazakhstan as derived from the PDE catalog (top), determined using our waveform cross-correlation procedure (middle), and estimated from satellite images by *Thurber et al.* [1994] (bottom). Note the reduced scatter in the revised locations compared to the PDE locations and the better agreement with the satellite locations.

The Lop Nor test site

For the Chinese test site, we examined data from IRIS stations for 7 events of $m_b > 5.5$ between 1990 and 1995. Figure 4 plots P arrivals at 10 different stations for a pair of events, a m_b=6.1 event on 15 May 1995 and a m_b=6.0 event on 17 August 1995. The vertical component data have been filtered to between 0.4 and 2 Hz. For this event pair, the waveforms are very similar and the cross-correlation functions show well defined peaks. Six events are similar enough to relocate with our method; our relocations for these events are compared to the PDE locations in Figure 5. The scatter in the location is reduced; the estimated location errors are generally between 1 and 3 km (in these examples, we do not attempt to solve for depth; we assume the sources are at the surface).

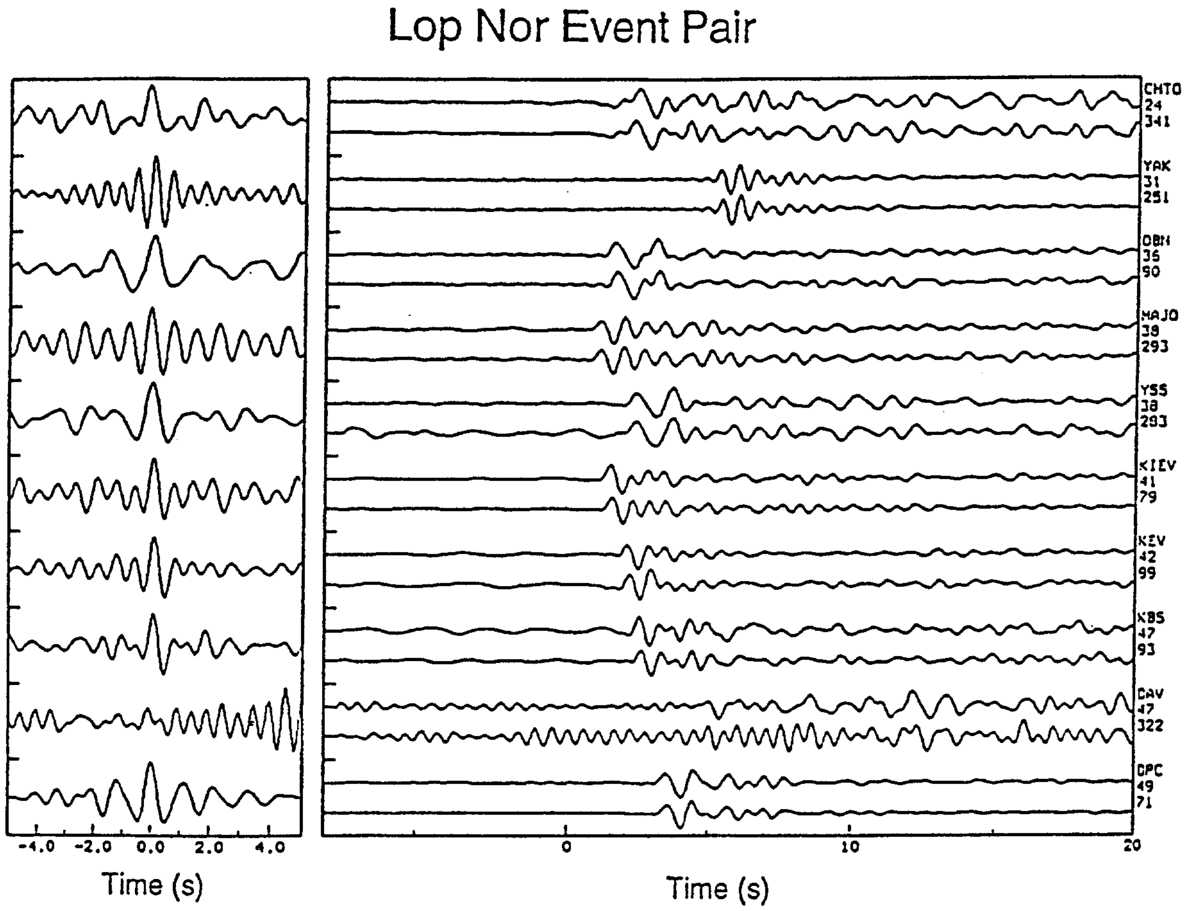

Figure 4. Teleseismic records of the P wave from a pair of nuclear explosions at,the Lop Nor test site in China. The top trace in each pair is from a m_b=6.1 event on 15 May 1995, the bottom trace is from a m_b=6.0 event on 17 August 1995. Station names, ranges, and azimuths are plotted on the right. Note the very similar waveforms produced by the two events. Cross-correlation functions for these traces are plotted on the left; the well-defined peaks for most of the stations can be used to define very accurate differential times.

One source of bias that is not removed through waveform cross-correlation is absolute timing errors for individual seismograms. This is not a problem for network data that are telemetered and recorded with a common time base. Unfortunately, in the global data, it appears that small timing errors of 0.1 to 0.3 s are common in many of the older records. This is apparent in careful examination of the cross-correlation results for the Kazakhstan data and probably is an important factor limiting the accuracy of our final results. Modern seismographs have more accurate clocks and are presumably less prone to such problems. In principle, the uncertainties associated with timing errors could be eliminated through the use of differential times between different phases, such as P and S. We plan to experiment with this approach to see if any improvements to our results are possible, and to begin characterizing the extent of timing problems in the global networks.

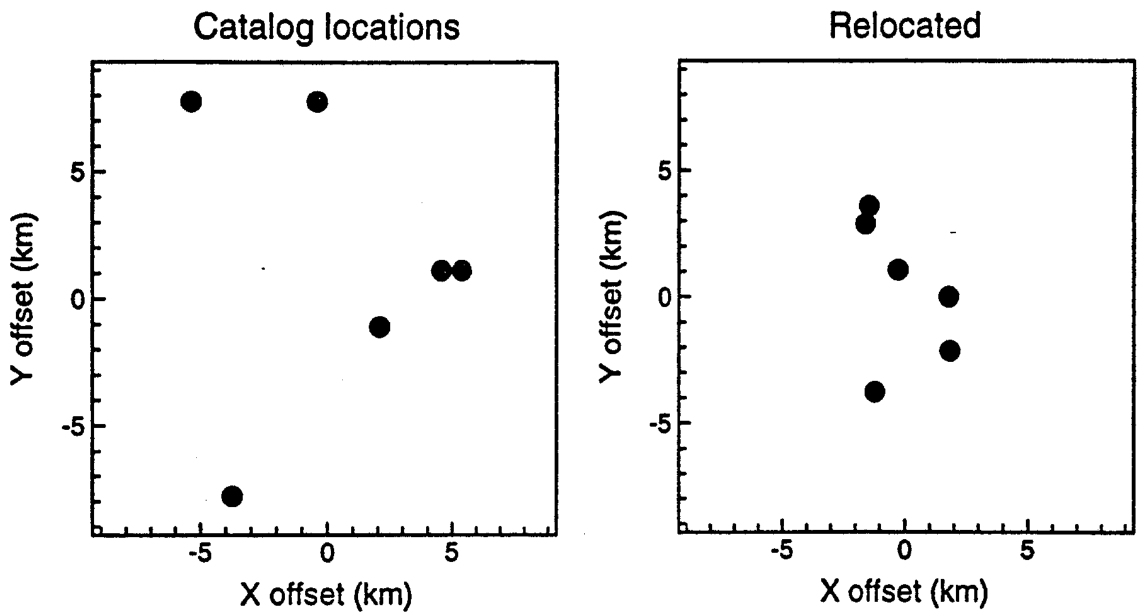

Figure 5. Relative locations for 6 events at the Lop Nor test site as derived from the PDE catalog (left) and determined using waveform cross-correlation (right). Note the reduced scatter in the revised locations.

CONCLUSIONS AND RECOMMENDATIONS

Differential locations provided by waveform cross-correlation methods promise to provide a useful complement to ongoing efforts in seismic tomography and joint-hypocenter-velocity (JHV) inversions, which improve absolute event locations but do not affect relative event locations at 1 to 20 km spacing. Waveform cross-correlation produces information in addition to differential times. For example, the optimal amplitude scaling between traces is provided by the cross-correlation function and could be used to compute differential magnitudes between event pairs. One could then solve for a best fitting magnitude for each event, probably obtaining much greater accuracy than the nominal 0.1 precision with which magnitudes are generally listed in earthquake catalogs. It also would be useful to explore the relationship between event focal mechanism and the degree of waveform similarity. If waveforms remain similar for closely spaced events with different focal mechanisms, differing primarily only in their amplitude and polarity, it might be possible to compute differential focal mechanisms using waveform cross-correlation. This would be analogous to a method used by *Ekström and Richards* [1994] to determine source parameters of closely spaced events using surface wave amplitudes. Finally, waveform cross-correlation might prove useful in detecting anomalous events in regions of known seismicity. For example, if new events were routinely cross-correlated against previous nearby events, this could provide an automated way to identify explosions.

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