An autocorrelation method to detect low frequency earthquakes within tremor

Justin R. Brown,[1] Gregory C. Beroza,[1] and David R. Shelly[2]

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[1] Recent studies have shown that deep tremor in the Nankai Trough under western Shikoku consists of a swarm of low frequency earthquakes (LFEs) that occur as slow shear slip on the down-dip extension of the primary seismogenic zone of the plate interface. The similarity of tremor in other locations suggests a similar mechanism, but the absence of cataloged low frequency earthquakes prevents a similar analysis. In this study, we develop a method for identifying LFEs within tremor. The method employs a matched-filter algorithm, similar to the technique used to infer that tremor in parts of Shikoku is comprised of LFEs; however, in this case we do not assume the origin times or locations of any LFEs *a priori*. We search for LFEs using the running autocorrelation of tremor waveforms for 6 Hi-Net stations in the vicinity of the tremor source. Time lags showing strong similarity in the autocorrelation represent either repeats, or near repeats, of LFEs within the tremor. We test the method on an hour of Hi-Net recordings of tremor and demonstrates that it extracts both known and previously unidentified LFEs. Once identified, we cross correlate waveforms to measure relative arrival times and locate the LFEs. The results are able to explain most of the tremor as a swarm of LFEs and the locations of newly identified events appear to fill a gap in the spatial distribution of known LFEs. This method should allow us to extend the analysis of Shelly et al. (2007a) to parts of the Nankai Trough in Shikoku that have sparse LFE coverage, and may also allow us to extend our analysis to other regions that experience deep tremor, but where LFEs have not yet been identified. **Citation:** Brown, J. R., G. C. Beroza, and D. R. Shelly (2008), An autocorrelation method to detect low frequency earthquakes within tremor, *Geophys. Res. Lett.*, *35*, L16305, doi:10.1029/2008GL034560.

1. Introduction

[2] Since the discovery of deep, non-volcanic tremor [*Obara*, 2002] many studies have attempted to locate it and understand its origin; however, tremor has proven difficult to study due to the lack of impulsive wave arrivals, such as those used to locate and constrain the mechanism of ordinary earthquakes. The character of tremor is similar at widely spaced stations, however, and this similarity has been exploited to localize the tremor source. An approach first used by *Obara* [2002] measures the relative arrival times of smoothed waveform envelopes to locate tremor. Another approach migrates waveform amplitudes to all possible locations to find areas of constructive interference [*Kao and Shan*, 2004]. Both these methods yield tremor locations, but are susceptible to large uncertainties, particularly in depth. They are also likely to result in large location uncertainties at times when the tremor source is spatially extended.

[3] A different approach to tremor location was introduced by *Shelly et al.* [2006] who located LFEs. LFEs are small, slow earthquakes [*Katsumata and Kamaya*, 2003; *Ide et al.*, 2007a, 2007b] that occur primarily during periods of deep tremor. Because LFEs have discernible *S*-wave, and sometimes *P*-wave, arrivals, they can be located by conventional methods. *Shelly et al.* [2006] found that LFEs locate on the down-dip extension of the seismogenic zone of the Nankai Trough. The mechanisms of LFEs were subsequently shown to be consistent with shear slip across the plate boundary [*Ide et al.*, 2007a]. Previously identified LFEs represent only a small fraction of tremor, but *Shelly et al.* [2007a, 2007b] demonstrated that much of the rest of tremor can be represented as a swarm of LFEs and in doing so they were able to localize that component of tremor under Shikoku to the plate interface.

[4] There remains an important fraction of deep tremor that does not match previously identified LFEs. Although its spectral behavior matches that of LFEs [*Shelly et al.*, 2007a], its location and mechanism remains uncertain. Moreover, in other regions where tremor has been detected, no LFEs have been identified, and hence tremor must be located by other, potentially less accurate methods. In Cascadia, for example, current locations of tremor span a very wide range in depths [*Kao et al.*, 2005], which has led to fundamentally different conclusions about the origin of tremor there. Polarization analysis of seismic array data, however, suggests that tremor in Cascadia may also be generated by slow plate-boundary slip [*Wech and Creager*, 2007].

[5] In this paper we present a new method for detecting LFEs using the running autocorrelation of tremor seismograms, and apply it to an hour of tremor under Shikoku previously analyzed by *Shelly et al.* [2007a]. We detect most of the known LFEs, as well as a large number of newly identified LFEs. The new detections fill temporal gaps in matches between tremor and LFEs. We measure the relative arrival times of the newly detected LFE waveforms, locate them, and find that they also may fill a spatial gap in previously identified LFEs. This suggests that periods of tremor in western Shikoku not previously matched with LFEs, are generated by the same mechanism, *viz.*, shear slip on the plate interface, and hence that the entirety of deep tremor in this region has a common origin.

2. Autocorrelation for Detection

[6] We analyzed velocity data from six high sensitivity (Hi-Net) stations: KWBH, OOZH, HIYH, TBEH, YNDH,

[1]Department of Geophysics, Stanford University, Stanford, California, USA.
[2]U.S. Geological Survey, Menlo Park, California, USA.

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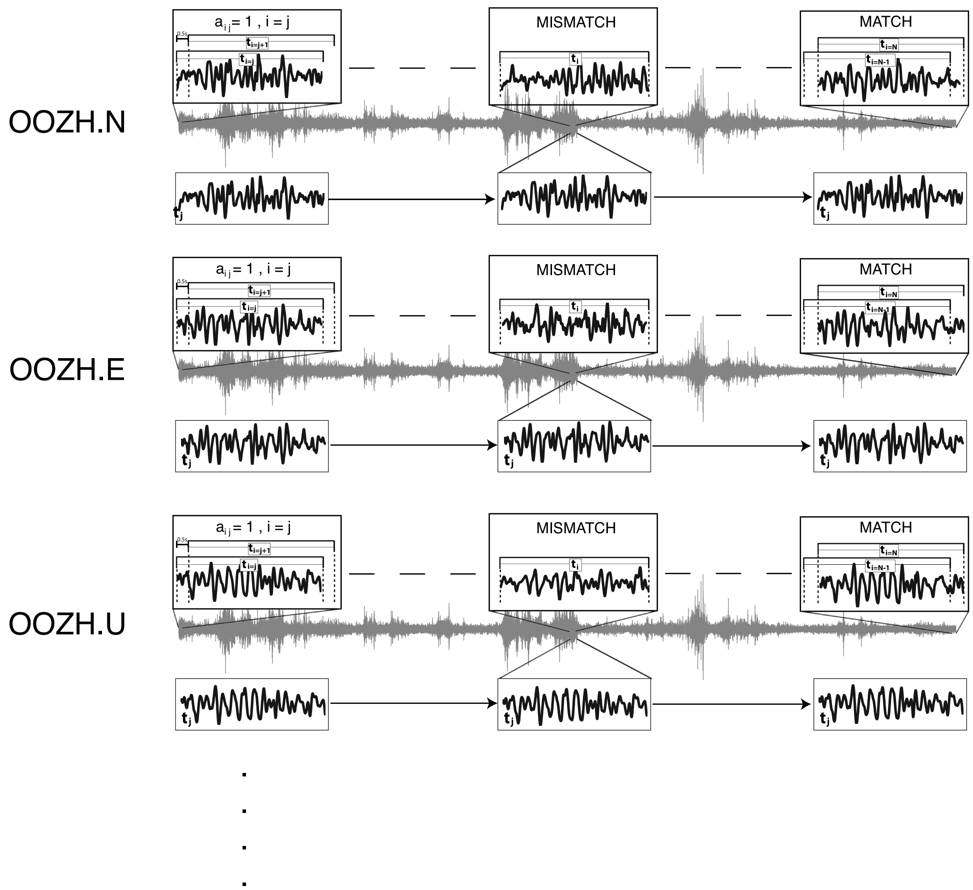

Figure 1. Technique schematic. One hour of tremor is segmented into 6 second windows lagged by 0.5 seconds. This corresponds to N = 7,188 windows. The summed normalized autocorrelation coefficient, a_{ij}, is calculated for every window pair at a common station and component.

TSYH. Hi-Net is composed of high sensitivity seismic stations installed across the Japanese archipelago after the 1995 Hyogoken-nanbu Earthquake by the National Research Institute for Earth Science and Disaster Prevention (NIED) [*Obara*, 2003]. Hi-Net stations are distributed with an average spacing of 20–30 km, and consist of three-component short period velocity seismometers installed in boreholes at depths of 100 m or greater.

[7] We bandpass filter the data from 1–8 Hz to emphasize the frequency range in which tremor and LFEs are most prominent. We use the autocorrelation of the data to search for waveforms that nearly repeat as observed across a seismic network. Our approach is closely related to that used to associate LFEs with tremor [*Shelly et al.*, 2007a]; however, in our case, the origin times and locations of potential LFEs are unknown, which means that we have to search for similarity at all possible lags. We analyze an hour on 29 August, 2005 from 17:00–18:00. We chose this window because it contains a mixture of tremor that was previously matched with LFEs and tremor that was not [*Shelly et al.*, 2007a]. We use the former to evaluate the effectiveness of our approach, and the latter to draw more general conclusions about the origin of tremor.

[8] We use the running-window autocorrelation to search for similarity at all stations and over all components. The tremor is segmented into 6-second windows that are lagged by 0.5 seconds (see Figure 1). This is longer than the 4-second window length used by *Shelly et al.* [2007a] because we do not know the move-out of the seismic phases across the network *a priori*. We experimented with longer windows, but that resulted in fewer significant detections. Because the waveform similarity is of limited duration, as is the case for known LFEs, using a longer time window results in a lower signal-to-noise ratio. We also experimented with different lag spacing. When the spacing is too small the computation time increases; whereas, large lags yield few detections because the similarity is aliased. A lag of 0.5 seconds has the potential to miss some detections, but as will become clear below, we found that it was sufficient to detect nearly all of the previously identified LFEs.

[9] Consider a network of n station components (3-component Hi-Net stations, 6 stations corresponds to n = 18) on which we record ground motion at windows represented by the vector u at time t_{i} and t_{j}. The corresponding network array correlation coefficient (CC) sum, a_{ij} can be written as:

$$a_{\mathrm{ij}} = \sum_{n} \mathrm{CC}_{\mathrm{n}} = \boldsymbol{u}(t_{\mathrm{i}}) \bullet \boldsymbol{u}(t_{\mathrm{j}}) \qquad (1)$$

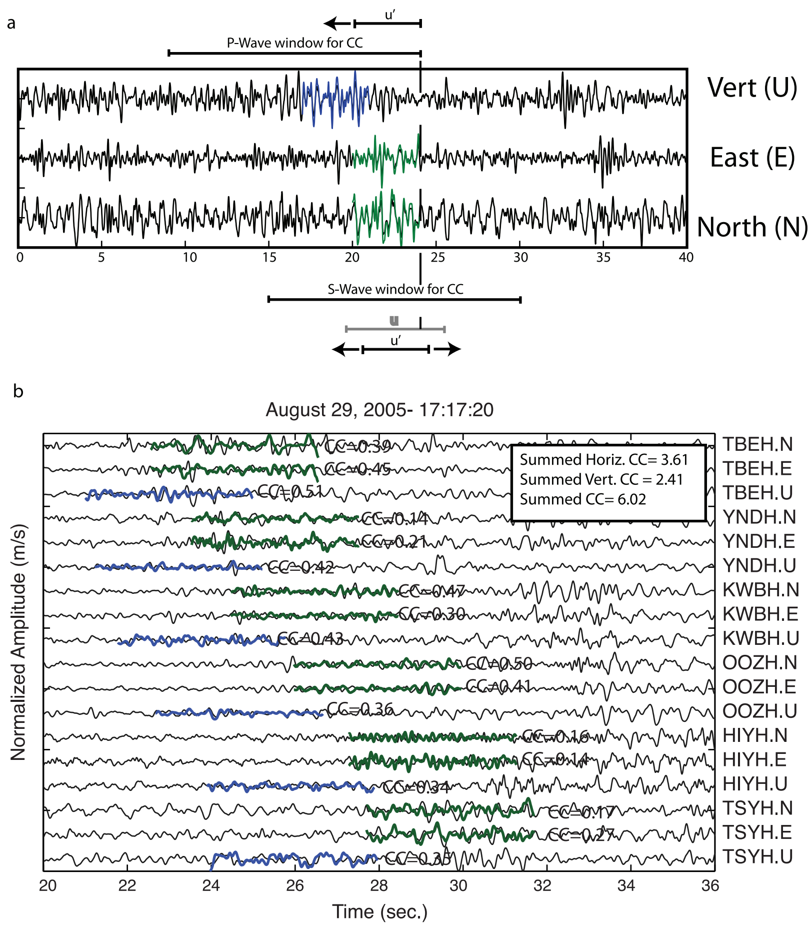

Figure 2. Waveform cross correlation. Original 6-second windows, **u**, are narrowed to a new 4-second window **u**′. (a) Horizontal components search within a 15-second time segment in order to align around the *S*-wave window (green). Subsequently, the vertical component searches for the *P*-wave window (blue) in a time segment that precedes the final horizontal alignment. (b) Continuous tremor waveforms are shown in gray. LFE waveforms are shown in blue (P-wave, vertical component) and green (S-wave, horizontal components). The normalized coefficient is shown for each. Although modest, coefficients taken together indicate a similarity that is unlikely to be due to random chance.

i.e., the sum of the normalized *CC* across the network. Summing across the network allows us to search for times when the entire network exhibits waveform similarity during tremor, and greatly enhances the ability to distinguish signal from noise. We detect on the statistics of a_{ij} relative to that of all other lags and use the median absolute deviation (MAD) to set a detection threshold [*Shelly et al.*, 2007a]. The MAD ensures that the detection statistics are not adversely affected by the fraction of the population with high values corresponding to positive detections. Time lags showing strong similarity in the autocorrelation represent either repeats, or near-repeats, of LFEs within the tremor. We save all window pairs that exceed our detection threshold of 5 times MAD, and define these as candidate events.

[10] We then apply waveform cross-correlation for all pairs of candidate events recorded at a common station. We decrease the window size of each detection window to the middle 4-seconds of the original window and remove the taper. At this stage, we treat all windows similar to "weak" detections found by *Shelly et al.* [2007a]. Closely spaced earthquakes with similar source processes should yield similar waveforms at a common station due to the similar source mechanisms and nearly identical source-receiver paths. Next, we cross-correlate the new windows at a sampling frequency of 100 Hz within a 15-second segment (appending ± 4.5 seconds to the initial window). For periods where the matched-filter running autocorrelation frequently revealed at least one detection every 15 seconds and we apply waveform cross-correlation at 0.01s precision within 15-second windows, we are effectively searching for near-repeats of tremor sample by sample. We sum the waveform cross-correlation coefficients for all components across the network and save event pairs with CC sum exceeding 5.4, which corresponds to an average coefficient value of 0.3 per component, based on typical CC measurements for previously detected LFEs [*Shelly et al.*, 2007a].

3. Event Verification and Location

[11] We organize the waveforms into 52 exclusive groups exhibiting a higher degree of similarity at all stations and components and stack them. Events showing similarity to

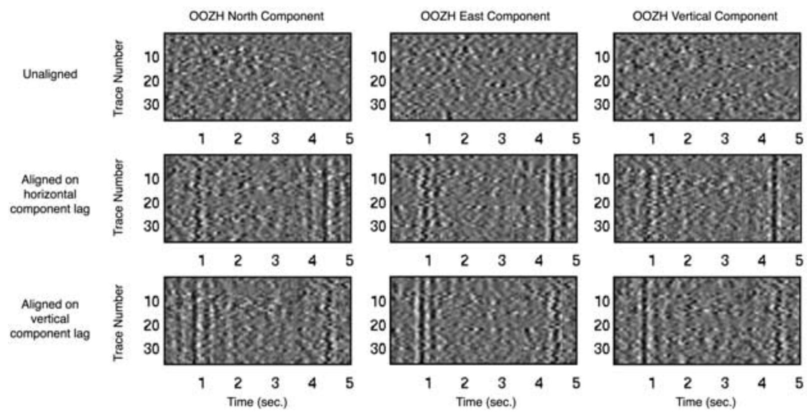

Figure 3. 38 LFEs recorded at Hi-Net station OOZH: (top) before and (middle and bottom) after cross-correlation alignment. The same seismograms are plotted below in grayscale (black = -1 and white = $+1$ amplitude) and are aligned corresponding to lags derived from respective component waveform cross-correlation in order to demonstrate the detection of both P and S arrivals. We plot 5-second waveforms to effectively demonstrate the alignment of P and S waves. Variations in *S-P* time, and hence location, lead to slightly variable *S* wave arrival times, which are apparent when the waveforms are aligned on the *P* wave.

more than one group are organized into the group where the CC value was highest. We treat each of these stacks as a template event and repeat the autocorrelation using the stacked waveform, as recorded across the network, as matched filters [*Ekstrom et al.*, 2003; *Gibbons and Ringdal*, 2006; *Shearer*, 1994]. In this round of correlation, we decrease lag to 0.05 s intervals. Because we only have 52 templates to consider, the processing time is manageable. The lag size decrease also enables us to search for a more precise window for which the correlation coefficient, a_{ij}, can be found. We increase the detection threshold to a very conservative value of 8*MAD to reduce the probability of false detections to extremely low levels [*Shelly et al.*, 2007a].

[12] Once we assemble this set of robust LFE detections, we apply waveform cross correlation to all the events recorded at a common station and component in order to solve for the lags at each. Since the data is sampled at 100 Hz, this allows us to align seismograms with a resolution of 0.01 s. We treat the horizontal and vertical components separately and analyze 15-second search windows. Windows for horizontal components are created as before, but for the vertical component, we append 9 s of tremor preceding the 6-second autocorrelation window in order to measure the *P*-wave arrival (Figure 2a). We first cross-correlate events pairs recorded at a common horizontal component and sum the waveform cross-correlation values across the entire network of horizontal components. If the average coefficient value of exceeds 0.3, then we perform a cross-correlation of vertical component cross-correlation and save values that exceed 0.3 (Figure 2a).

[13] To avoid possible repetition of overlapping events, we allow no more than 1 detection every twelve seconds, which results in a catalog of 287 events. Included in these 287 events are 174 of the 188 events previously detected by *Shelly et al.* [2007a] during the same period. The fact that a few events go undetected may be attributable to the fact that we are not comparing these events to the stronger LFEs that were previously identified by the Japanese Meteorological Agency (JMA). Also, applying this approach to a longer time interval, or even multiple tremor episodes, should allow us to recover more events.

[14] The waveforms for a representative LFE are shown in Figure 2b. The correlation coefficients are modest, but overwhelmingly positive and therefore unlikely to occur due to chance. The new detections fill temporal gaps (Figure 4a) in matches between tremor and LFEs, strongly suggesting that this part of the tremor is composed of nearly repeating LFEs.

[15] Figure 3 illustrates an alignment of 38 events that yield significant correlations across the network as seen on the three components of station OOZH. The waveform similarity on all components indicates that we are detecting a near-repeat of this LFE. We assume the alignment in the horizontal and vertical components correspond to *S*- and *P*-wave arrivals respectively, and extract *S-P* times for these events. For this hour of tremor, estimated *S-P* times at OOZH are 3.85 seconds (±0.60 seconds, Figure 4b), which indicates that the events are tightly clustered in space. *S-P* times for other stations vary from 3.5 to 4.5 seconds. We use *tomoDD* [*Zhang and Thurber*, 2003] to estimate event locations assuming a fixed velocity model from *Shelly et al.* [2006] using the cross-correlation derived relative arrival time measurements.

[16] Figures 4c and 4d show our locations for 287 LFEs, together with previously detected LFEs from *Shelly et al.* [2007a]. Our result suggests that periods of tremor that were not previously matched with known LFEs can be explained as a swarm of LFEs on the plate interface as well. Hence, our LFE locations provide strong additional evidence that tremor in this region is generated by shear slip on the plate interface.

4. Conclusions

[17] We develop a new method for detecting low frequency earthquakes within tremor using a running window autocorrelation. This method of extracting LFEs from

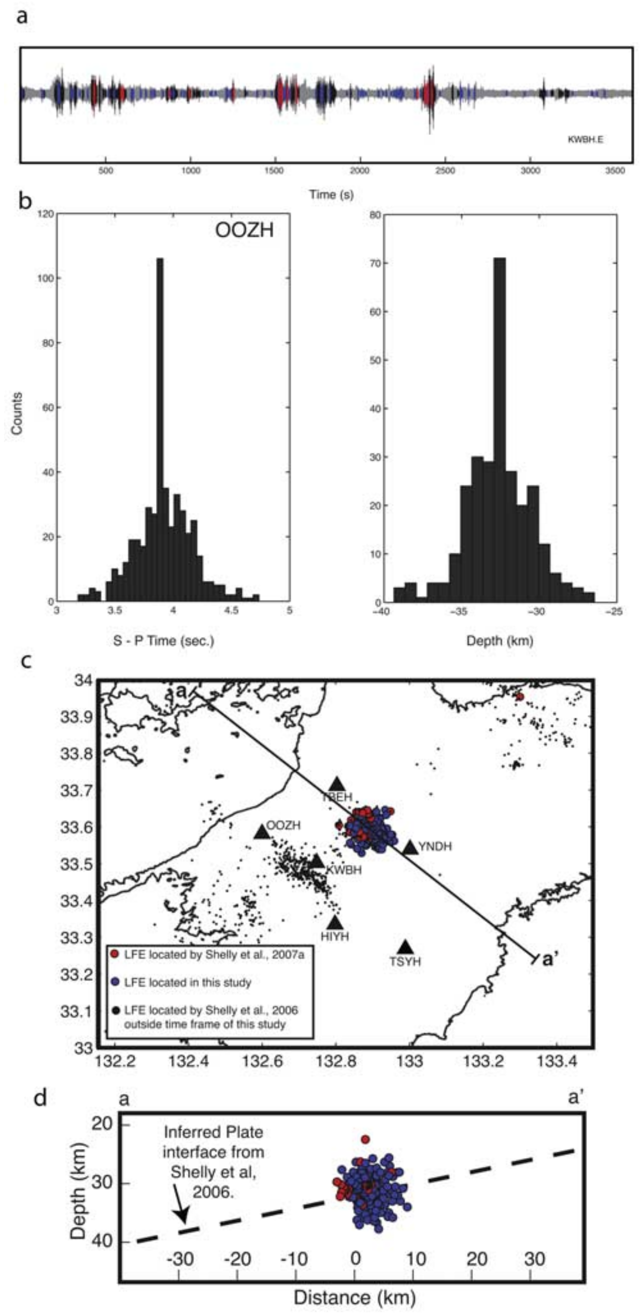

Figure 4. LFE detections and locations. (a) Temporal detections of one hour of LFEs from tremor. Black ticks indicate LFEs detected by both the previous and current study. Blue ticks are the additional events, whereas red events are events are missed LFE detections in this study. (b) Histograms for S-P times and depth distribution of locations. S-P times determined from waveform CC alignment around 3.85 sec. (±0.6 sec.) at station OOZH. Depths of LFE center around 33 km below sea level in the vicinity of the plate interface. (c) Map view and (d) cross-section view of LFEs. Blue circles indicate the 287 located in this study. Red circles indicate locations of previously identified LFEs [*Shelly et al.*, 2007a]. Black dots are other LFEs. The dashed line denotes inferred plate interface. It is worth noting that the color schemes for 4a and 4cd are different.

tremor detects both previously identified LFEs, as well as a large number of previously unidentified LFEs, without the use of prior information. Our study supports the hypothesis that deep tremor in southwest Japan is a swarm of repeating LFEs that occur on the plate interface down-dip of the primary seismogenic zone between 30–35 km. The newly identified LFEs fill temporal gaps in detections from tremor and are spatially co-located with the previous LFEs during the same hour of tremor. Applying this approach to a complete tremor sequence should allow us to generalize this conclusion. It may also allow the analysis of tremor using LFEs in other regions where deep tremor is observed.

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G. C. Beroza and J. R. Brown, Department of Geophysics, Stanford University, 397 Panama Mall, Stanford, CA 94305-2215, USA. (beroza@stanford.edu; jrbrown5@stanford.edu)

D. R. Shelly, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025, USA. (dshelly@usgs.gov)