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Authors

Ghosh, Abhijit
Huesca-Pérez, Eduardo
Brodsky, Emily
et al.

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Key Points:

- Systematic search reveals very low frequency earthquakes (VLFEs) in Cascadia
- VLFEs are associated with tremor and migrate with it in space and time
- VLFEs cluster near the peak slip during episodic tremor and slip event

Supporting Information:

- Table S1

Correspondence to:
A. Ghosh,
aghosh.earth@gmail.com

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Very low frequency earthquakes in Cascadia migrate with tremor

Abhijit Ghosh[1], Eduardo Huesca-Pérez[1], Emily Brodsky[2], and Yoshihiro Ito[3]

[1]Department of Earth Sciences, University of California, Riverside, California, USA, [2]Department of Earth and Planetary Sciences, University of California, Santa Cruz, California, USA, [3]Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan

Abstract We find very low frequency earthquakes (VLFEs) in Cascadia under northern Washington during 2011 episodic tremor and slip event. VLFEs are rich in low-frequency energy (20–50 s) and depleted in higher frequencies (higher than 1 Hz) compared to local earthquakes. Based on a grid search centroid moment tensor inversion, we find that VLFEs are located near the plate interface in the zone where tremor and slow slip are observed. In addition, they migrate along strike with tremor activity. Their moment tensor solutions show double-couple sources with shallow thrust mechanisms, consistent with shear slip at the plate interface. Their magnitude ranges between *Mw* 3.3 and 3.7. Seismic moment released by a single VLFE is comparable to the total cumulative moment released by tremor activity during an entire episodic tremor and slip event. The VLFEs contribute more seismic moment to this episodic tremor and slip event than cumulative tremor activity and indicate a higher seismic efficiency of slow earthquakes in Cascadia than previously thought. Spatiotemporal correlation of VLFE and tremor activity suggests that they are the results of the same physical processes governing slow earthquakes.

1. Introduction

It has become clear in the last decade or so that fault slip covers a wide range of motion including fast slip in the form of ordinary earthquakes, slow slip, and associated seismic events occurring adjacent to the seismogenic zone in most cases [*Gomberg*, 2010]. Multiple styles of slip likely interact and affect the stress field along the fault plane including the seismogenic zone, where damaging earthquakes nucleate. It has recently been recognized that slow earthquakes occur in major plate boundary faults worldwide, in most cases downdip of seismogenic zone [*Schwartz and Rokosky*, 2007]. Seismic signatures of slow earthquakes—tremor, low-frequency earthquakes (LFEs), and very low frequency earthquakes (VLFEs)—are, however, difficult to detect and locate. Tremor is the most common form of seismic signal associated with slow earthquakes. LFEs have been found in a number of places where tremor is abundant [e.g., *Sweet et al.*, 2014; *Shelly et al.*, 2007; *Brown et al.*, 2009]. VLFEs, however, remain elusive in many regions that experience slow earthquakes. So far, the most convincing evidence of VLFEs comes from southwest Japan [*Ito et al.*, 2007] and Royuku trench [*Ando et al.*, 2012]. In Cascadia, finding VLFEs remain challenging even though it is one of the well-studied regions in terms of slow earthquakes and tremor. Imaging with mini-seismic arrays shows a number of interesting tremor migration characteristics during episodic tremor and slip events [*Ghosh et al.*, 2009, 2010a, 2010b, 2012; *Zhang et al.*, 2011; *Vidale et al.*, 2011]. Activities of VLFEs and their spatiotemporal distribution in Cascadia, however, remain largely unknown. Here we did a systematic search for VLFEs in the Cascadia subduction zone under Washington (WA) state during an episodic tremor and slip event. We detect and locate VLFEs, estimate their source parameters by a moment tensor inversion method, analyze their spatiotemporal distribution relative to tremor, and explore implications on possible source characteristics of slow earthquakes.

2. Data and Methods

We analyze three-component publicly available seismic data from six broadband stations in northern Washington and a station in southern Vancouver Island for August 2011, which is a period of vigorous tremor activity in this region during an episodic tremor and slip event. We use a grid search moment tensor inversion algorithm [*Ito et al.*, 2009] to detect VLFEs and estimate their locations and moment tensors. We initially divide the study area in a 3-D grid with 0.1° spacing horizontally and 5 km spacing vertically. The grid covers a wide geographic area containing the tremor zone and extends beyond it

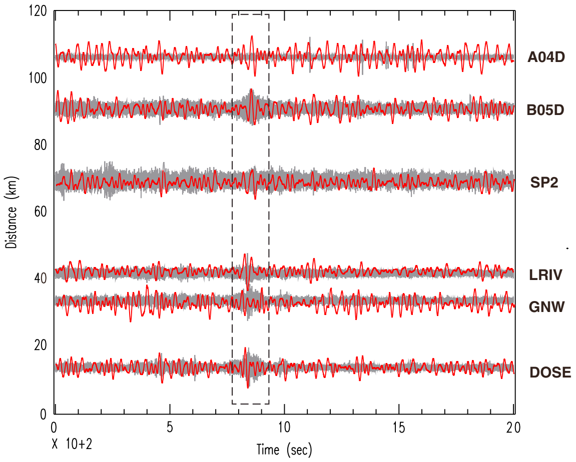

Figure 1. VLFE (red) and tremor (grey) seismograms. Red and grey velocity seismograms are recorded at vertical channels, and filtered in 0.02–0.05 Hz and 2–8 Hz, respectively. Different amplitude scales are used for red and grey seismograms. The dashed rectangle encloses the VLFE signal. This VLFE occurs on 21 August 2011 at 04:09:06 UTC with an *Mw* 3.7. More details on this event can be found in Figures 2–4.

in east and west. In other words, we are not constraining the location in the tremor zone in any direction. After removing instrument response from the seismic data, we filter the displacement seismograms in 0.02–0.05 Hz and use a 90 s sliding time window with 1 s time step. At each time step, we obtain a point source centroid moment tensor solution at each grid node, assuming an impulse function source, and identify the solution that maximizes the variance reduction, which is a measure of the misfit between observed and synthetic waveforms. To identify VLFEs, we select the time periods with high variance reduction relative to the background. We eliminate the windows with cataloged earthquakes and teleseismic or regional wave trains. Finally, we use different combinations of stations to obtain solutions with a finer horizontal (0.025°) and vertical grid (1 km) at each target window and keep only the stable solutions. We use a 1-D seismic velocity structure for this area [*Crosson*, 1976]. A VLFE catalog produced in this study is provided as a supporting information.

3. Observations

3.1. Very Low Frequency Earthquakes

We detect and locate five VLFEs under WA state and southern edge of the Vancouver Island. They are enriched in frequencies between 0.02 and 0.05 Hz but are depleted in higher frequencies compared to regular earthquakes (Figures 1 and 2). Four out of five VLFEs are located north of WA near the bend in the subduction zone where strike changes from NS in the south to NW-SE in the north (Figure 4). There is one VLFE located near Puget Sound, south of the cluster. The best estimated depths range between 30 and 55 km with an average of 49 km. Due to limited broadband coverage and low-frequency nature of the signal, depths are not well constrained. Moment magnitudes (*Mw*) range between 3.3 and 3.7. Focal mechanisms show one shallowly dipping nodal plane striking generally NW-SE (Figures 3 and 4). Shallow thrust focal mechanism and the orientations of the nodal planes are consistent with thrust faulting at the subduction interface in this area. All the VLFEs we detected occur between 17 and 26 August, even though we have examined the entire month of August, applying the same method. Based on the

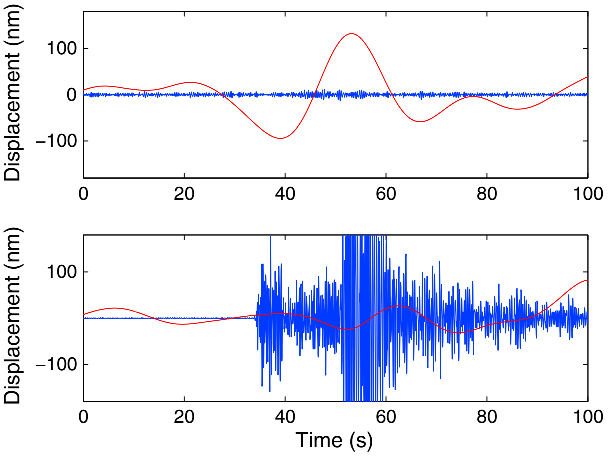

Figure 2. Comparison between VLFE and local regular earthquake in Cascadia. Red and blue seismograms are filtered in 0.02–0.05 Hz and 2–8 Hz, respectively. (top) Time period containing a VLFE and (bottom) a local regular earthquake. Note that VLFE is enriched in lower frequency and depleted in higher frequencies compared to the local regular earthquake. EW channel of station B05D is used. The same VLFE is used in Figures 1 and 3. The local regular earthquake occurs on 12 August 2011 at 06:02:11.52 UTC and has a local magnitude of 3.3 (Advanced National Seismic System composite catalog event ID 201108122020).

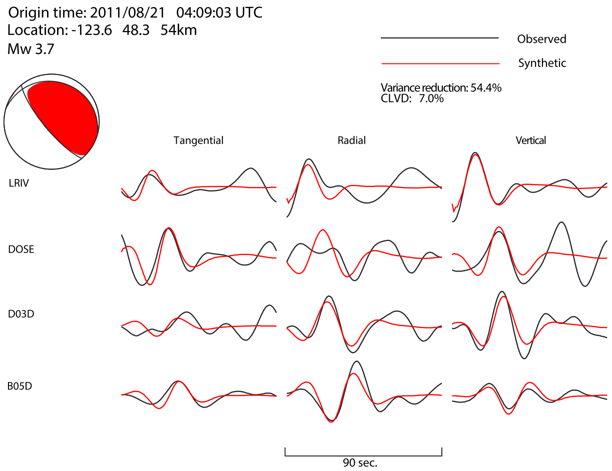

Figure 3. An example of results of centroid moment tensor solution of a VLFE. The same VLFE is used in Figures 1 and 2.

tremor activity, the episodic tremor and slip event appears to start at the end of July and continue till early September 2011.

3.2. VLFEs, Tremor, and Slow Slip

We chose to investigate August 2011 because this time period includes an episodic tremor and slip event with prolific tremor activity and slow slip. We find VLFE activity during 10 days in the middle of the episodic tremor and slip event, although the total tremor and slip event lasted for about a month. Four out of five VLFEs cluster in the area that often produces peak geodetic slip in episodic tremor and slip events [*Szeliga et al.*, 2008]. Interestingly, VLFEs are located within a relatively narrow zone along strike where tremor is located, even though our search area extends much beyond the tremor zone.

VLFE activity is correlated with tremor activity both in space and time. Tremor activity started south and slowly migrated northward along strike at ~8 km/day (Figure 5). The first VLFE occurred on 17 August near the Puget Sound when tremor was migrating under this area. After a quiescence of 3 days, the next event is detected just north of WA, under the Strait of Juan de Fuca. In next 6 days, we detected four VLFEs in the same general area. By this time, tremor has also moved to this area continuing its northward migration. These events form the northern VLFE cluster that coincides with high tremor activity and peak slow slip during this episodic tremor and slip event [*Szeliga et al.*, 2008]. Overall, it appears that VLFE activity migrates with tremor and by inference, slow slip, and is most active in the area of peak slow slip.

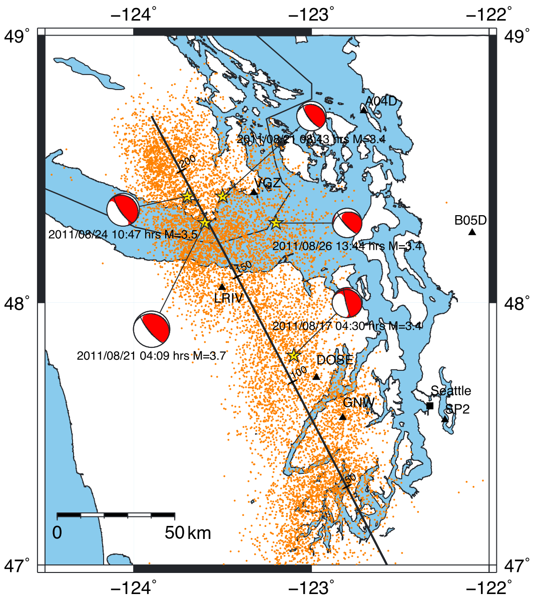

Figure 4. Tremor (orange dots), VLFEs (yellow stars), and their focal mechanisms during August 2011. The date of occurrences and moment magnitudes (*Mw*) of VLFEs are noted. Black triangles are the seismic stations used to obtain source parameters of the VLFEs. The black solid line is approximately parallel to the average strike of the subduction zone and is used to make Figure 5. The tremor catalog is obtained from http://pnsn.org/tremor. Tremor detected between 31 July and 2 September 2011 is used to show the tremor distribution during this episodic tremor and slip event.

VLFEs detected in Cascadia are quite similar to the ones found in southwest Japan in terms of their frequency characteristics, magnitude, and spatiotemporal distribution. They disappear fairly quickly outside the frequency band of 0.02–0.05 Hz. The lowest detectable VLFEs are *Mw* 3.3 and they do not reach up to *Mw* 4. VLFEs are located within the tremor band and track the slow migration of tremor along strike. Interestingly, they appear to be clustered in the patch that experiences the highest slip during this slow earthquake in Cascadia. Similar spatial clustering has been observed in southwest Japan where VLFEs tend to occur only in parts of the area ruptured by slow earthquakes [*Obara*, 2011].

4. Implications and Conclusions

A clear correlation between VLFE and tremor activity in space and time suggests that they are results of the same processes along the plate interface during slow earthquakes. Moreover, location of the VLFE cluster in the peak slow slip

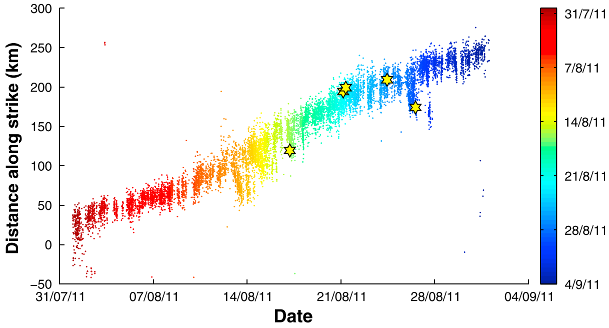

Figure 5. Spatiotemporal distribution of tremor (dots) and VLFEs (yellow stars) in space time domain. The abscissa represents time, and the ordinate shows distance along the black solid line in Figure 4. Tremor is color coded by time. Note that VLFE activity migrates with tremor.

area indicates a strong association with slow earthquakes. In addition, they are characterized by low stress drop and slow rupture velocity [*Ito and Obara*, 2006], similar to other seismic events associated with episodic tremor and slip. While tremor represents the higher-frequency seismic manifestation of slow earthquakes, VLFEs may represent the lower part of the spectrum. VLFEs generally occur during strong bursts of tremor. However, not all strong bursts are associated with detected VLFEs. Therefore, whether tremor and VLFEs represent different parts of the frequency spectrum of the same slow seismic event remains an open question.

Slow earthquakes (episodic tremor and slip events) are considered to be seismically inefficient as seismic moment released by tremor activity is a tiny fraction of total geodetic moment, typically equivalent to *Mw* 6.8 event in this part of Cascadia [*Kao et al*., 2010]. Total cumulative moment released by all tremor activity during an entire episodic tremor and slip event [*Kao et al*., 2010] is comparable to the moment released by a single VLFE detected in this study. Hence, VLFEs contribute more seismic moment to this episodic tremor and slip event than cumulative tremor activity. Total cumulative moment released by five VLFEs found in this study is equivalent to an *Mw* 3.9 event. It is still 5 orders of magnitude smaller than a typical episodic tremor and slip event in this region in terms of the total moment release constrained by geodetic data. The rest of the moment is generally attributed to the "silent" slip. Presence of VLFEs in Cascadia suggests that slow earthquakes are seismically not as inefficient as previously thought based solely on tremor activity. Relatively larger sizes of VLFEs combining with improved detection may boost the energy radiated seismically accounting for part of the missing moment and provide a better estimate of seismic efficiency of slow earthquakes.

It is worth noting that the stringent criteria we applied to detect and locate VLFEs in this study result in robust solutions but a rather conservative estimate of VLFE activity. It is likely that there are more VLFEs that are occurring in this time period but not detected in this study. Poor signal-to-noise ratio and limited broadband station coverage are additional limitations contributing to the lower level of detection. Nevertheless, VLFEs constitutes an important seismic signature of slow earthquakes and present an opportunity to study their source physics. Discovery of VLFEs in Cascadia opens up new avenues to study mechanisms controlling slow earthquakes, frictional properties in the transition zone, and physics of fault motion.

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