Repeating VLFEs During ETS Events in Cascadia Track Slow Slip and Continue Throughout Inter-ETS Period

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Abstract

Episodic tremor and slip (ETS) events in Cascadia include slow earthquake phenomena such as slow slip events, tremor, low frequency earthquakes (LFEs), and very low frequency earthquakes (VLFEs; Rogers & Dragert, 2003, https://doi.org/10.1126/science.1084783). Using VLFEs detected from a grid-search centroid moment tensor inversion algorithm in the 2011 (Ghosh et al., 2015, https://doi.org/10.1002/2015GL063286) and 2014 (Hutchison & Ghosh, 2016, https://doi.org/10.1002/2016GL069750) ETS events as templates, we apply a matched filter algorithm to create a VLFE catalog for each ETS event. We also use the 2011 template events to create a VLFE catalog from July 2011 through the end of 2012, which encompasses both the 2012 ETS event and an inter-ETS period. The successful application matched filtering intrinsically suggests that VLFEs are repeating events, of which thousands were detected during each ETS event. The findings contained herein come shortly after the successful application of a similar matched filter methodology in Western Japan where a number of VLFEs were also successfully detected (Baba et al., 2018, https://doi.org/10.1002/2017GL076122). The high temporal resolution of these VLFE catalogs show a significant increase in VLFE activity during ETS events that drops off immediately before and after the ETS period. A comparison of VLFE activity to GPS data shows that VLFE tracks slow slip, even when tremor is not occurring or is behaving anomalously during ETS periods. Finally, we find continued VLFE activity during the inter-ETS period for all template events, though the extent of reactivation of VLFE asperities and their spatiotemporal coincidence with tremor is varied among the template events.

1. Introduction

Very low frequency earthquakes (VLFEs), like low frequency earthquakes (LFEs) and tremor (a cluster of LFEs) are a type of seismic event that are interpreted to represent shearing on the fault plane, typically in the transition zone (e.g., Ghosh et al., 2015; Ide, Beroza, et al., 2007; Ide, Shelly, & Beroza, 2007; Ito et al., 2009; Shelly et al., 2006). VLFEs and LFEs are types of earthquakes that are thought to obey an empirically derived slow earthquake linear moment scaling law that differentiates these events from regular earthquakes (Ide, Beroza, et al., 2007). Slow earthquakes are an umbrella term that encompasses aseismic slow slip events (SSEs), VLFEs, LFEs, and tremor, which consists of clustered arrivals of LFEs. There remains uncertainty as to the source properties of these events, their relationships to each other, if they are differing manifestations of the same event (Gomberg et al., 2016), or if the slow earthquake scaling relationship is even a valid characterization of such events. Many studies indicate spatiotemporal correlations between tremor and VLFE activity in Japan (Ito et al., 2009), Cascadia (Ghosh et al., 2015), and Costa Rica (Walter et al., 2013). These observations prompted the development of a model suggesting that VLFEs might be the result of filtering a seismic signal of clustered LFEs in the 20- to 50-s period band and do not represent discrete seismic events (Gomberg et al., 2016). Hutchison and Ghosh (2016), however, detected VLFEs during the 2014 ETS event in Cascadia that occurred asynchronously with peak tremor/LFE activity, contradicting this alternative source model for VLFEs. Nonetheless, determining the nature of VLFEs is significant as they contribute the largest seismic moment in ETS events and because slow earthquakes can increase the probability of regular earthquakes (Obara & Kato, 2016). Moreover, a recent study in Alaska revealed a VLFE acting as a transition between a foreshock sequence and the nucleation of an Mw 3.7 earthquake in a strike-slip setting in Cascadia (Tape et al., 2018).
The characteristic period band of VLFEs is 20–50 s, unlike the more commonly studied LFEs and tremor that have a characteristic frequency band of 2–8 Hz (Ide, Beroza, et al., 2007; Ide, Shelly, & Beroza, 2007). It is notable that this characteristic period band for VLFE is derived empirically from observations of signal-to-noise ratios and that the mechanism, if one exists, for such a distinctive frequency output is still unknown. VLFE signal duration in a seismogram can last from 50 to 200 s, though in Cascadia, their signal duration is typically ~90 s. Magnitudes of VLFEs in Cascadia range between $M_w$ 3.1 and 4.3; thus, for an individual event, its moment release is greater than that of any other discrete slow seismic event. Like other types of slow seismic events, VLFEs are thought to result from the rupture of rate weakening patches within a rate strengthening background (Ghosh et al., 2015). The rupture duration of a VLFE can last from several to tens of seconds (Ide, Beroza, et al., 2007; Ide, Shelly, & Beroza, 2007). Slow earthquakes that occur downdip of the locked zone are shown to load stress updip to the locked part of the fault, potentially increasing the probability of generating a megathrust earthquake (Beroza & Ide, 2011; Rogers & Dragert, 2003).

Cascadia is the first region where VLFEs have been observed as occurring both spatiotemporally coincidentally and asynchronously with tremor during different ETS events. A study by Ide (2016) stacked tremor events and filtered the signal in the very low frequency band (0.02–0.05 Hz), inverting the results for VLFE locations. The VLFE source locations were consistent with tremor locations, indicating that VLFE signals were abundant throughout the region of this study during periods of tremor and slow slip. Given the detection method, findings from this study inherently suggest a relationship between tremor and VLFE. Further, during the 2011 ETS event, VLFEs and tremor were spatiotemporally coincident (Ghosh et al., 2015). However, in the 2014 ETS event, VLFEs and tremor were spatiotemporally asynchronous (Hutchison & Ghosh, 2016). Baba et al. (2018) used a matched filter method, similar to that applied herein, and found a strong correlation between long-term SSEs and ETS events and the number of VLFEs, though this correlation was not ubiquitously observed across all three regions included in the study. One region behaved differently than the neighboring regions in that the number of VLFEs did not correlate as clearly with ETS events and long-term SSEs, though tremor near the area did show a correlation, suggesting that different VLFE source regions may behave differently.

Given the contrasting activity during the 2011 and 2014 ETS events in Cascadia, it is important to characterize VLFE behavior in order to determine more about their source mechanics and elucidate their role in ETS activity. Currently, a limited catalog of VLFE events exists for the 2011 and 2014 ETS events. Here we expand the catalog during these ETS events using the existing VLFEs as templates using a matched filter method (Shearer, 1994). Additionally, we analyze the inter-ETS period between the 2011 and 2012 ETS events, which suggest inter-ETS VLFE activity for all template events.

### 2. Data and Methods

#### 2.1. Data

The seismic data used for this study is from three-component broadband stations in the Pacific Northwest Regional Network (UW), the Canadian National Seismograph Network (CN), and the U.S. Transportable Array (TA). For the 2011 ETS event, we analyze 1 July 2011 to 1 October 2011 though the ETS event occurred from 23 July 2011 to 6 September 2011; for the 2014 ETS event, we analyze 1 October 2014 to 1 February 2015, though the ETS occurred from 3 November 2014 to 10 December 2014 and was divided into two subevents, which are separated into distinct events on 23 November 2014. We also generate a catalog that begins on 1 July 2011 and ends on 1 December 2012. This time period includes two ETS periods and one inter-ETS period, which we define as 23 July 2011 to 6 September 2011, 30 August 2012 to 11 October 2012, and 6 September 2011 to 30 August 2012, respectively. These date ranges are based on tremor data from the Pacific Northwest Seismic Network (PNSN; Wech, 2010).

#### 2.2. Grid Search Centroid Moment Tensor Inversion

Before searching for additional VLFEs, instrument response is removed and data are filtered between 0.02 and 0.05 Hz. Our template events were detected using a grid search centroid moment tensor inversion method (Ghosh et al., 2015; Hutchison & Ghosh, 2016; Ito & Obara, 2006) that provides parameters such as the location, time, and moment tensor solution. The grid, with horizontal spacing of 0.1° × 0.1° and 5 km in depth, extends from the trench to just east of Cascade Range. The moment tensor inversion algorithm uses...
a 90-s time window with a 0.1s time step, and a solution is calculated for each node using a Green's function derived from a 1-D velocity model (Crosson, 1976). Initially detected events are confirmed with a second grid search centroid moment tensor inversion that contains a finer grid with node dimensions of 0.025° × 0.025° and 1-km depth to maximize spatial resolution. We also ensure stability of the solution by using different sets of stations to confirm the same solution. The optimal solution (i.e., the best configuration of stations) will have the highest variance reduction (a measure of similarity between the synthetic and observed seismograms) and a low compensated linear vector dipole value.

2.3. Matched Filter Method

Using the five template VLFEs detected during the 2011 ETS event and the eight templates during the 2014 ETS, we perform a cross correlation or a type of matched filter analysis: Super-Efficient Cross Correlation (SEC-C; Senobari et al., 2018). It should be noted that the source location of these template events, and thus matched filter source locations, can be up to ~100 km apart (Figure 1 and Table 1). Each template event is generated using three-component broadband data from the stations included in the best moment tensor inversion solution. Each template event is compared to continuous waveform data from the same respective stations and channels as the template event with a sliding time window. A summed cross-correlation coefficient value is calculated for each time step (1 s). Time windows with values above a determined threshold value are cataloged as VLFEs.

We perform an extensive matched filter analysis of background noise to select cross-correlation threshold values. Theoretically, VLFEs should have higher cross-correlation values than background noise because they are real repeating events. If correct, this hypothesis can provide a quantitative method to derive cross-correlation threshold values for selecting VLFEs above the background. We select 100 random time windows that presumably consist of background noise because they were not detected by the template events. Using the station configuration for each respective template event, we create background noise
catalogs for all 100 background noise time windows during the same time period (1 June 2011 to 1 December 2013) as the template events. We then determine the mean of the third highest summed cross-correlation coefficients (third only to the maximum) for each configuration of stations for each respective VLFE template event. We use this value, which varies for each template event as a cross-correlation threshold value for VLFEs. We chose this value because it conservatively enforces a direct comparison to the background noise levels in the VLFE frequency band, but it nonetheless yielded somewhat similar results to using 6 times the median absolute deviation (MAD) of all the summed cross-correlation values. Additionally, we used the third highest value as opposed to the second or the fourth, because the third highest represents an empirical “happy medium” between such a high threshold that we may be missing events and such a low value that we begin to detect too many erroneous events. Using this method for threshold picking will allow for more automated VLFE cataloging in the future. Applying Gaussian statistics, 6 times the MAD of the summed cross-correlation values is equal to ~4 standard deviations, equating to a false detection probability of $3 \times 10^{-5}$. This corresponds to a false detection rate of ~0.6 per template/per day if using the MAD approach for selecting a cross-correlation threshold, which accurately captures our findings and the background noise.

Once a catalog of matched filter detected VLFEs is generated, we stack the detections from each template at each station from each individual channel (Figure 2). We invert the stacked seismograms from the VLFE-matched filter detections for each individual template event, using its respective station configuration. Theoretically, since the stacked seismogram should be very similar to that of the original template event, the stacked inversion and original template event should be similar. This process is conducted to ensure that our matched filter process was completed properly and because the results of the stacked inversion can reveal source properties of the matched filter detections including the focal mechanism and location of the events (though these should mimic that of the original template event). The variance reduction of each stacked centroid moment tensor inversion is greater than 40%.

### 2.4. Spatiotemporal Analysis of VLFE Versus Tremor Versus Slow Slip

Using the enhanced VLFE catalogs, we perform spatiotemporal analyses to explore the relationship between VLFE, tremor, and slow slip. The stacked moment tensor inversion solutions for each stacked event are inferred as the source location of the repeating events detected by the respective template event. Then, a 50-km radius is taken around the inferred epicenter of the repeating VLFEs. To establish a relationship between VLFE and tremor, we perform a spatiotemporal comparison of the tremor that falls within the 50-km radius of the source location for each stacked solution for both ETS events. Given the poorer temporal constraints on geodetic data, we simply compare position data from the closest GPS stations (stations ALBH, P435, P436, and P064) against the VLFE and tremor data.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
<th>Lon (°W)</th>
<th>Lat (°N)</th>
<th>Depth (km)</th>
<th>Magnitude (Mw)</th>
<th>Template number</th>
</tr>
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<tr>
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<td>04:30:28</td>
<td>123.075</td>
<td>47.825</td>
<td>53</td>
<td>3.4</td>
<td>1</td>
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<td>21/08/2011</td>
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<td>48.3</td>
<td>54</td>
<td>3.7</td>
<td>2</td>
</tr>
<tr>
<td>21/08/2011</td>
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<td>48.4</td>
<td>52</td>
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<td>24/08/2011</td>
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<td>48.35</td>
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<td>3.5</td>
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<td>26/08/2011</td>
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<td>55</td>
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<td>5</td>
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<td>02/12/2014</td>
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<td>48.825</td>
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<td>3.6</td>
<td>6</td>
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<td>47</td>
<td>3.7</td>
<td>7</td>
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<td>48.825</td>
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<td>3.6</td>
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<td>3.9</td>
<td>9</td>
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<td>11/12/2014</td>
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<td>3.8</td>
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<td>36</td>
<td>4.1</td>
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<td>49.1</td>
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Note: In addition, each event is assigned a template number in the final column that corresponds to Figure 1.
3. Results

Using the matched filter method, we were able to efficiently detect thousands of new VLFEs during each ETS and during the 2011–2012 ETS period. For both ETS events, we observe increased VLFE activity during ETS events and decreased VLFE activity when ETS events are not occurring (Figure 3). Spatial analyses comparing VLFE to tremor and slow slip as recorded by GPS, however, reveals that each ETS event has a distinct relationship between tremor and VLFE activity (Figures 4 and 5). Some activity, however, is also detected in the inter-ETS period from 2011 to 2012 (Figure 6).

Time windows above the summed cross-correlation coefficient threshold value are cut and stacked (Figure 2). The grid-search centroid moment tensor inversion algorithm is then applied to the stacks to ensure that the stacked solutions closely match that of the original template event in terms of their moment tensor, location, variance reduction, and compensated linear vector dipole value. The similarity of stacked and the original moment tensor solutions further confirm that the VLFEs are repeating events. We performed this analysis for each template event across the entire catalog, then also for ETS periods and inter-ETS periods to confirm that both time periods were producing similar inversion solutions.

3.1. The 2011 ETS Event

For the 2011 ETS event, matched filtering produced 1,394 new detections. The 2011 ETS event began on 23 July 2011 and ended on 6 September 2011, based on tremor activity reported by the PNSN. Notably, there is an increase in VLFE activity during the ETS event. The number of VLFEs decrease immediately before and after the ETS event. Spatiotemporal analyses of the 2011 ETS event show a clear spatiotemporal relationship between tremor, slow slip, and VLFEs. Not only do the VLFE detections gradually ramp up, peak, and ramp back down with tremor, but the same trend exists for each individual template event but with moderate variations. For example, in one template event, there is a sudden burst of VLFE activity in the middle of peak tremor activity, but for another, there is a more gradual increase and decline in VLFE activity that closely mirrors surrounding tremor activity (Figure 4). This spatiotemporal consistency among slow earthquake activity is largely consistent with past studies and also reflects the behavior of the template events (Ghosh et al., 2015). During the 2011 ETS event, VLFE and tremor activity are also consistent with slow slip. The GPS motion on
These time series plots show the relationship between tremor, slow slip, and VLFEs in Cascadia during the 2011 (left) and 2014 (right) ETS events. In the top panel in both graphs, the red line indicates daily VLFE activity, while the blue histogram shows the number daily tremor events within a 100-km radius of the geographic center of the template events. Since we are looking at the stacked relationship between all the template events, we use a larger radius than used for spatiotemporal analysis of individual VLFEs (50 km). The bottom panel gives GPS motion from four stations (ALBH, P435, P436, and P064) near the VLFE source locations. In both cases, there is a clear increase in VLFEs during ETS, but VLFE activity decreases when there is no ETS activity indicating there exists a temporal relationship between VLFE and ETS. ETS = episodic tremor and slip; VLFE = very low frequency earthquake.

This figure illustrates the relationship between an individual template event’s VLFE detections with tremor and VLFE. (top) The temporal distribution of VLFE (red) detected by an individual template event (17 August 2011, 04:30:28) is compared tremor (blue) within a 50-km radius of the inferred source location shown on the map (right). (center) GPS data are also given from four GPS stations (ALBH, P435, P436, and P064) in the panel beneath the tremor and VLFE activity. The geodetic data are consistent with both the tremor and the VLFE activity indicating that these three types of slow earthquakes are spatiotemporally coincident during the 2011 episodic tremor and slip event. (bottom) Similarly, the matched filter detections (red) from VLFE template from 21 August 2011, 04:09:03 compares well spatiotemporally with tremor (blue) that occurs within a 50-km radius of the template event and GPS stations ALBH, P435, P436, and P064 (bottom panel). This behavior is consistent with the VLFE activity observed throughout the 2011 episodic tremor and slip event. (right) Map showing center of VLFE template 1 in red with a 50-km radius and the center of VLFE template 2 in blue. VLFE = very low frequency earthquake.
four GPS stations indicates that westward motion begins and ends at approximately the same time that tremor and VLFE activity pick up and drop off (Figures 3 and 4).

### 3.2. The 2014 ETS Event

Matched filtering produced 2001 new detections for the 2014 ETS event. The story of VLFEs with respect to tremor and slow slip during the 2014 ETS event is quite different than 2011. First, however, it is evident that VLFE activity once again increases during the ETS event and weakens immediately before and after the ETS period (Figure 3). It should be noted that this ETS event can be divided into two subevents. Tremor first emerges in northern Vancouver Island on 3 November 2014 then migrates south to central/southern Vancouver Island through 23 November 2014. Tremor picks up again in central Washington on 23 November 2014, propagating northward toward Puget Sound, where the tremor stops on 10 December 2014. VLFEs occur throughout the entirety of both ETS events; however, the maximum VLFE activity occurs during the end of the ETS event. This matched filter catalog provides an improved temporal catalog of VLFE activity. The matched filter locations for the 2014 ETS event are inferred to be similar or the same to the template events given in Hutchison and Ghosh (2016). Here individual template events also behave
differently with respect to tremor, while cumulatively they show an overall increase in VLFE activity during the ETS event. One set of detections from an individual template event shows little activity during the first half of the ETS event but a large peak in the second half (Figure 5). A different set of detections from a VLFE template that occurred after the ETS event ended (i.e., tremor stopped), on 14 December, shows a high peak in activity before the onset of tremor and then increases again during the second sub-ETS event (Figure 5). By the end of the second ETS event, as it is defined by PNSN, tremor has shut off, but there is slow slip in the direction opposite subduction that is still detected by multiple GPS stations (Figures 3 and 5). As such, during this ETS event, VLFE more accurately tracks slow slip than tremor. Further, VLFE tracks slow slip, even if tremor is not occurring at all. Some individual templates show peak VLFE activity that is coincidental with the second ETS period, whereas other template events show VLFE activity that peaks after tremor has shut off.

3.3. Inter-ETS VLFE Activity

Using the same five template events from the 2011 ETS event, we perform matched filtering from 1 June 2011 to 31 December 2012. This period includes a second ETS event in 2012 that occurred from 30 August 2012 to 11 October 2012, based on tremor data obtained from the PNSN. We thus define the inter-ETS period as 1 October 2011 to 30 August 2012. A fair amount of VLFE activity is detected between the two ETS periods (Figure 6). However, only three of five of the template events detected show an increase in activity during the second ETS event. The other two template events showed no increase in the rate of VLFE activity per day during the inter-ETS period or the 2012 ETS event.

To ensure that such detections were not noise, we select at random 100 time windows during the 2011 ETS event that are not included in our VLFE catalog and create noise template events. We analyze these noise catalogs as well for the entire time period and found no clear trend in the noise detections during ETS events and inter-ETS time period. These are also the noise detections we use to determine our cross-correlation threshold values. The averaged stacked noise template detections and VLFE template detections are plotted together against tremor within a 100-km radius of the geographic center of the VLFE template source locations in Figure 6. As previously noted, we stack the inter-ETS VLFE time windows and inverted for locations, magnitudes, and focal mechanisms. These events closely resembled their original template events, to validate that they are indeed VLFEs and to infer their source locations.

4. Discussion

The similarity between the waveforms and the moment tensor inversion solutions of the template events and their respective matched filter detection stacks indicate that VLFEs are repeating events. They rupture on the fault plane on the same or nearby patches, which have similar mechanical and frictional properties. Thus, we consider the VLFEs detected through matched filtering events with source locations that are nearby but not...
necessarily exactly the same. Further, the matched filter results indicate that many VLFEs occur below the background of what is detectable using the grid-search centroid moment tensor inversion approach. Beyond matched filtering simply proving an effective method for VLFE detection, it also enables the observation of VLFE activity with a significantly higher degree of temporal resolution. Thus, this method and subsequent results should be considered for inclusion in a public database of slow earthquakes (Kano et al., 2018).

It is largely thought that VLFEs, tremor, and slow slip are all manifestations of a greater, quasi-periodic shearing activity that occurs on the plate interface that obey a unique linear moment scaling relationship (Ide et al., 2008; Shelly et al., 2007). More recently, Hawthorne and Bartlow (2018) estimate the spectral distribution of moment rates in Cascadia for large SSEs using the sums of other types of slow earthquakes as subevents in the moment rate distribution. The findings of this study further support the findings of the linear moment scaling relationship of slow earthquakes and an interconnectedness of events.

Tremor is already thought to be a good proxy to locate and track the movement of a SSE along the plate interface (Aguiar et al., 2009). Previously, it was only possible to make broad inferences about the relationship between VLFE, tremor, and SSEs in Cascadia due to the small handful of VLFEs detected through grid-search centroid moment tensor inversion. Further, more recent studies, such as that of Hawthorne and Bartlow (2018) further suggest that VLFEs are an inherent part of SSEs due to their moment scaling relationships. Fortunately, as a result of this research thousands of events detected through matched filtering make it possible to more deeply examine the role of VLFEs in ETS cycling. Many of the VLFE patches, which are separated by up to 100 km, rupture simultaneously, indicating that they are being triggered by the passage of the same SSE, a behavior also observed in LFEs (Shelly et al., 2007).

In both the 2011 and 2014 ETS catalogs, VLFEs are occurring throughout the ETS event and their activity weakens immediately prior to and after the ETS period. However, because VLFEs behave differently with respect to tremor during the 2011 and 2014 ETS events, but show consistent behavior with slow slip, it appears that the VLFEs may be a reliable indicator for a more detailed spatiotemporal analysis of the progression of slow slip through seismic monitoring even when tremor is behaving anomalously or is not occurring at all.

In 2011, there is a very clear relationship between tremor, VLFE, and slow slip. There is also a clear rise and fall where tremor and VLFE activity gradually increase and then taper off. These findings are all consistent with previous studies that found similar spatiotemporal behavior between types of tremor and VLFEs (Ghosh et al., 2015; Hawthorne & Bartlow, 2018; Ide et al., 2008; Ito et al., 2009; Shelly et al., 2007). These results are strong evidence in favor of the model suggesting that VLFEs are the result of the same source process as other slow earthquakes and do not contradict models that suggest VLFEs are a result of filtering clustered LFEs in a 20- to 50-s period band (Gomberg et al., 2016). Because the VLFEs in 2011 are spatiotemporally coincident with tremor and have moment tensor solutions similar to that of the plate interface with a spatial distribution that matches with the transition zone, we infer that these VLFEs are the result of shear slip occurring on rate weakening patches in a creeping segment of the plate interface.

During the 2014 ETS event, the relationship between the various types of slow earthquakes is more complex. In this case, tremor almost entirely terminates before slow slip, such that VLFEs give a better spatiotemporal representation of the progression of the SSE (Figure 3). Tremor occurs within the window of slow slip but shuts off before the SSE ends. VLFEs, however, mirror the slow slip throughout the entire ETS event, even after tremor has shut off. Once tremor stops, there is a large increase inVLFE activity that corresponds to a large westward slow slip transient during the ETS event. This behavior indicates that the asperities responsible for generating both VLFEs and tremor are likely driven by slow slip but are not necessarily intrinsically linked to one another (Hutchison & Ghosh, 2016). This observation conflicts with the model proposing that VLFEs are a result of filtering clustered LFEs in the 20- to 50-s period band (Gomberg et al., 2016). An inference cannot be made from the other VLFE detections in the region with regard to this model because template event generation in this study relies on stacking and filtering tremor detections in the region in a very low frequency period band (Ide, 2016), or they have simply been spatiotemporally coincident with tremor (Ghosh et al., 2015). Given the longer source duration of VLFEs relative to LFEs, their source patches likely have a larger area, or different spatial or mechanical properties, than the asperities responsible for generating LFEs and thus tremor (Ito et al., 2007). It follows that asperities of significantly varied areas or mechanical properties are likely to take different amounts of time and require differing amounts of (slow) slip on the surrounding rate strengthening region along the plate interface to reach their yield stress. In other words, LFE patches may slip...
Figure 7. These plots give tremor within a 100-km radius of each template event’s source location (blue) versus a cumulative function of the VLFE detected by each template event (red). Each VLFE template behaves differently during the inter-ETS period with respect to reactivation during tremor bursts and with respect to an increase in activity during the first and second ETS events. The template events are numbered 1–5 from the top to bottom. The distinctive behavior of VLFEs detected by these different template events suggests that their respective source patches along the plate interface are reactivated due to the path of the slow slip front or discrete properties such as fault geometry, frictional characteristics, or the presence of fluids.
more quickly once a slow slip front begins to pass through, whereas the regions responsible for VLFE require a different amount of slip or slip rates in the surrounding creeping region of the plate interface before they are ready to rupture. Because the VLFE activity during the 2014 ETS event more accurately tracks slow slip (as measured by the closest GPS station) than tremor, VLFEs were a better proxy for the seismic observation of SSE behavior in this particular ETS event. In both the 2011 and 2014 ETS events, VLFE activity was consistent with geodetic data of slow slip from the closest GPS stations. As such, VLFE is an alternative proxy for slow slip transient observation even when tremor is not active or not behaving consistently with the geodetic observations during ETS events. This probably suggests that VLFEs are directly related to slow slip, though not necessarily directly to tremor.

When observing VLFE activity over both the 2011 and 2012 ETS events, we observe continuous VLFE activity detected by all template events (Figure 6), though the behavior of VLFEs detected by each template event is distinctive (Figure 7). Three of the template events detect an increase in activity that corresponds with the second ETS event, while two of the template events do not. We interpret this to suggest that those template events that show an increase in activity during the latter (2012) ETS event occur on a part of the plate interface that was reactivated during the propagation of slow slip, while those which did not show an increase in activity during the second ETS event were on a part of the fault that did not reactivate. This is likely a result of geometric heterogeneities along the fault plane and/or other variations such as the presence of fluids or differences in frictional properties. Additionally, it should be noted that the lack of template events in other regions does not rule out the possibility that there may also be activity there. Additionally, it is possible that some VLFEs do not produce signals with sufficiently large SNRs to stand out above the background with the station coverage currently available. Thus, the picture of VLFE activity contained herein may be a piece of the puzzle but is likely still an incomplete picture of VLFE behavior.

Across all of the template events, our application of the matched filter method during the inter-ETS period between the 2011 and 2012 ETS events indicates continuous VLFE activity (Figure 6). While several of the template events detect a distinctive increase in VLFE activity during tremor, our observation of continuous VLFE activity throughout the inter-ETS period for when there is no tremor present further indicates that VLFEs are discrete events that can occur with or without tremor. Previous studies also observed inter-ETS tremor (Wech et al., 2009) and inter-ETS small SSEs (Frank, 2016) in Cascadia. The observation of inter-ETS VLFEs supports the idea that there is likely slow earthquake activity of smaller magnitudes occurring between ETS events, more frequently than previously thought. This is particularly valid in the context of the extensive noise analyses conducted to ensure that the signals detected by the template events are above the noise background level. In comparison with the matched filter VLFE catalog in Japan, the present study does agree with the findings that there is an overall increase in the number of VLFEs during the ETS events. However, only in one region of three in the Baba et al. (2018) study is there a reasonable amount of inter-ETS VLFE. We do not find that these are conflicting findings but rather consistent in that inter-ETS VLFE likely is a result of slow earthquake processes occurring at smaller magnitudes. Perhaps some source regions have mechanical properties that make them more prone to smaller SSEs, whereas others are inherently more likely to generate larger SSEs, or perhaps this is a product of the evolution of the stress field. It might be beneficial to generate values for regions of slow earthquake activity similar to those of B values in the locked zone where there are regular earthquakes, analyzing the data both spatially and temporally. As the development of geodetic data collection and observation continues, our ability to resolve this relationship should improve.

5. Conclusion

The results of this study show that VLFEs in Cascadia are repeating events. Further, the matched filtering technique provides an efficient and computationally effective VLFE detection method, capable of making thousands of detections, which can provide a more comprehensive understanding of the behavior of slow earthquakes. Such findings should be considered for addition to the public database of slow earthquake activity (Kano et al., 2018). We find that VLFE activity increases during ETS events and drops off when ETS events are not occurring. In other words, these events can track slow slip at the plate interface during ETS events. The 2011 ETS event shows that VLFE and tremor can correspond spatiotemporally, while the 2014 ETS event shows that VLFE activity does not always correspond to peak tremor activity during an ETS, but
in both cases VLFE activity mimics GPS observations of slow slip. VLFEs thus have potential to act as an alternative seismic proxy to study the evolution and passage of an SSE during an ETS event, particularly when tremor is behaving anomalously. We interpret this to signify that both tremor and VLFE might be related to SSE processes but not necessarily to each other. Finally, we observe that during the inter-ETS period, VLFEs show continuous activity, though each template event has distinctive behavior when it comes to reactivation during the subsequent ETS event and with respect to activity that is spatiotemporally coincident with inter-ETS tremor. This suggests that some patches are more susceptible to VLFE-producing slip than others.

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References


