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Alexandra Hutchison

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Key Points:

- During the inter-ETS period, VLFs and tremor can occur in the same source at (slightly) different times
- During inter-ETS periods, VLFs and tremor can occur in different places at the same time
- Quasi-spatiotemporal relationships between tremor and VLFs in Cascadia suggest that these events share an underlying source process

Supporting Information:

- Supporting Information S1
- Figure S1
- Table S1
- Table S2

Correspondence to:

A. A. Hutchison,
allie.hutchison@gmail.com

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Inter-episodic Tremor and Slip Event Episodes of Quasi-spatiotemporally Discrete Tremor and Very Low Frequency Earthquakes in Cascadia Suggestive of a Connective Underlying, Heterogeneous Process

Alexandra A. Hutchison¹

¹Université Côte d'Azur, CNRS, IRD, Observatoire de la Côte d'Azur, Géoazur, France

Abstract Exploring relationships between different types of slow earthquakes is essential for determining their source properties and controlling parameters. Studies show that very low frequency earthquakes (VLFs) and tremor are discrete events that necessitate a further comprehensive study with respect to each other. Spatiotemporal analyses of VLFE and tremor catalogs from three interepisodic tremor and slip (inter-ETS) events in Cascadia show that seemingly uncorrelated events have more nuanced quasi-spatiotemporal relationships. Some of these events are either only related spatially, where tremor and VLFs occur in the same location at different times, or related temporally, occurring at a distance but during the same time period. Including quasi-related events, nearly all VLFs and tremor that do not exhibit immediate spatiotemporal relationships become correlated. I interpret this to mean they are related by a connective process that either is itself heterogeneous or has heterogeneous expressions based on other physical characteristics.

Plain Language Summary Slow earthquakes comprise a massive part of the earthquake cycle, though the nature and extent of their involvement is still largely unknown. Different kinds of slow earthquakes have been thought to be different manifestations of the process, but sometimes they occur discretely and without apparent relation to each other. Here I show that apparently uncorrelated events may actually be correlated, either in space or in time, but not necessarily both. This observation suggests that an underlying process is responsible for connecting the different types of seismic slow earthquakes but that how they manifest may be heterogeneous due to a number of possible controlling physical parameters.

1. Introduction

Slow earthquakes are an umbrella term for events, both seismic and aseismic, whose source properties are considered distinct from regular earthquakes due to slower deformation rates and unique frequency contents. There is some debate over whether these events have different moment scaling relationships from regular earthquakes, where end-member models include a linear scaling law (Ide et al., 2007), or that they have the same moment scaling relationship as regular earthquakes (Michel et al., 2019). Very low frequency earthquakes (VLFs) and tectonic tremor are seismic slow earthquakes that are often associated with transient deformation, including deep creep (e.g., Johnson et al., 2013; Shelly & Johnson, 2011) and slow slip events (SSEs) (e.g., Hawthorne & Rubin, 2013; Rubin & Armbruster, 2013; Obara et al., 2010). When they occur with slow slip, it is called an episodic tremor and slip (ETS) event. In Cascadia, these events occur at a somewhat regular interval of every ~12–14 months (Rogers & Dragert, 2003). Unlike tremor, which has been observed in both continental (Hutchison & Ghosh, 2017; Shelly, 2015) and subduction settings (Ghosh et al., 2009, 2012; Obara, 2002; Wech & Creager, 2008), VLFs have only been observed in subduction zones (Baba et al., 2018, 2019; Ghosh et al., 2015; Walter et al., 2013) thus far, though this may be due to a simply lack of such an observation. Tremor primarily emits energy from 2 to 8 Hz and is thought to consist of a bundled arrival of low-frequency earthquakes, short-duration signals with energy content in the same pass band, but with distinct phase arrivals. The energy of VLFs lives in the 0.02–0.05 Hz pass band. Tremor and VLFs are typically long-duration seismic signals (tens to hundreds of seconds), though VLFs have magnitudes between 3 and 4 (e.g., Ghosh et al., 2015; Hutchison & Ghosh, 2016; Ito & Obara, 2006), whereas tremor typically has a magnitude less than 2 (e.g., Kao et al., 2010).

Until recently, observations of VLFs were spatiotemporally coincident with those of tremor (Ghosh et al., 2015; Ide, 2016). Theoretical models even suggested that VLFs may simply be an artifact of tremor (Gomberg et al., 2016). More recent observations, however, identify VLFE without tremor in Cascadia (Baba et al., 2019; Hutchison & Ghosh, 2016, 2019), and models show that VLFs can be generated independently from tremor by rapid stress drops followed by rate strengthening processes (Wu et al., 2019). The elucidation that these events are in fact discrete implies that the same source regions can produce VLFE and tremor simultaneously or at separate times. This is consistent with other studies that suggest that even slow slip and tremor, which are typically, but not ubiquitously spatiotemporally coincident, may have different origins (e.g., Kostoglodov et al., 2010). If sources from the same location are capable of generating different seismic behaviors at the same time or at different times, it suggests that the driving mechanism for these events has a dynamic but static physical properties, or rheological contrasts may influence how this connective driving mechanism manifests. Alternatively, there may be slight differences in source locations of various types of slow earthquakes that dictate the resulting behavior. Ultimately, little is known about what combination of physical mechanisms and properties might result in enabling conditions for discrete kinds of seismic and aseismic behaviors.

I examine the inter-ETS period as opposed to the ETS period because I am interested in smaller clusters of slow seismic earthquakes (e.g., Wech & Creager, 2008) that do not have immediately apparent relationships to each other (Hutchison & Ghosh, 2019) in order to maximally isolate their spatiotemporal activity. Small SSEs have been observed in several subduction zones (Frank, 2016; Frank & Brodsky, 2019), in addition to discrete bursts of tremor (e.g., Wech & Creager, 2008) and VLFE (Hutchison & Ghosh, 2019). Thus, by examining the inter-ETS period, I hope to ascertain the unique processes that may lead to discrete types of slow earthquake activity.

Here I generate a catalog of VLFs from the Puget Sound Region of Cascadia during three inter-ETS periods from (1) 6 September 2011 to 29 August 2012, (2) 11 October 2012 to 6 September 2013, and (3) 9 October 2013 to 2 November 2014. I perform simple spatiotemporal analyses to compare inter-ETS VLFE with inter-ETS tremor. I identify two types of unique relationships between tremor and VLFE that suggest a uniting underlying process, though either the process itself may be heterogeneous or the material properties that influence it are heterogeneous, presenting in discrete episodes of aseismic and seismic behavior.

2. Data and Methods

To generate the VLFE catalog (Table S1 in the supporting information), I use broadband seismic data from the U.S. Transportable Array, the Canadian National Seismic Network, and the Pacific Northwest Seismic Network around Puget Sound. I then apply a grid-search centroid moment tensor inversion algorithm (e.g., Ghosh et al., 2015; Hutchison & Ghosh, 2016; Ito & Obara, 2006) over the time period of interest. First, I divide the subduction zone into a grid of $0.1^\circ \times 0.1^\circ$ horizontally and 5-km depth vertically to a depth of 75 km. I generate a Green's function for each grid node based a laterally homogeneous velocity model (Crosson, 1976). The implication of a 1-D velocity model is that it becomes more challenging to accurately constrain depth. Since VLFs are generally understood to occur if not on, at least near, the plate interface, I qualitatively infer source depths that correspond to the approximate depth of the plate interface at a given source's coordinates. Using a 10-s triangle-shaped source time function, synthetic seismograms are generated for each grid node. Using a 90-s sliding time window, the characteristic duration of VLFs in Cascadia (e.g., Hutchison & Ghosh, 2019), the algorithm compares observed data with synthetic data from the source grid to find a best fit solution for each time window. The best fit solution produces a value for variance reduction, which is a measure of the fit. Only candidate windows with a variance reduction of >0.4 are considered. Using the waveforms, the algorithm can produce a moment tensor and focal solution for the signal. I also eliminate events with a compensated linear vector dipole value greater than 25%. Because I am interested in the processes related to the subduction zone, we only include focal mechanisms that are consistent with the general direction of subduction. In addition, each of these events has been cross-referenced with the Advanced National Seismic System earthquake catalog (now ComCat). Finally, I use the tectonic tremor catalogs available through the Pacific Northwest Seismic Network to develop spatiotemporal comparisons between VLFE activity and tremor. I also perform the same spatiotemporal analyses with the World

Figure 1. These time series compare daily tremor (blue histogram, left y-axis) to daily VLFE occurrences (red line, right y-axis) during three inter-ETS periods. Example periods of correlated VLFE and tremor are outlined in yellow, example periods of VLFE only are outlined with dashed orange boxes, and example periods of only tremor are outlined by dashed light blue boxes. (a) The first inter-ETS period is from 6 September 2011 to 29 August 2012. This inter-ETS period shows a wide variety of activity. (b) The inter-ETS period from 11 October 2012 to 6 September 2013 has many periods with a lot of tremor and no VLFE. (c) The inter-ETS period from 9 October 2013 to 2 November 2014 has a lot of VLFES and much less tremor occurring without VLFE than in the previous inter-ETS event.

Tremor DataBase (WTD) tremor catalog (Idehara et al., 2014) to ensure the findings contained herein are robust.

3. Results

At first glance, it appears that there are discrete kinds of seismic activity: (1) only tremor, (2) only VLFE, and (3) VLFE and tremor simultaneously (Figure 1). However, there are two additional types of relationships between tremor and VLFE that are observed. The first is a temporal relationship between tremor

Figure 2. This is an example of an inter-ETS event related through time. This event occurred over several weeks from 12 December 2011 to 1 January 2012. (a) VLFs are plotted with orange stars. Their geographic center is shown with a large red star. Tremor during the same time window is shown with blue points. Radii of 100 and 200 km are drawn around the geographic center of the VLFs. (b) A time series of the number of tremor events per day (blue histogram, left y-axis) versus VLFs (red line with a yellow star; magnitude is indicated on the right-hand y-axis) within a 100-km radius of the geographic center of the VLFs. (c) A time series of tremor events per day versus VLF activity. When the radius around the VLF is expanded, it appears that there is a relationship between tremor and VLF. In other words, they are occurring simultaneously in different places.

and VLFE, where the events occur simultaneously along the subduction zone but they are not in the same region (>100 km) and thus have a quasi-spatial relationship. I use a 100 km radius around each individual event to establish spatial correlations because this generous distance was previously been used to identify a demonstrate a spatial correlation between VLFs and tremor during the 2011 ETS event, and to show a lack of spatial correlation between these types of activity during parts of the 2014 ETS event (Ghosh et al., 2015; Hutchison & Ghosh, 2016). An example from December 2011 shows this kind of correlation between the two kinds of seismic slow earthquakes where there is no immediate spatial relationship between these events; however, they are occurring contemporaneously, but at a reasonable distance (Figure 2). Alternatively, there are periods of time (less than 2 weeks) where the same section of the subduction zone generates VLFE and tremor, but not simultaneously (Figure 3; Hutchison, 2018).

In total, over the three inter-ETS VLFE periods, 470,321 VLFs were detected. Many of the VLFs occur on the same date and at nearly the same location, so we consolidate these events, reducing the number of events we analyze to 366. Nearly half of the VLFs (49%) have a true spatiotemporal relationship with tremor (i.e., they occur within 100 km of tremor). If we use a new radius of 300 km in the same time period, we find that an additional 19% (89) of the VLFs correlate to tremor activity. We use the 300-km radius because most SSEs in Cascadia do not span more than that along strike (e.g., McCaffrey, 2009); thus, if these events are connected, it is fair to assume that they cannot be connected by distances larger than the largest observed slow earthquakes. Meanwhile, $\sim 10\%$ of VLFs occur within ± 10 days and within 100 km of tremor. By accounting for quasi-related VLFs and tremor, nearly all of the VLFE activity in Cascadia becomes connected to tremor (95%). Tremor, on the other hand, has a $\sim 7\%$ true spatiotemporal correlation with VLFE. Tremor that occurs within the 300-km radius of VLFE in the same period increases to 11% of the events. Finally, tremor that occurs within ± 10 days of VLFE and within a 100-km radius of VLFE makes up $\sim 6\%$ of tremor activity. While nearly all VLFs can be correlated to tremor, not all tremor can be correlated to VLFs. I find only 232 days out of the three ETS periods (1,039 days) when tremor and VLFE occur on the same day. This emphasizes that while there is almost always some flavor of slow earthquakes occurring, they truly only occur simultaneously (on the same day) $\sim 20\%$ of the time. (Table 1). These analyses are also conducted using the WTD tremor catalog (Table S2 and Figure S1). The same quasi-spatiotemporal between tremor and VLFE are observed with the WTD catalog. Notably, all VLFs can be related to tremor if we account for directly correlated tremor and VLFE, or VLFE that is either only spatially or only temporally correlated with tremor.

Figure 3. (a) A map showing VLFs (orange stars) with their geographic center (red star) and tremor (blue dots). A 100-km radius is drawn around the geographic center of the VLFs. (b) A time series of the number of tremor events per day (blue histogram, left y-axis) versus VLF occurrence and magnitude (red lines with yellow stars, right y-axis). Temporally, there is essentially anticorrelation between VLFs and tremor. (c) The y-axis gives distance along strike, and the x-axis is time. Tremor location along strike as a function of time plotted is with points, the color corresponds to temporal evolution (color bar, right). VLF occurrence (yellow stars) along strike as time evolves is also shown. The same section of the subduction zone seems to be active throughout this 2-week period (3 to 18 February 2012), although it produces different varieties of seismic activity.

4. Discussion

VLFE and tremor are widely thought to be driven, or at minimum controlled, by slow slip (e.g., Bartlow et al., 2011; Wech & Bartlow, 2014). There are some models to the contrary that suggest that tremor may be actively involved in the propagation of slow slip, as opposed to simple manifestations of it (e.g., Hall et al., 2019; Shelly, 2015). Alternatively, slow slip and seismic slow earthquakes may be separate events that are both manifesting the same process but do not necessarily influence each other (Shelly et al., 2007). The correct model remains unknown; it may be some combination of these theories, or it may be none of them. The observations contained herein paint a complicated picture, where these quasi-related seismic events seem to be linked in space, and time, but are nonetheless distinct features. This opens the door to several conceptual models that may be responsible for distinct types of VLFE and tremor behavior.

Colella et al. (2011) used an earthquake simulator based on rate-and-state friction to generate SSEs in Cascadia. Their study shows that small SSEs ($M < 5.5$) small incoherent slip patches distributed along the plate interface that occur simultaneously, whereas large SSEs ($M > 5.5$) saturate the width of the transition zone and nucleate into large, coherent slip transients. One possible solution for this observation is to take the

Table 1

The Number of Tremor and VLFs That Have Immediate Relationships With Each Other and Have Either Only Spatial or Temporal Relationships With Each Other

Event (number or percentage)	Immediate spatiotemporal relationship	Temporal relationship (within 300 km, same time window)	Spatial relationship (within 100 km, $\pm$ day time window)
# of VLFs	232	89	45
% of VLFs	~49%	~19%	~10%
# of tremor	7,120	11,152	6,141
% of tremor	~7%	~11%	~6%

Note. The total number of tremor events is 99,985, and the total number of VLFs is 386.

approach that VLFs and tremor are driven by slow slip. If we assume this explanation, the morphology of the slip patch(es) may explain heterogeneous distributions of VLFE and tremor. Large SSEs would then be analogous to ETS events, whereas small SSEs may account for the inter-ETS periods when and where there is seismic behavior that is quasi-related. Small SSEs have previously been observed in Cascadia and Guerrero, Mexico (Frank, 2016). This supports the idea, then, that slow slip and associated processes may occur nearly all the time in discrete episodes but that they are occurring at different frequencies and on different scales in space and in time (Frank & Brodsky, 2019). The concept of ubiquitous slow-earthquake “chatter” is echoed in machine learning, which indicates that this activity is essentially telling how and where the rate of displacement in the subduction zone is changing (Rouet-Leduc et al., 2019). If this is the case, currently, our best approach to constraining this activity is through seismic studies since events this small and this deep are likely beyond the threshold of geodetic detectability.

An alternative, or supplementary, theoretical model involves the innate complexities of a fault system wherein much of the deformation that is categorized as slow earthquake activity occurs over a volume that both includes and surrounds the plate interface. This model is an alternative to one in which each variety of slow earthquake is part of the same shearing process, constrained to the (presumably planar) plate interface (e.g., Ide et al., 2007). A simple version of such a volumetric model would be a complex distribution of sub-faults and fractures along the plate interface. In other words, slow earthquake deformation is distributed over a heterogeneous fault zone as opposed to a fault plane. Such a configuration could accommodate slip volumetrically, such that a collection of these substructures might accommodate deformation simultaneously, but produce different measurable outcomes based on different factors within that volume, such as rigidity, the size and density of fractures, preexisting stresses, fluids and rheology, and localized slip and slip rates. Geologic studies show that high shear strain rates can cause strain partitioning accommodated through both viscous deformation and brittle deformation (Fagereng et al., 2014). There is further evidence, based on geologic data and thermal models, that the region of the fault zone responsible for generating slow earthquakes is likely within a semifrictional regime, made up of heterogeneous volumes that are composed of rigid blocks within a network of viscous material (Fagereng et al., 2014; Gao & Wang, 2017). Within this framework, it is possible that small structures that are very close in space may slip simultaneously, or at least close in time, but have different material properties and deformation styles that can dictate the various slow earthquake behaviors that are observed. Moreover, deformation in a more viscous medium may be responsible for slow slip that does not coincide with the production of seismic energy.

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5. Conclusion and Summary

Here I find that VLFs and tremor often show a quasi-spatiotemporal relationship, suggesting that an underlying cohesive process is responsible for their occurrence, despite an apparent separation in space and time. This finding raises more questions than it answers, but it necessitates the investigation of slow earthquake activity from a perspective where some of the simplifications that have been made in the past should no longer be assumed. Areas worthy of deeper investigation include exploration of cohesive or non-cohesive slip patches, analysis of whether seismic activity drives slow slip or vice versa, and consideration of the extent to which slow earthquakes are processes localized strictly to a planar plate interface. This study shows that different kinds of slow earthquakes indicate heterogeneous but connected processes and the manner in which these occur is as complex as the media over which they are taking place.

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Erratum

In the originally published version of this article, Piero Poli was missing from the acknowledgments. This error has since been corrected, and the present version may be considered the authoritative version of record.