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Journal

Geophysical Research Letters, 42(9)

ISSN

0094-8276

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Publication Date

2015-05-16

DOI

10.1002/2015GL063286

Peer reviewed

RESEARCH LETTER

10.1002/2015GL063286

Key Points:

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

Supporting Information:

- Table S1

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Citation:

Ghosh, A., E. Huesca-Pérez, E. Brodsky, and Y. Ito (2015), Very low frequency earthquakes in Cascadia migrate with tremor, *Geophys. Res. Lett.*, 42, doi:10.1002/2015GL063286.

Received 27 JAN 2015

Accepted 30 MAR 2015

Accepted article online 1 APR 2015

Very low frequency earthquakes in Cascadia migrate with tremor

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Abstract We find very low frequency earthquakes (VLFs) in Cascadia under northern Washington during 2011 episodic tremor and slip event. VLFs 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 VLFs 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 M_w 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 VLFs 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 down-dip of seismogenic zone [Schwartz and Rokosky, 2007]. Seismic signatures of slow earthquakes—tremor, low-frequency earthquakes (LFEs), and very low frequency earthquakes (VLFs)—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]. VLFs, however, remain elusive in many regions that experience slow earthquakes. So far, the most convincing evidence of VLFs comes from southwest Japan [Ito *et al.*, 2007] and Royuku trench [Ando *et al.*, 2012]. In Cascadia, finding VLFs 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 VLFs and their spatiotemporal distribution in Cascadia, however, remain largely unknown. Here we did a systematic search for VLFs in the Cascadia subduction zone under Washington (WA) state during an episodic tremor and slip event. We detect and locate VLFs, 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 VLFs 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 M_w 3.7. More details on this event can be found in Figures 2–4.

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 (M_w) 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 VLF. The same VLF is used in Figures 1 and 2.

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 VLFs in the same general area.

Figure 4. Tremor (orange dots), VLFs (yellow stars), and their focal mechanisms during August 2011. The date of occurrences and moment magnitudes (M_w) of VLFs are noted. Black triangles are the seismic stations used to obtain source parameters of the VLFs. 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://psns.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.

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

3.2. VLFs, 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 VLFs cluster in the area that often produces peak geodetic slip in episodic tremor and slip events [Szeliga *et al.*, 2008]. Interestingly, VLFs are located within a relatively narrow zone

along strike where tremor is located, even though our search area extends much beyond the tremor zone.

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.

VLFs 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 VLFs are M_w 3.3 and they do not reach up to M_w 4. VLFs 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 VLFs 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 VLFs (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, VLFs may represent the lower part of the spectrum. VLFs generally occur during strong bursts of tremor. However, not all strong bursts are associated with detected VLFs. Therefore, whether tremor and VLFs 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 M_w 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, VLFs contribute more seismic moment to this episodic tremor and slip event than cumulative tremor activity. Total cumulative moment released by five VLFs found in this study is equivalent to an M_w 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 VLFs in Cascadia suggests that slow earthquakes are seismically not as inefficient as previously thought based solely on tremor activity. Relatively larger sizes of VLFs 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 VLFs in this study result in robust solutions but a rather conservative estimate of VLFE activity. It is likely that there are more VLFs 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, VLFs constitutes an important seismic signature of slow earthquakes and present an opportunity to study their source physics. Discovery of VLFs in Cascadia opens up new avenues to study mechanisms controlling slow earthquakes, frictional properties in the transition zone, and physics of fault motion.

Acknowledgments

This study is supported by the NSF GeoPRISMS program award OCE-1144695, Frontier in Earth System Dynamics program award EAR-1135455, and the Department of Earth Sciences, University of California, Riverside (UCR). We appreciate the comments by Ken Creager and Roland Bürgmann. They help improve the manuscript. We thank the Pacific-Northwest Seismic Network, the Geological Survey of Canada for collecting, and the Incorporated Research Institutions for Seismology (data accessible at <http://ds.iris.edu/ds/nodes/dmc/data/>), the Canadian National Data Center (data accessible at http://www.earthquakescanada.nrcan.gc.ca/stndon/wf_index-eng.php) for archiving the seismic data used in this study. Thanks to the member of the Earthquake Seismology Group at the UCR for stimulating discussions.

The Editor thanks Ken Creager and Roland Bürgmann for their assistance in evaluating this paper.

References

- Ando, M., Y. Tu, H. Kumagai, Y. Yamanaka, and C.-H. Lin (2012), Very low frequency earthquakes along the Ryukyu subduction zone, *Geophys. Res. Lett.*, **39**, L04303, doi:10.1029/2011GL050559.
- Brown, J. R., G. C. Beroza, S. Ide, K. Ohta, D. R. Shelly, S. Y. Schwartz, W. Rabbel, M. Thorwart, and H. Kao (2009), Deep low-frequency earthquakes in tremor localize to the plate interface in multiple subduction zones, *Geophys. Res. Lett.*, **36**, L19306, doi:10.1029/2009GL040027.
- Crosson, R. S. (1976), Crustal structure modeling of earthquake data: 2. Velocity structure of Puget Sound Region, Washington, *J. Geophys. Res.*, **81**(17), 3047–3054, doi:10.1029/JB081i017p03047.
- Ghosh, A., J. E. Vidale, J. R. Sweet, K. C. Creager, and A. G. Wech (2009), Tremor patches in Cascadia revealed by seismic array analysis, *Geophys. Res. Lett.*, **36**, L17316, doi:10.1029/2009GL039080.
- Ghosh, A., J. E. Vidale, J. R. Sweet, K. C. Creager, A. G. Wech, and H. Houston (2010a), Tremor bands sweep Cascadia, *Geophys. Res. Lett.*, **37**, L08301, doi:10.1029/2009GL042301.
- Ghosh, A., J. E. Vidale, J. R. Sweet, K. C. Creager, A. G. Wech, H. Houston, and E. E. Brodsky (2010b), Rapid, continuous streaking of tremor in Cascadia, *Geochim. Geophys. Geosyst.*, **11**, Q12010, doi:10.1029/2010GC003305.
- Ghosh, A., J. E. Vidale, and K. C. Creager (2012), Tremor asperities in the transition zone control evolution of slow earthquakes, *J. Geophys. Res.*, **117**, B10301, doi:10.1029/2012JB009249.
- Gomberg, J. (2010), Slow-slip phenomena in Cascadia from 2007 and beyond: A review, *Geol. Soc. Am. Bull.*, **122**, 963–978, doi:10.1130/B30287.1.
- Ito, Y., and K. Obara (2006), Very low frequency earthquakes within accretionary prisms are very low stress-drop earthquakes, *Geophys. Res. Lett.*, **33**, L09302, doi:10.1029/2006GL025883.

- Ito, Y., K. Obara, K. Shiomi, S. Sekine, and H. Hirose (2007), Slow earthquakes coincident with episodic tremors and slow slip events, *Science*, 315, 503–506, doi:10.1126/science.1134454.
- Ito, Y., K. Obara, T. Matsuzawa, and T. Maeda (2009), Very low frequency earthquakes related to small asperities on the plate boundary interface at the locked to aseismic transition, *J. Geophys. Res.*, 114, B00A13, doi:10.1029/2008JB006036.
- Kao, H., K. Wang, H. Dragert, J. Y. Kao, and G. Rogers (2010), Estimating seismic moment magnitude (M_w) of tremor bursts in northern Cascadia: Implications for the “seismic efficiency” of episodic tremor and slip, *Geophys. Res. Lett.*, 37, L19306, doi:10.1029/2010GL044927.
- Obara, K. (2011), Characteristics and interactions between non-volcanic tremor and related slow earthquakes in the Nankai subduction zone, southwest Japan, *J. Geodyn.*, 52, 229–248, doi:10.1016/j.jog.2011.04.002.
- Schwartz, S., and J. Rokosky (2007), Slow slip events and seismic tremor at circum-Pacific subduction zones, *Rev. Geophys.*, 45, RG3004, doi:10.1029/2006R6000208.
- Shelly, D. R., G. C. Beroza, and S. Ide (2007), Non-volcanic tremor and low-frequency earthquake swarms, *Nature*, 446, 305–307, doi:10.1038/nature05666.
- Sweet, J. R., K. C. Creager, and H. Houston (2014), A family of repeating low-frequency earthquakes at the downdip edge of tremor and slip, *Geochem. Geophys. Geosyst.*, 15, 3713–3721, doi:10.1002/2014GC005449.
- Szeliga, W., T. Melbourne, M. Santillan, and M. Miller (2008), GPS constraints on 34 slow slip events within the Cascadia subduction zone, 1997–2005, *J. Geophys. Res.*, 113, B04404, doi:10.1029/2007JB004948.
- Vidale, J. E., A. J. Hotovec, A. Ghosh, K. C. Creager, and J. Gombert (2011), Tiny intraplate earthquakes triggered by nearby episodic tremor and slip in Cascadia, *Geochem. Geophys. Geosyst.*, 12, Q06005, doi:10.1029/2011GC003559.
- Zhang, J., P. Gerstoft, P. M. Shearer, H. Yao, J. E. Vidale, H. Houston, and A. Ghosh (2011), Cascadia tremor spectra: Low corner frequencies and earthquake-like high-frequency falloff, *Geochem. Geophys. Geosyst.*, 12, Q10007, doi:10.1029/2011GC003759.