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Peer Review History of

Very low frequency earthquakes in between the seismogenic and tremor zones in Cascadia?

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Author Response to Peer Review Comments

Peer Review Comments on 2021AV000542

Reviewer #1

I'll start by saying I sincerely apologize for the lateness of my review!

The authors present a very meticulous whodunit of three very low-frequency sources in Cascadia that appear to be triggered by a M6.9 earthquake. Given their proximity to slow slip and their resemblance to "classical" VLFEs (oxymoron?), the authors suggest they have observed some of the largest VLFEs to date. They validate the observations with both seismic and strain records, and build a convincing case that these are in fact independent tectonic events and not say, scattered waveforms from the triggering earthquake. The manuscript is well written and the figures are clear and informative.

I commend the authors for the careful work presented here. That said, I would say the two "big picture" takeaways here are a bit overblown (more details in comments below). Re megathrust extending into the downdip gap: there has already been much debate about this possibility and I'm not sure how an observation of a large VLFE moves the debate forward. Re slow earthquake scaling: the manuscript does not discuss two major papers (noted below) that have already called into question the M ~ T scaling proposed by Ide et al., Nature, 2007 more than two years ago now. That is why my overall feeling is that while the manuscript and observations are carefully presented and should be published, I'm not sure that this paper is quite appropriate for the intended broad audience of AGU Advances.

I detail below my list of comments:

- I would avoid using acronyms in a plain language summary, especially jargon laden ones like ETS
- Line 59 Brown et al. is a paper about LFEs, not tremor
- Line 60 "couple" implies a physical interaction with some mechanism, when it is just rather a spatiotemporal correlation that defines this phenomenological relationship
- Line 62 "semi-regularly" every 11-15 months (add average recurrence time)
- Line 97-108 I think it would read better to put the following paragraph here first, describing the method first, and then discussing how and why the method is efficient for the study at hand
- Line 133 I don't quite understand what this optimal location is, if it isn't the location that provides the minimum misfit...?
- Lines 144, 147, etc. no hyphen needed for focal mechanism
- Line 144-158 same remark as before: the method should be described before it's stated why it's effective
- Line 159 how are the synthetic waveforms aligned with the observed waveforms? Because if there are differences in arrival times with the best-fit source, that phase difference will impact the correlation coefficient if the synthetics aren't properly aligned. This is likely not a major issue, but I'm still curious. If there is no alignment to account for errors in travel times and location, is this at least part of the reason why focal mechanisms can't be estimated for the other two events?
- Line 203 why not just define this equation as a function of C, the number of components of the strain meter? As written, the number of terms seems arbitrary. Something rather like epsilon = sqrt[sum(g_c) / C] would be more straightforward
- Line 212 stresse -> stress
- Line 274 relinquishing = strange word choice
- Line 283 a subhorizontal dip is a bit surprising, no? How does it compare to the expected dip from slab models? What sort of uncertainty is estimated for the dip angle?
- Line 288 The expected depth based on Slab 2.0 should be in text
- Line 293 the m in Newton meters shouldn't be capitalized

- Line 328 contracts -> I assume "contrasts"?
- Line 334-336 One big question (I know it is not a simple one): why did this M6.9 EQ trigger these events and not these other bigger earthquakes? How do the dynamic stresses at the location of E3 compare for each of these earthquakes? For example, a significant difference in dynamic stressing could explain
- Line 420-439 I'm not sure why this takeaway message is presented as novel (megathrust could extend into gap zone). We see that some slow slip extends into this region, but tremors do not (line 416); this is similar to neighboring but not overlapping tremor and slow slip in Boso (Nankai) and Guerrero (Mexico). It is mechanically difficult to explain that this gap zone is creeping continuously between a long-term locked up dip zone (mega thrust) and a short-term locked down dip zone (slow slip). The simplest solution is then that this gap zone is locked on some intermediate time scales, slipping sometimes as slow slip or VLFEs or perhaps even in a future earthquake. Basically, I'm not sure what the observation of a VLFE within the gap zone demonstrates further than what we already knew?
- Line 441-462 New observations related to the scaling of slow earthquakes have been reported by Michel et al., Nature, 2019 and Frank and Brodsky, Sci. Adv., 2019, with both studies suggesting the M ~ T does not hold (although the assumptions made in each paper are different). The message from the results here corroborates the takeaway that a M ~ T scaling conflicts with observations, but the takeaway presented here that M ~ T scaling doesn't hold is not necessarily new. In any case, these papers should be discussed in light of the observation made here
- I would suggest that it's essential to show a figure similar to Bartlow et al., GRL, 2020 Figure 3a that maps the cumulative distribution of slow slip. That way it becomes obvious to the reader how the location of the reported VLFEs compare to the distribution of slow slip, which is a key message the authors want to convey here.
- I would strong suggest against using the acronym ETS. It conflates geodetic observations with seismic observations, with no real added value. It can even be misleading as in line 428: the loading stresses discussed are due to the aseismic slow slip, not the seismic tremor. I would suggest just simply using "slow slip" for transient aseismic slip and "tectonic tremors" for the seismic signal. This would not only simplify the discussion of what actually happens in the gap zone (i.e. slow slip extends up dip, but tremor does not), but make the entire manuscript more friendly to the uninitiated by having one less acronym.

Reviewer #2

[Please see attachment enclosed on the following page.]

Review of "Very low frequency earthquakes in between the seismogenic and tremor zones in Cascadia?"

<u>Summary:</u>

This is an overall strong paper with significant contributions worthy of publication with minor revisions. New VLFEs were detected in the Cascadia subduction zone, with at least one located in the gap zone between ETS events and the locked seismogenic zone. This event is the largest VLFE recorded to date and very impressively the first to be detected geodetically. The location of these VLFE(s) in the gap zone has implications for the modes of slip that we can expect in the gap zone and thus the seismic hazard. The paper is well organized, and the figures are clear and descriptive. I would like to see more details about the two VLFEs that were not modeled and more of a background about VLFEs in general and in Cascadia to better set the stage for this paper's significance in the context of what we currently know about VLFEs and slow slip.

<u>General comments:</u>

- Could the 2009 ETS have been triggered by the 2009 Gulf of California earthquake? Please address this in the discussion section.
- Provide a figure showing the VLFEs (at least E3) compared to a local earthquake and tremor (i.e., 20-50 s band-pass filter for VLFE, 2-8 Hz band-pass filter for tremor, high-pass filter for earthquake). This will provide more confidence that you have detected new VLFEs.
- The analysis of E3 is robust and I think you have found a new VLFE. I am less certain about E1 and E2, but I am okay with this because you do not interpret these as much. However, I still want to see more waveforms of these events if you are going to call them VLFEs. Please include a figure either in the main text or supplement showing the waveforms for E1 and E2, perhaps something like the waveforms in Figure 5 at a station far enough away for there to be a separation between the triggering earthquake code and the VLFEs.

<u>Comments by section:</u>

Abstract/Introduction:

- Key Point 2: Based on the location uncertainties, E2 and possibly E1 may not be in between the seismogenic and tremor zones. Consider changing to "These VLFEs **likely** occurred…"
- Key Point 3: The geodetic detection of E3 is an important finding and contribution in this paper. Consider adding this to Key Point 3, something like: "The largest VLFE has a moment magnitude of 5.7; **this is the largest VLFE detected and is the first to be detected geodetically.**"
- Abstract Line 24: "Out of all types of slow earthquakes, very low frequency earthquakes (VLFEs) are most similar to regular earthquakes" – I do not agree with this statement. How are VLFEs more similar to regular earthquakes than LFEs, which although are depleted in higher frequencies do have some overlapping frequency content with local earthquakes, unlike VLFEs? Further, if "the physical nature of VLFEs are poorly understood despite their frequent occurrence" (line 26) then how

do you know they are most similar to regular earthquakes? This requires more explanation, or should be rephrased, stating instead that they could potentially be the most similar to regular earthquakes. Last point, is the occurrence of VLFEs really that frequent? Not many VLFEs have been reliably detected, which is partly why this work is significant.

- Introduction: There should be more background discussing VLFEs in general and particularly in Cascadia. For example, please include that VLFEs are rich in low-frequency energy in a band of ~20-50 seconds and depleted in frequencies higher than 1 Hz compared to local earthquakes of similar magnitudes and compared to tremor which has most energy in a 2-8 Hz band. It would also be good to include that VLFEs are thought to be a seismic manifestation of slow slip, similar to tremor and LFEs. Please also discuss a little background of VLFEs detected in Cascadia from other studies like Ghosh et al. 2015 (i.e., spatiotemporally correlated with the 2011 ETS event) and Hutchison and Ghosh, 2016 (i.e., temporally but not spatially correlated with tremor during the 2014 ETS event but located in the ETS depth zone). This will be important later in the discussion where you make the point that these VLFEs are different than previously detected VLFEs in the region.
- Line 54: State *how* slow earthquakes differ from regular earthquakes
- Line 59: Why "seismic tremor" instead of "tectonic tremor" or "non-volcanic tremor" which is how the references you provide refer to it? All tremor – volcanic and non-volcanic - is "seismic."
- Line 65: "Additionally, typical VLFEs in the region can have equivalent moment magnitudes ranging from 2.1 to 4.1…These events accommodate a portion of the slip deficit at the subduction zone and concentrate along a band at depths of 30–50 km, about 10 to 15 km deeper than the downdip edge of the seismogenic zone." This makes it sound like the *VLFEs* concentrate at 30-50 km but I *think* you are referring to ETS concentrating at 30-50 km – please make this clear. Again, please also state somewhere in the Introduction where VLFEs have previously been located in Cascadia. Same depths as ETS?
- Line 85: You state in the Abstract that this earthquake occurred in the Gulf of California, state that here too for consistency. Also state what day in August it occurred and give some more background about this earthquake. You give more information about this earthquake in the first paragraph of Results, but it would be better to introduce this here.

Datasets and Methods:

- Why use vertical components instead of horizontals to find VLFEs? Please explain.
- Line 115: Give a brief, one sentence explanation of what quality control is done because this is important. It does not need to be long, but please provide some idea of what QC entails, either in the main text or the supplement.
- Line 125: "Due to the *spatiotemporal* correlation" Is it a spatiotemporal correlation, or just a temporal correlation? The 3 VLFEs are not located near the mainshock event, I would not call them spatially correlated. The main correlation is temporal, i.e., the VLFEs occurring just after the passing of the mainshock. If you are instead trying to

make the point that the 3 VLFEs are nearly co-located compared to the mainshock distance, please make this clear.

- Line 128: Do you think more subarrays detected E3 (i.e., SNR is higher) because it is larger magnitude than E1 and E2 (it likely is because static strains are not evident following these events), or because E1 and E2 occur during the coda waves from the triggering earthquake? Or both?
- Line 182: This sentence stating why the near-field stations are not used should be stated sooner in this section.

Results:

- Results paragraph 1: the background provided for the Canal de Ballenas earthquake should be included earlier in the paper.
- Line 264: In addition to the time after the triggering earthquake origin time, include how long E3 occurred after the triggering earthquake passed its location. If it is being dynamically triggered, this is the timing that is most important.
- Line 275: I don't like the logic that since they are in the vicinity of Cascadia slow earthquakes, they are most likely VLFEs. They should be identified as VLFEs for observational reasons; you stated this well in the previous sentence. Further, you argue that these VLFEs are not collocated with ETS. I suggest removing "Therefore, being in the vicinity of the Cascadia slow earthquakes, our newly located sources are most likely VLFEs."

Discussion & Conclusion:

- Very thorough and well-written discussion section!
- Line 458: How are these VLFEs different from previous events? Please be explicit since this is an important point. As stated in my earlier comment about giving more background about previously identified VLFEs in the area in the Introduction, previous studies should again be discussed here and similarities/difference be analyzed.
- Could the ETS event 3 days after E3 have been triggered by the triggering earthquake? You do a nice job discussing the possible triggering of the ETS event by E3, but please discuss triggering by the mainshock in Section 4.2 as well. This could include a discussion of dynamic stresses from the mainshock vs static stress changes from the VLFEs.
- Very strong and concise Conclusion.

Minor edits/comments:

- Line 35: Change "which" to "whose"
- Line 109: "The **AELUMA** method…"
- Line 110: Change "propagating" to "propagate"
- Line 124: "soon after" – please be more specific
- Lines 131 & 137: Figure 1, not Figure 2, shows the location uncertainty
- Line 196: Missing a "."
- Line 212: Change "stresse" to "stress"
- Line 328 – contracts should be contradicts?

- Line 435: ***whose*** duration, not *which* duration
- I could not find a reference to Figure 9 in the main text – if it is missing, please add it. I think this figure could also be moved to the supplement.

Figures:

- Figures in general are very clear. Please add scale bars to all of your maps.
- Figure 1: Include the August 3, 2009 date of the VLFEs somewhere, either on the map or in the figure caption, not just the time of day. Include the origin time of the mainshock time somewhere as well so it's easy for the reader to see the temporal correlation/dynamic triggering. Label tectonic plates.
- Figure 3: Briefly describe the polarity plot more, either in the caption or in the main text, in case the reader is not familiar with what a polarity plot is.
- Figure 5: I like that you show the waveforms of mainshock and E3.
- Figure 8a: Can the colors for E1-E3 be consistent with Figure 1 and 2? Or at least have E3 be indicated in red instead of E1.
- Include a figure (even in the supplement) showing the best VLFE (E3) compared to a local earthquake and tremor (i.e., 20-50 s filter for the VLFE, 2-8 Hz filter for tremor, HP filter for earthquake). This will provide more confidence that you have detected new VLFEs.
- Include a figure either in the main text or supplement showing the waveforms for E1 and E2, perhaps something like the waveforms in Figure 5 at a station far enough away for there to be a separation between the triggering earthquake and the VLFEs.

Reviewer #3

This paper reports dynamically triggered earthquakes in the Cascadia region. Geodetic analysis by strain meters strongly supports that these events occurred in this region. These are very interesting phenomena and should be worth of publications. The text is clearly written and methods seem to be sound. In the presented observations, however, it is not clear to me whether these events actually occurred between the seismogenic and tremor zones, while the title is "Very low frequency earthquakes in between the seismogenic and tremor zones in Cascadia?". In addition, quantitative discussion should be necessary to support that these are very low frequency earthquakes. I think that this is a significant finding whether they are VLFE or not, and whether they occur at the gap region or not. After modifying discussion and conclusions, this paper should be worth publishing in AGU Advances.

#1 Location of very low frequency earthquakes
Error of located epicenters seems to be too large to conclude that these events occurred between seismogenic and tremor zones (i.e. the gap region). Ellipsoids shown in Fig. 1 overlap tremor zone, even in the narrowest case (i.e., E3). Moreover, the geodetically located source region of chi^2=1 in Fig. 7c largely overlaps the tremor zone. These results seem to suggest that E3 occurred in the gap region or tremor zone. In the discussion and conclusions, however, it is concluded that E3 occurred only in the gap region without evidences to constrain the region. I think that a dynamically triggered M5.7 earthquake in the tremor zone is also very interesting, and worth reporting. Discussion and conclusion of such a case (i.e. events in the tremor zone) should be also included.

#2 Very low frequency earthquakes
It is not clear whether detected events are actually VLFEs. At first, the definition of very low frequency earthquakes (VLFEs) should be clarified in this paper. In terms of the definition of the scaling law by Ide et al. (2007), E3 is not a VLFE, as the slip of an M5.7 slow event is expected to last for more than several days (as discussed in Section 4.4). In this paper, VLFEs seem to be defined by the high frequency radiation. However, quantitative discussion cannot be found, even in Fig. S1. High frequency waves around E3 are recognized in Fig6b and Fig. S1. If regular earthquakes with similar seismic moment occur close to E3, comparison of spectra would give sufficient information. Otherwise, theoretically expected amplitude in the case of regular earthquakes would be useful to show that these are VLFEs.
In addition, typical duration of M6 regular earthquakes are about 10 s. Fig 4c suggests that the source duration is similar to that of regular earthquakes. Thus, I am not sure if this event is a VLFE. Some discussion on this point might clarify the difference from regular earthquakes.

The following comment is optional.
Some numerical models of VLFEs are recently proposed, for example, Wu et al. (2019,

GRL, https://doi.org/10.1029/2019GL084135), and Wei et al. (2021, Nat. Comm., https://doi.org/10.1038/s41467-021-25823-w). Perhaps, VLFEs in the latter paper may be similar to the detected events. Discussion of numerical models might be also interesting.

#3 Comparison of geodetic observation (Fig. 6)
It is not clear to me whether the observed strain change can be well explained by the synthetic data. Fig. 6a shows synthetic strain change expected from model. Fig 6b shows the observed strain changes. I think that Fig 6a and 6b cannot be compared directly, as they are related by the calibration coefficients given in Table S3.
A figure to compare the amount and direction of strain might be significant to justify the modeled fault. In addition, values shown in contours in Fig 6a are too small to read, while bottom part of maps is not used. If possible, please magnify the target region.
The discussion of geodetic observation is an essential part to support that these are really local events and not caused by seismic velocity structure. A nice figure would make this paper more convincing!

#4 Strain meter, B003
In this paper, large misfit at B003 is attributed to the effect of non-linear ocean tide and uncertainty of the location of lobes (Lines 339-347). However, other stations (e.g. B004) are also close to ocean, and seem to have the same problem in terms of non-linear tide. Effect of lobes seems to be less sensitive in the case of RMS and areal strain. Can the data of B003 be ruled out by these reasons? In addition, if the effect of lobes is true, the geometry of fault might be strongly constrained.

#5 Existence of similar events
I am interested in how rare such events are. Some comments would clarify the rarity of these events, if author analyzed long-term continuous data. This is just an optional comment.

#6 Events E1 and E2
Can the magnitude of E1 and E2 be roughly estimated, for example based on amplitude? At the timing of E1 and E2, can small high frequency waves be found as in Fig. S1?

#7 Fig. 4
In Line 746 (caption), "N.M" should be "Nm". An explanation of the color scale in Fig. 4b, 4c should be added.