Authors' Response to the Review Comments

Journal:	Geophysical Research Letters
Manuscript #:	2022GL101987
Title of Paper:	Deep long-period earthquakes at Akutan Volcano from 2005-2017 better track magma influxes compared to volcano-tectonic earthquakes.
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Date Sent:	Feb 28, 2023

We thank the editor and reviewers for their precious time and efforts in reviewing our manuscript. The constructive and insightful comments provided are particularly helpful for us to improve this manuscript. In response to the feedbacks from reviewers, we have carefully revised the manuscript, and we believe that it is now suitable for publication at GRL. Changes have been highlighted within the revised manuscript. A point-by-point response to the reviewers' comments and concerns is listed below.

Reviewer 01

Overall Comment: This paper investigates multi-year seismicity beneath Akutan volcano with a focus on detecting and distinguishing deep long-period (DLP) and VT seismicity. The authors employ what are now relatively standard methodologies: template matching, frequency index (FI) spectral classification, and high-precision relocation. The resulting catalog is further analyzed using seismicity clustering and moment release estimations. The application of these methods to this particular dataset is new here and the discussion of the results for this volcano is thus potentially of interest to the volcano seismology, seismology, and volcanology communities. This paper can be improved by addressing the comments below.

Response: Thank you for taking the time to evaluate our work. Our point-by-point responses to your comments are detailed below.

Comment #1: Line 85-87: this statement as written does not mention shallow long-period seismicity <5 km, which is a major, probably the most important (for forecasting), type of volcanic seismicity. I suggest to cite here, for example, Chouet, 1996. Also relevant to cite here: *Matoza, R.S., B.A. Chouet, P.B. Dawson, P.M. Shearer, M.M. Haney, G.P. Waite, S.C. Moran, and T.D. Mikesell (2015), Source mechanism of small long-period events at Mount St. Helens in July 2005 using template matching, phase-weighted stacking, and full-waveform inversion, J. Geophys. Res. Solid Earth, 120, 6351-6364, doi:10.1002/2015JB012279* which demonstrated template matching for LPs. See also the recent review: Matoza and Roman (2022) for many additional citations: *Matoza, R.S., and D.C. Roman (2022), One hundred years of advances in volcano seismology and acoustics, Bull. Volcanol., 84, 86, doi:10.1007/s00445-022-01586-0*

Response: Thank you for pointing this out - we concur that it is crucial to include shallow long-period earthquakes in the introduction. We have updated the paragraph in *line 82-110* to also introduce shallow LPs before explaining the importance of studying deep long-period earthquakes which is the focus of our manuscript:

Lines 82-89: "Earthquakes recorded at volcanic regions that are rich in high-frequency content are usually referred to as volcano-tectonic events (VTs). VTs are commonly observed in the crust (e.g. Matoza et al. (2014)) and are considered to be related to stress perturbation from processes such as shear failures in volcanic edifice (B. A. Chouet & Matoza, 2013) or dike propagation (Roman & Cashman, 2006). In contrast, long-period earthquakes (LPs) radiate low-frequency (1-5 Hz) energy predominantly and have been detected in the shallow crust down to the upper mantle (R. A. White, 1996; Pitt et al., 2002; Melnik et al., 2020)"

Lines 93-96: "LPs occurring in the shallow crust have been attributed to pressure disruptions in the magmatic and hydrothermal systems (B. Chouet, 1992; Lokmer et al., 2008; Matoza et al., 2015; Matoza & Roman, 2022) or slow rupture in unconsolidated materials (Bean et al., 2014)."

Lines 104-110: "Since DLPs could provide a crucial window into the deep plumbing system and are potential eruption precursors (R. A. White, 1996; Power et al., 2013), identifying the specific processes underlying DLPs will improve our ability to interpret unrest episodes and forecast eruptions. However, while VTs' utility for eruption forecasting is well-studied (Li et al., 2021; R. White & McCausland, 2016), our understanding of how DLP activity might relate differently to inflation and eruption episodes remains limited."

Comment #2: Line 97: Bean et al. (2014) seems to be a mis-citation here, since Bean et al. largely argue for the opposite interpretation. Bean et al. argue for no fluids in the source, whereas this statement is referencing fluids at the source. The appropriate citation is more correctly then Chouet, (1996) (LPs and fluid resonance) together with Chouet and Matoza, (2013) (review of DLPs). Note also that Bean et al. is cited at line 343 (used more correctly in this case).

Response: Thank you for the careful review. We have corrected corresponding citations in *line 103* and checked throughout the manuscript according to your suggestions. Citation for Bean *et al.* (2014) in *line 249* has also been deleted.

Comment #3: Section 3: The methodology followed in this section follows almost identically the workflow and methodology proposed and introduced by Matoza et al. (2014). Although this paper is cited near the beginning of this section, the impression to the reader is given that this method follows Buurman and West (2010), which is only partially the case. The Frequency Index (FI) as initially developed by Buurman and West (2010) was only a single-station metric. Matoza et al. (2014) first performed a "station-averaged FI" (actually a median) as used also in the method presented here. The station-averaging helps make the FI more robust to path and site effects. Although a relatively small step, it was a new contribution at the time and helped to popularize the approach of Buurman and West (2010). So I would appreciate it if you reflect that in the citation. This comment could be addressed by citing Matoza et al. 2014 together with Buurman and West (2010) on line 175 and also by citing Matoza et. al. (2014) on line 185 (sentence about median FI across all available stations

Matoza, R.S., P.M. Shearer, and P.G. Okubo (2014), High-precision relocation of long-period events beneath the summit region of Kilauea Volcano, Hawai`i, from 1986 to 2009, Geophys. Res. Lett., 3413-3421, 41, doi:10.1002/2014GL059819

Response: Thank you for the comments. Corresponding citations in *line 183 and 194* have been updated accordingly.

Comment #4: Comments about the discussion of results: The methods employed in this study are now relatively standard, but their application to this new dataset is a new contribution. Consequently, the discussion and interpretation of the new results for Akutan are critically important in framing this paper for the GRL audience. In general, the discussion and overall conclusions are somewhat vague and it is not clear what the major take-home points are for the volcano seismology, seismology, and volcanology communities. Most of the discussion points and main conclusions are not surprising statements and reflect what is already well established in the literature. For example, (from the abstract): "VTs represent fault rupture triggered by magma/fluid movement or larger earthquakes, while the DLPs are directly related to unsteady magma movement through a complex pathway or represent slow fault ruptures triggered by magma movement." This statement reflects the already current knowledge based on many papers (e.g., see Chouet and Matoza, 2013; Matoza and Roman, 2022).

I would invite the authors to make clearer the case for what is interesting or different about Akutan and the results presented here compared to other volcanoes studied previously in the literature. This should be highlighted more strongly and clearly in the abstract and conclusions.

Response: Thank you for the comment – we apologize for not better communicating the novelty of our study in the previous manuscript. We believe our results are interesting, novel, and important because:

Firstly, while earthquake swarms have been found to sometimes coincide with ground deformation, few studies have quantified how VT and DLP swarms in the same locale might behave differently over decadal timescales and relate differently with various magmatic processes. From our analyses at Akutan, we find that while both DLP and VT swarms occur preferentially during inflation periods over the past 12 years, the moment release rates of DLP swarms better correlate with inflation periods than VTs. This suggests that even though precursory VT swarms might be triggered by magma movement, they are likely also related with many other non-magmatic processes whereas DLP swarms provide a more direct way to track magma movement. Similar analyses at other volcanoes would improve our understanding of how to incorporate VT and DLP activity differently for probabilistic forecasting.

Secondly, although DLPs have been suggested as a potential eruption precursor with various source mechanisms proposed, it is often difficult to ascertain which source mechanism best explains observed DLPs at different locales. For example, previous studies interpreted DLPs at Akutan Volcano to be related to magmatic processes (e.g. Syracuse et al. 2015 and DeGrandpre et al. 2017) without explaining whether they are related to magma movement or stalled magma (which has different implications for forecasting), or showing why they could not have just been due to site/path effects or represent slow fault ruptures. Our study demonstrates how a detailed analysis of available seismic data can differentiate the various possible source mechanism for DLPs , and in the case of Akutan Volcano led us to conclude that the DLPs are caused by non-stationary source effects, most probably magma movement through a complex pathway, hence they provide a relatively direct way to track magma influx into the shallow reservoir from depth. Similar workflow can be extended to other volcanoes to better understand where DLPs have similar value, and DLPs should not be blithely interpreted to represent magma movement without careful analysis which might lead to inaccurate interpretation of unrest activity and forecasting.

We have revised the manuscript to better communicate the points discussed above in the following lines:

Lines 8-9 (in the key points): "Moment release rates of deep long-period events correlate more strongly with inflation episodes compared to volcano-tectonic events."

Lines 10-11 (in the key points): "Akutan deep long-period earthquakes are likely due to non-stationary source effects like unsteady magma transport through complex pathways."

Lines12-13 (in the key points): "Akutan volcano-tectonic earthquakes represent fault ruptures triggered by magma/fluid movements or larger earthquakes."

Lines 22-27: "……moment release rates of DLP swarms show a stronger correlation with inflation and their low-frequency content is likely a source instead of a path effect. Therefore, we infer that DLPs are directly related to unsteady magma movement through a complex pathway. In comparison, repeating events are observed in VTs. Thus, we conclude that they represent fault rupture triggered by magma/fluid movement or larger earthquakes."

Lines 39-44: "Some earthquakes have predominantly low-frequency energy which suggests a different source mechanism compared to regular earthquakes. Furthermore, the largest events are more strongly correlated with surface inflation. Therefore, we conclude that these lower-frequency earthquakes are more directly related to unsteady magma movement through a complex pathway compared to regular earthquakes which represent fault rupture triggered by magma/fluid movement or larger earthquakes."

Lines 107-110: "……while VTs' utility for eruption forecasting is well-studied (Li et al., 2021; R. White & McCausland, 2016), our understanding of how DLP activity might relate differently to inflation and eruption episodes remains limited."

Lines 271-279: "Earthquake swarms have been found to sometimes coincide with surface deformation driven by high-pressure fluid or magma injection, e.g. Green and Neuberg (2006), Shelly et al. (2013), and Ji et al. (2017), or aseismic slip propagation, e.g. Gualandi et al. (2017) and Yukutake et al. (2022). However, few studies have quantified how VT and DLP swarms might behave differently over decadal timescales and in relation to various magmatic processes. Such an analysis could help us better decipher the swarms' underlying physical processes and utility for eruption forecasting.

Therefore, we analyze temporal correlations between identified swarms and surface deformation at Akutan Volcano."

Lines 386-388: "The low-frequency content of DLPs is relatively uniform across the seismic network, thus is likely a source instead of only path or site effect."

Lines 391-397: "……both DLP and VT swarms occur preferentially during inflation episodes. However, the largest DLP swarms (in terms of cumulative moment release) coincide well with inflation episodes whereas the largest VT swarms occur during non-inflation periods. Furthermore, repeating events are only detected in VTs and not in DLPs. Therefore, we infer that compared to VT swarms that likely reflect fault slips triggered by magma inflation, fluid diffusion or larger earthquakes, DLP swarms are more directly related to unsteady magma movement through a complex pathway."

Reviewer #02

General comments:

This paper presents a fairly comprehensive analysis of VT and DLP seismicity at Akutan volcano, a frequently active volcano in the Aleutian Arc. Although Akutan did not erupt during the time period of this study, the authors use inflation as a window into magmatic activity and propose that there is a stronger correlation between inflation and DLP events than between inflation and VTs. The paper shows that there is little to no correlation between inflation and VTs, but I have a harder time with the contention that a correlation exists between DLPs and inflation. This is my biggest issue with the paper...if this can be clarified then I support publication of the article.

Response: Thank you for your valuable comments. We apologize for not better communicating one of our main observations/conclusions. We are not saying that there is no corelation between VT and volcanic inflations. Instead, what we find is that when looking at swarm/event rates, both DLPs and VTs correlate well with inflation periods. However, when looking at cumulative moment release rates, DLPs correlate much better with inflation periods compared to VTs. Our point-to-point responses to your detailed comments are outlined below.

This study compares correlations between inflation events and DLP and VT activity at Akutan. The authors conclude that both the event rate (events/year) and the cumulative moment release for DLP swarms correlates with periods of inflation, but I didn't find this argument to be compelling. The authors note that 3 of 8 swarms occur during an inflation episode and indeed, their data do show a slightly elevated likelihood of a DLP swarm occurring during inflation. But the amount is not huge: 37% of swarms occur during inflation, which occurs 27% of the time. Further, two of the DLP swarms took place during the same inflationary period, so that complicates the correlation. If we ask the question differently...how many inflationary periods are associated with DLP swarms?...then we get a very different answer, as it appears that inflation is as likely to occur with DLP activity as it is to occur without it (two inflations with DLP activity, two without).

Response: Thank you for the comment. We would argue that having 3 out of 8 DLP swarms (38%) occurring during inflation that only occurs 27% of the time, which means that the swarm rate during inflation of 0.92/year is 61% higher than the swarm rate of 0.57/year during non-inflation period, is a significant increase in likelihood. However, we understand your concern considering the small sample size. That is why we also look at the event rate and find that 73 out of 179 DLPs which belong to a swarm (41%) occur during inflation, which means that the swarm event rate during inflation of 22.5/year is 88% higher than the swarm event rate of 12/year during non-inflation period. The general trend where the rate is higher during inflation holds when we use different parameter values during the clustering process, as well as during the Jack-knife test where we iteratively leave out a swarm before recalculating the statistics to check that the trend is not biased by any individual swarm. Finally, when we look at the overall event rate (without clustering into swarms), we find that 203 out of 632 DLPs (32%) occur during inflation which means that the DLP rate during inflation of 63.5/year is 31% higher than the DLP rate of 48.6/year during non-inflation period. Considering the consistency of the trend across different ways of looking at the data, we conclude that the observation is robust and significant.

Regarding the observation that only half of 4 inflation episodes co-occurred with DLP swarms, we think this is not unlike previous studies of precursory signals. For example, Pesicek et al. (2018) found that only 30% of eruptions in Alaska have statistically significant precursory seismic rate increase and Biggs et al. (2014) found that only 74% of volcanoes that erupted showed deformation and only 46% of those that deformed erupted. Nevertheless, our observation that there is a rate increase during inflation compared to non-inflation period is still valuable, and quantifying the strength of correlation will be helpful for probabilistic assessment and interpretation of future unrests.

Biggs, J., Ebmeier, S., Aspinall, W. et al. Global link between deformation and volcanic eruption quantified by satellite imagery. Nat Commun 5, 3471 (2014). https://doi.org/10.1038/ncomms4471

We have revised the manuscript to better communicate the points discussed above in the following lines:

Lines 54-56: "…… only 30% of recent eruptions among Alaskan volcanoes have statistically significant precursory increase in seismicity rate (Pesicek et al., 2018)."

Lines 284-289: "We find that 3 (73 DLPs) out of the 8 DLP swarms (179 DLPs) and 13 (225 VTs) out of the 34 VT swarms (541 VTs) occurred during inflation episodes. This means that the rate of DLP and VT swarms are 0.92 and 4.00 per year (22.46 DLPs/year and

69.23 VTs/year) respectively during the inflating periods, which is almost twice the rate of 0.57 and 2.38 per year (12.00 DLPs/year and 35.77 VTs/year) during the non-inflating periods (Fig. 2a)."

Lines 292-298: "We also applied Jack-knife test by iteratively recalculating all these statistics after dropping out one cluster at a time to evaluate whether our observed trend could be a by-product of overwhelming influence from any individual swarm. The Jack-knife test results show the range of event rate for both DLP and VT swarms in inflating periods remains higher than non-inflating periods (Fig. 2a), indicating that our conclusion is not biased by any individual swarm. Both DLP and VT occurrences are strongly correlated with magma inflation."

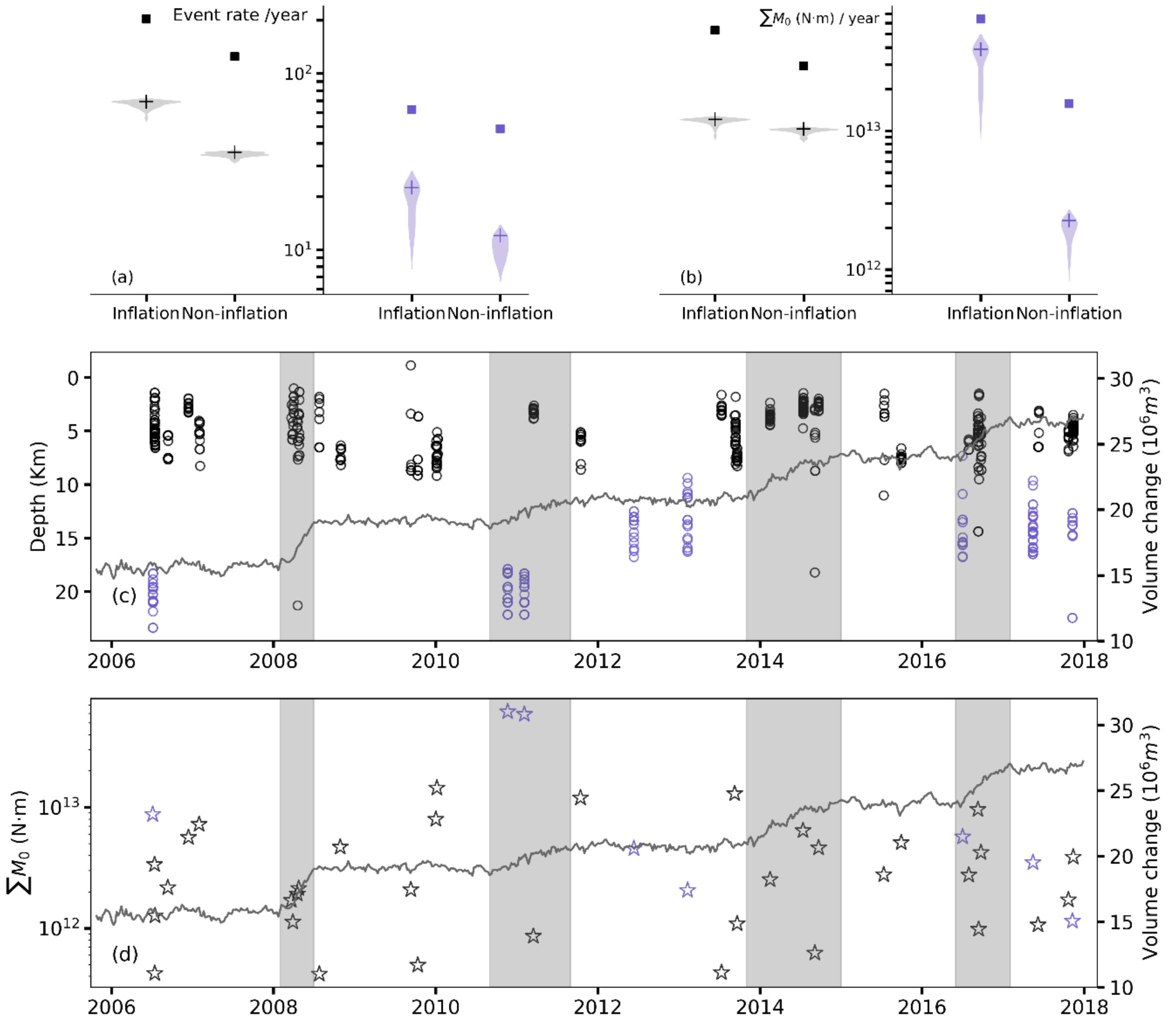

Figure 2. Properties of earthquakes at Akutan Volcano from 2005 to 2017. Event rates (a) and moment release rates (b) of DLPs (purple) and VTs (black) during inflation and non-inflation periods. The violin plots show results of Jack-knife test where we leave one swarm out and recalculate properties iteratively. The violin widths are scaled by data counts. Cross symbols and squares indicate properties of clustered earthquakes and all earthquakes, respectively. (c) Temporal evolution of earthquake depths. Purple and black circles represent DLP and VT swarms, respectively. Gray curve represents volume changes of deformation source as calculated by Xue et al. (2020). Shaded areas mark inflation episodes. (d) Cumulative moment release of earthquake swarms. Purple and black stars indicate DLP and VT swarms, respectively.

The stand-out number is the cumulative moment: the authors show that the largest cumulative moment DLP clusters occurs during inflation periods. But if I'm reading Figure 2 properly, this is entirely because of the two swarms in 2011: these have much higher moment than any other, and thus they drown out the signal from other swarms. The authors state (lines 339-340) that "the DLP swarms...are strongly correlated with inflation episodes", but I'm unconvinced that this is the case.

Response: Thank you for raising this important concern. To assess whether our conclusion is biased by any individual swarm, we conduct the Jack-knife test i.e. recalculating the cumulative moment release rate during inflation vs non-inflation periods iteratively by leaving out one swarm at a time. The Jack-knife tests suggest that the cumulative moment release rate of DLPs in the inflation episodes remain significantly higher (at least 7 times larger) than in the non-inflation periods no matter which swarm is dropped out (Fig. 2b). In comparison, the cumulative moment release rate of VTs in the inflation episodes is similar to during non-inflation periods (Fig. 2b), and 4 out of the 5 largest VT swarms all occurred during non-inflation period (Fig. 2c). This trend also holds when we use different parameter values during the clustering process (Fig. S10). Therefore, our conclusion that the cumulative moment release rates of DLPs are more strongly correlated with inflation episodes compared to VTs is robust.

We have revised the manuscript to better communicate the points discussed above in the following lines:

Lines 284-289: "We find that 3 (73 DLPs) out of the 8 DLP swarms (179 DLPs) and 13 (225 VTs) out of the 34 VT swarms (541 VTs) occurred during inflation episodes. This means that the rate of DLP and VT swarms are 0.92 and 4.00 per year (22.46 DLPs/year and 69.23 VTs/year) respectively during the inflating periods, which is almost twice the rate of 0.57 and 2.38 per year (12.00 DLPs/year and 35.77 VTs/year) during the non-inflating periods (Fig. 2a)."

Lines 292-298: "We also applied Jack-knife test by iteratively recalculating all these statistics after dropping out one cluster at a time to evaluate whether our observed trend could be a by-product of overwhelming influence from any individual swarm. The Jack-knife test results show the range of event rate for both DLP and VT swarms in inflating periods remains higher than non-inflating periods (Fig. 2a), indicating that our conclusion is not biased by any individual swarm. Both DLP and VT occurrences are strongly correlated with magma inflation."

Lines 310-314: "We find that the moment release rates of DLP swarms during inflation periods is 3.88×10^{13} N·m/year, which is 15 times larger than 2.26×10^{12} N·m/year during non-inflation periods. Comparatively, the moment release rates of VT swarms in inflation periods (1.21×10^{13} N·m/year) is only 17% higher than that in non-inflation periods (1.03×10^{13} N·m/year)."

Lines 316-318: "The Jack-knife test results also show the same trend (Fig. 2b) which means that this conclusion is not biased by any individual swarm even when clustering parameter changes (Fig. S10)."

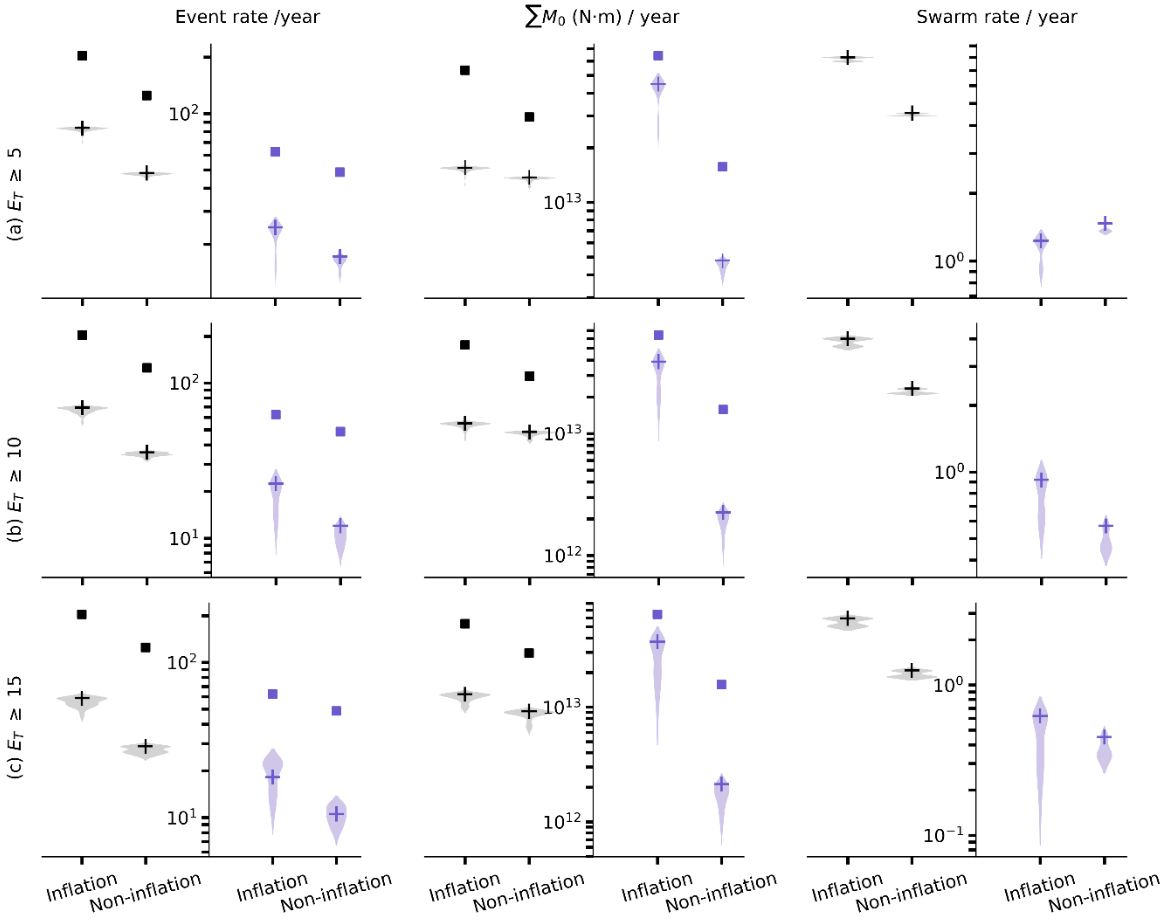

Figure S10. Comparison of earthquake properties at Akutan Volcano in both inflation and non-inflation episodes from 2005 to 2017. Earthquakes are clustered by the minimum E_T of 5 (a), 10 (b), and 15 (c) respectively. The violin plot shows Jack-knife test results where we leave one swarm out and recalculate the properties iteratively for DLP (purple) and VT (black) swarms. The violin widths are scaled by data counts. Crosses and squares show the properties for clustered earthquakes and all earthquakes.

There are a variety of metrics that one could use to look for correlations: the presence of DLP swarms, the number of events in the swarm, the event rate, the cumulative moment, etc. The authors have chosen two that fit their model, but it isn't clear to my why event rate, for example, should be a more compelling choice of parameters than simply the occurrence of a swarm. Further, given the short duration of swarms and inflation events, what happens if we consider the number of events per day, for example? In other words, it would be helpful to have more justification of why these specific metrics were used.

Response: We agree that there are a variety of metrics that one could use to look for correlation. We now use all the metrics listed: swarm rate, swarm event rate, event rate, swarm cumulative moment release rate, and all events cumulative moment release rate. We find that the results remain consistent: when looking at swarm rate, swarm event rate, and event rate, both DLPs and VTs show similar correlation with inflation episodes. However, when looking at cumulative moment release rate, DLPs show much stronger correlation with inflation episodes compared to VTs. Therefore, we infer that this is related to differences in their underlying mechanism – DLPs are directly related to magma movement, while some VTs are fault rupture triggered by magma movement (and also fluid movement, other earthquakes etc.).

We have revised the manuscript to better communicate the points discussed above in the following lines:

Lines 289-292: "This finding is relatively robust, since we find that both DLP and VT swarms rates during inflating episodes remain higher than during non-inflating periods even when we do not cluster earthquakes (Fig.2a) or use minimum E_T of 5 or 15 instead during the clustering process (Fig. S10)."

Lines 303-308: "We find that the two largest DLP swarms in terms of cumulative moment releases indeed occurred during an inflation episode (Fig. 2d). The third DLP swarm *that occurred during an inflation episode in 2016 had comparable cumulative moment releases with the two largest DLP swarms that occurred during non-inflation periods. In comparison, the largest VT swarms in terms of cumulative moment releases do not coincide with inflation episodes (Fig. 2d)."*

Lines 308-314: "We also estimate the moment release rates of DLP and VT swarms during inflation and non-inflation periods (Fig. 2b). We find that the moment release rates of DLP swarms during inflation periods is 3.88×10^{13} N·m/year, which is 15 times larger than 2.26×10^{12} N·m/year during non-inflation periods. Comparatively, the moment release rates of VT swarms in inflation periods (1.21×10^{13} N·m/year) is only 17% higher than that in non-inflation periods (1.03×10^{13} N·m/year)."

Line 316: "The Jack-knife test results also show the same trend (Fig. 2b)……"

The authors do not comment on the rate of inflation during any of the periods presented in the paper, which is something one might expect to be a factor. The two largest DLP swarms, in fact, seems to take place during a period of very slow inflation; in contract, the rapid inflation in 2008 is accompanied by a small DLP swarm. If the DLP swarms are associated with magmatic injection, why are the largest swarms associated with the most gradual inflation? This would be a compelling thing to consider and would add strength to the paper.

Response: We agree that this is a compelling thing to consider. Our results are similar to previous studies such as at Sierra Negra volcano (Bell et al., 2021) and Santorini volcano (Druitt et al., 2019), where seismic moment release rates are not directly correlated with inflation rates. This might be because the seismicity accounts for only a fraction of the moment release of the deformation and is also affected by other factors such the stress state of the region. We have revised the manuscript to discuss these points in the following lines:

Lines 319-326: "Interestingly, the two largest DLP swarms occurred during the 2011 inflation period which has relatively slower inflation rate (Fig. 2d). This is similar to *observations at Sierra Negra Volcano (Bell et al., 2021) and Santorini Volcano (Druitt et al., 2019) where seismic moment release rates do not always correlate with inflation rates. Possible explanations include the seismic moment release being only a fraction of the moment release of the deformation (Gualandi et al., 2017), and is also affected by factors such as the background stress state of the region (Pedersen et al., 2007)."*

Smaller suggestions follow:

Line 22: maybe say "spatial migration" instead of just migration?

Response: We have revised the sentences as suggested (now line 22)

Line 51: change "forecasted" to "forecast"

Response: This sentence has been revised a bit.

Lines 50-53: "Precursory increases in seismicity rate are detected sometimes before major eruptions (R. A. White & McCausland, 2019), such as 1991 Pinatubo (Harlow et al., 1996), 2000 Hekla (Einarsson, 2018), and 2004 Mount St. Helens (Morgan et al., 2008) eruptions."

Lines 50-52: this is a pretty short list of eruptions that were forecast based on seismicity. Maybe add a few others? Mount St. Helens 2004 was a good one, if memory serves *(Moran, S. C., Malone, S. D., Qamar, A. I., Thelen, W. A., Wright, A. K., & Caplan-Auerbach, J. (2008). Seismicity associated with renewed dome building at Mount St. Helens, 2004-2005. US Geological Survey professional paper, (1750), 27-60))*, and table 1 in White and McCausland (2019) has a long list of eruptions for which there were precursory seismic sequences.

Response: Thank you for the suggestion. We have included a few more citations (including Mount St. Helens) in the revised manuscript, though we only meant to provide a few examples instead of an exhaustive list. The revised sentence is as follow:

> *Lines 50-53:* "*Precursory increases in seismicity rate are detected sometimes before major eruptions (R. A. White & McCausland, 2019), such as 1991 Pinatubo (Harlow et al., 1996), 2000 Hekla (Einarsson, 2018), and 2004 Mount St. Helens (Morgan et al., 2008) eruptions.*"

Line 62: replace "earthquake occurrence are often" which "earthquake occurrence is often"

Line 63: replace "are" with "is" in the second word.

Line 69: consider replacing "is commonly termed swarms" with "is described as swarm activity".

Line 74: A new paper regarding deep activity beneath Kilauea (Wilding et al., 2022) might be nice to cite here it addresses diffusion in deep sills.

Line 83: add "and" between "are" and "considered" ("and are considered to be related...")

Response: We have incorporated your suggestions in the manuscript *(now in line 63, 64, 70, 75, 84)*, thanks for the careful review.

Line 88: emergent arrivals make DLPs harder to locate, but are they also harder to detect? I guess this depends on the detection algorithm that is being used? The reference is somewhat old, so I wonder if the more recent recognition of the important of LP events means that detection algorithms may also have become better tuned to detect them? Also, the reference for this (Pitt, 2022) is incomplete and I suspect it should be Pitt et al., 2002?

Response: For detecting DLPs, we believe the detection algorithm that earthquake monitoring agencies use today is still not well-tuned compared to for detecting VTs.

However, the template matching technique has been shown to perform well in detecting LPs (e.g. Shapiro et al. (2017) and Wimez & Frank, (2022)). This is consistent with our observations because based on detections from template matching at Akutan Volcano, we get 561 additional LPs which is 2 times more than the number of LP templates provided by AVO. In comparison, 1,516 newly detected events are VTs which is similar to the number of VT templates. The larger number of new detection relative to the available templates for LP events might reflect AVO's current event detection system being less well-optimized for detecting LP events. Thank you for raising this point, we have added brief descriptions of detection methods improvements in the lines listed below. The citation has also been corrected *(now in line 91)*.

Lines 89-93: "Characterized by emergent phase arrivals and dominant low frequency contents, LPs are difficult to detect using traditional earthquake detection methods (Pitt et al., 2002; Shapiro et al., 2017; Wimez & Frank, 2022), though recently, matched filter detection techniques have proven to be quite effective for improving existing LP catalogs (Hotovec-Ellis et al., 2018; Kurihara et al., 2019; Kurihara & Obara, 2021)."

Lines 201-205: "Overall, 561 newly detected events are LPs which is 2 times more than the number of LP templates. In comparison, 1,516 newly detected events are VTs which is similar to the number of VT templates. The larger number of new detection relative to the available templates for LP events may reflect AVO's current event detection system being less well-optimized for detecting LP events."

Line 91: the notion that DLPs have potential as eruption precursors is complicated-many DLPs are identified that do *not* precede eruptions, which is worth mentioning here.

Response: We agree that not all DLPs precede eruption. Therefore, we rephrased this paragraph a bit by describing the various inferred mechanisms of both shallow and deep LPs in more detail (some of which might explain why DLPs are also observed outside of eruption periods). The relevant lines have been outlined below:

Lines 93-99: "LPs occurring in the shallow crust have been attributed to pressure disruptions in the magmatic and hydrothermal systems (B. Chouet, 1992; Lokmer et al., 2008; Matoza et al., 2015; Matoza & Roman, 2022) or slow rupture in unconsolidated materials (Bean et al., 2014). In comparison, the inferred source mechanisms of LPs occurring from mid-crust to upper mantle (Power et al., 2004; Kurihara & Obara, 2021), known as deep long-period events (DLPs), is quite diverse but generally fall into two categories……"

Lines 104-107: "Since DLPs could provide a crucial window into the deep plumbing system and are potential eruption precursors (R. A. White, 1996; Power et al., 2013), identifying the specific processes underlying DLPs will improve our ability to interpret unrest episodes and forecast eruptions."

Line 104: the manuscript suggests that 14 seismometers were deployed on Akutan in 1996, but I don't think that's correct. The 1996 network had six stations, but more were deployed over time (here's the link to the info about the original 6: https://pubs.usgs.gov/of/2001/0189/pdf/of01-189.pdf).

Response: We apologize for the misleading information caused by ambiguity of this sentence and agree that the network was developed and augmented gradually since 1996 at Akutan volcano. The relevant sentence has been carefully corrected now:

Lines 113-115: "Seismometers have been deployed at Akutan volcano since 1996 forming a network of 14 stations at present with which both VTs and DLPs are documented (Power et al., 2004)."

Line 109: add "observed" at the front of the line ("...observed every 2-3 years")

Lines 123-123: I don't think there's any need to include the latitudes and longitudes in the text. The figures show clearly where the events lie.

Lines 124-126: cut the last part so it simply reads "All waveforms are resampled to 50 Hz and bandpass filtered at 1-15 Hz". The remainder of that sentence is repeated in the next paragraph.

Response: We agree with these suggestions and have revised the sentences accordingly *(lines 118, 132, 133)*.

Lines 189-190: I don't understand why there is overlap between the two clusters, when plotted by FI. I suspect this has to do with the averaging of FI over all of the stations, but it isn't quite clear to me.

Response: According to the catalog maintained by AVO, the long-period events were manually labelled by analysts based on visual inspection. However, as Matoza *et al.* (2014) showed previously, such manual classifications can be inconsistent. This is why we opted to reclassify the earthquakes using FI in a more systematic way. The bimodal distribution of FI suggests general consistency between FI values and manual labels, i.e. most manually-labelled LPs are characterized by low FI due to their dominant low-frequency energy. Overlaps between the two clusters highlight events that should have been classified as LP/VT according to FI but labelled as VT/LP by analysts instead. To illustrate this issue more clearly, we have edited the text in *line 195-198* to the following:

Lines 195-198: "Figure 1b shows the FI distribution of earthquakes in the AVO catalog, color-coded by their manual labels (Power et al., 2019). There is a clear bimodal *distribution and near the boundary, manual labels can be inconsistent i.e. events with the same FI values can have different labels."*

Line 260-261: this line states that hydrothermal fluids "reduce elastic moduli and hence aftershock production", citing Garza-Giron et al. My reading of that paper is that the authors actually find that there are similar rates of aftershocks in volcanic regions: they state "...aftershock sequences are a common property of crustal earthquakes independent of whether they occur in a volcanic or nonvolcanic environment."

Response: We apologize for the confusion. We originally discussed about aftershock productivity to help differentiate the underlying mechanism of earthquakes swarms and mainshock-aftershock sequences. However, we have decided to delete this citation and just focus on how VT and DLP swarms might behave differently over decadal timescales, through which we can better explain the underlying physical process of swarms. The revised paragraph in *lines 271-277* is as follow:

Lines 271-277: "Earthquake swarms have been found to sometimes coincide with surface deformation driven by high-pressure fluid or magma injection, e.g. Green and Neuberg (2006), Shelly et al. (2013), and Ji et al. (2017), or aseismic slip propagation, e.g. Gualandi et al. (2017) and Yukutake et al. (2022). However, few studies have quantified how VT and DLP swarms might behave differently over decadal timescales and relate differently with various magmatic processes. This could help us better decipher their underlying physical processes and utility for eruption forecasting."

Last word of line 291: replace "have" with "had"

Lines 319-320: change "hence regions without pervasive fluids" to "interpreted as regions with low fluid content"

Response: We have updated the manuscript accordingly *(lines 305, 349)*.

If I'm reading this properly, the caption to Figure 2 is a little confusing in that a single dot represents different things in different panels (a single event or a single cluster). Maybe use a different symbol to represent a cluster?

Response: Thanks for the suggestion. We have updated *Fig. 2* by using stars as markers of cumulative moment release for swarms. The captions have also been updated accordingly.

The caption to Figure 3 describes the deep VT events as "Western", but their location is not otherwise addressed in the paper. Consider removing this descriptor or adding text about the location.

Response: Thank you for the suggestion. We have improved *Fig. 3* by representing DLP and deep VT to the west more properly and intuitively. Accordingly, the captions have been also updated.

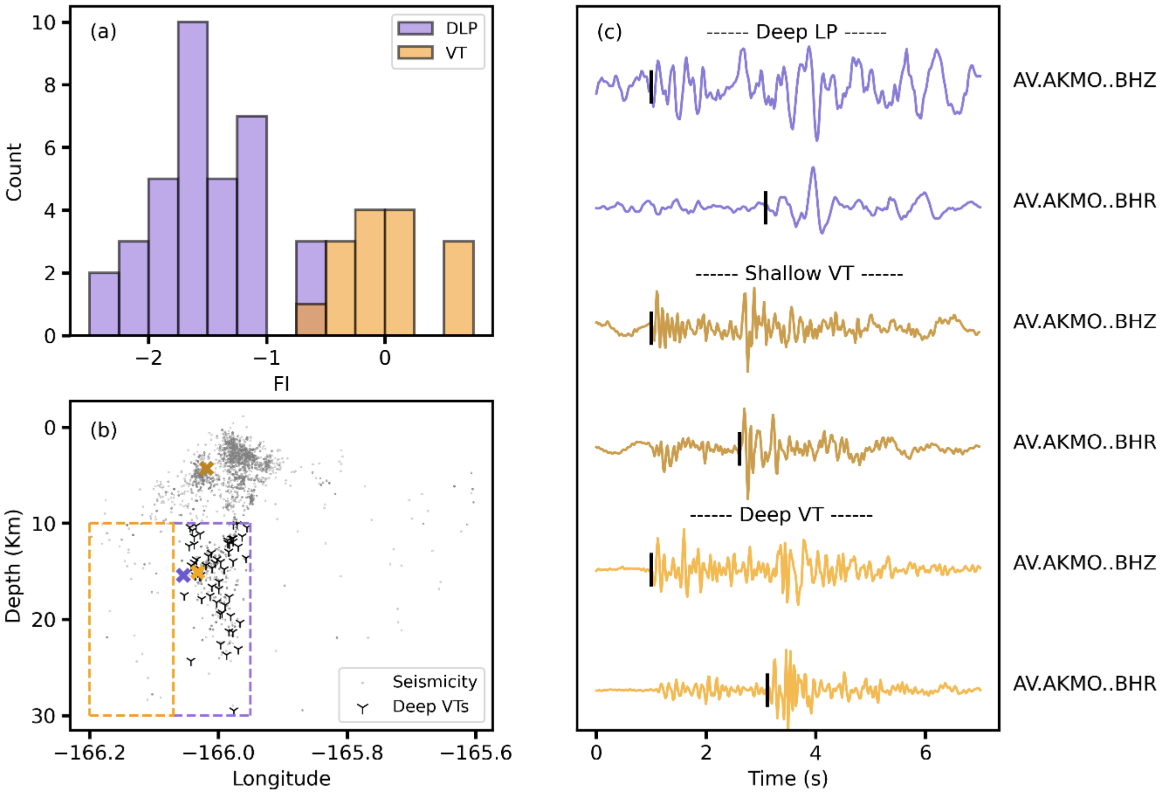

Figure 3. FI analysis on deep VTs and DLPs. (a) FI measured at station MTBL (Fig. 1a) for DLPs and deep VTs to the west of the caldera, with their spatial boundaries outlined by purple and yellow boxes respectively in panel b. (b) Seismicity distribution during 2005-2017 are shown by gray dots. VT detections within the DLP source region are marked as black trident scatters. Purple, light yellow, and dark yellow crosses show locations of DLP, deep VT and shallow VT shown in panel c; (c) Representative waveforms of DLP (purple), deep (light yellow) and shallow (dark yellow) VTs recorded by the same local station at vertical and radial channels. Black vertical lines indicate phase arrivals.

There are strange formatting issues in the references-lack of capitalization, and the unnecessary words "[journal article]".

Response: The reference list has been updated *(lines 411-795)*.

The paper frequency references the "shallow magma reservoir", but doesn't specifically discuss a deep one. I'm guessing this relates to the presence of DLPs at depth and the interpretation that they may be associated with magma?

Response: Sorry for the confusion. According to the inversion results from seismic and geodetic data (Syracuse *et al.*, 2014; DeGrandpre *et al.*, 2017), there is an inferred magma reservoir beneath Mt. Akutan at ~ 8 km depth. In this study, the DLPs are located below it. No deeper magma reservoir has previously been imaged, though presumably there is deeper source(s) of magma responsible for feeding magma into the imaged reservoir at 8 km depth. To avoid confusion, we now use “inferred magma reservoir” instead of “shallow magma reservoir” in the updated manuscript *(line 20, 207, 209, 210, 373, 386)*.