

**Response to Editors and Reviewers' Comments**  
**(Manuscript Number: G54254)**

We appreciate the editor and two reviewers' comments and suggestions. We have made extensive modifications to address the issues raised in the previous round of review. We hope our revision has improved the paper to a level of satisfaction. Below are our detailed responses in a point-to-point manner.

## Response to Editor's Comments

Reviewers have now commented on your Geology submission, G54254. Their comments are appended below. You will see that they are advising revisions to your manuscript. Although this might be considered 'minor' revisions, I concur with the second reviewer who states, "Although I feel the content is fantastic, and worthy of publishing in Geology, I think the manuscript would benefit from some heavy editing (somewhere between minor and major) to help clarify points and bring the manuscript up-to-date."

Thank you for your comments. In the revision, we have performed heavy editing by removing replication in proeses and reducing the use of "We" to help clarify points in both the main text and supplementary materials.

I also note, "As a co-author on the former, and lead author on the latter, it's probably best to introduce both, but move on from the MMR & SMR framework as the new 3D imagery is so much more accurate and parts of the MMR & SMR is just wrong for obvious reasons when one takes 2D data and makes a 3D model or surface. I've suggested a lot of edits in this regard; I think it will make the manuscript cleaner and less confusing if you stick to the much better model from 3D reflectivity data. And it better matches your interpretations." Following the edits will make for a much clearer and more readable paper.

In the revision, we have moved on from the MMR & SMR framework and focused on the new 3D imagery throughout the main text instead.

In addition, we also performed the following tests to evaluate the robustness of the tremor locations:

- 1) performed particle motion analyses to confirm that the recorded tremors are associated with S-waves. The analysis and result have been added in [Text S1](#) and [Fig. S8](#) of the supplementary materials.
- 2) performed velocity searches throughout 0.5-4.0 km/s and listed relevant references on the S-wave velocity of gabbro within the crust around Axial Seamount to validate the reasonableness of the S-wave velocity of 2.0 km/s used in the location process. The clarifications and result have been added in [Text S1](#) and [Figs. S9, S10](#) of the supplementary materials.
- 3) discussed that depth uncertainties introduce minor uncertainties in the horizontal locations and origin time of the tremor signals. The result has been added in [Fig. S11](#) of the supplementary materials.
- 4) discussed that the uncertainties in wave propagation velocity does not significantly affect the spatial migration characteristic and the origin time of the tremor signals. The result has been added in [Fig. S12](#) of the supplementary materials.

We benefited a lot from your comments and suggestions in revising the manuscript. Thank you again.

## Response to Reviewer #1's comments

Migrating tremors indicate the activation of satellite melt bodies days before the 2015 Axial Seamount Eruption

By J. Zhu et al. for publication in *Geology*

In this paper, the authors analyse volcanic tremors recorded by 8 permanent ocean bottom seismometers (OBS) at the Axial Seamount, in the Northeast Pacific. Their analysis focuses on the 2015 eruption. Out of 8 OBS, seven lie close to the caldera in the vicinity of the initiation of the 2015 eruption and one is placed about 20 km SE of the caldera, and hence the spatial coverage outside the caldera region is very poor. Using these instruments, they located 415 volcanic tremors. These tremors seem to initiate at 19 km SE of the caldera about 60 hours before the onset of the 2015 eruption and migrates towards the caldera. They observed three phases of volcanic tremors: first starting about 60 hours before the onset (146 episodes) lasting five hours, then there is a quiescence of about 39 hours, followed by the second phase that lasts about 14 hours (167 episodes), and finally the third phase after the onset of eruption. They find that these events migrate towards the caldera at a speed of 1.1-1.8 km/hr. They suggest first episodes is related to satellite melt body, which migrates toward the caldera and triggers the eruption. This is an interesting observation (or interpretation). Monitoring a volcanic eruption is an important science problem and hence the paper is worth publishing in *Geology*. However, I have certain concerns that should be addressed before any publication.

Thank you for your comments. We have responded to your comments in detail below.

1. A recent study (Kent et al., Nature 2025) suggests that the main magma domain is bounded at the top by a funnel-shaped lithosphere-asthenosphere boundary (LAB), which is a thermal boundary. This body dips away from the caldera reaches to a depth of >6 km within their study area. If satellite melt bodies are present at ~19 km from the caldera, as suggested by the authors, they should be much deeper, below 6 km depth. As the authors do not have any constraints on the depth of these events, errors in depth would introduce errors in their locations. The authors should estimate uncertainties associated with the depth and origin time of the events.

We tried to add source depth searches from 0 to 9 km in 0.5 km increments during our grid-search location process. The results indicate that the Root Mean Square (RMS) arrival time difference distributions do not converge when source depth is included. Minimum RMS arrival time difference values at each assumed depth are quite similar, making it difficult to identify an optimal depth. Additionally, horizontal locations of the tremors remain consistent across the depth range, suggesting that **the assumed source depth has minimal impact on their horizontal positioning**. In the revision, we have added a new supplementary Fig. S11 to illustrate a typical failure case for depth searches for a 1-minute tremor episode.

The **uncertainties in the origin time of these tremors have minor effect on the inferred origin time of tremors relative to the 2015 Axial Seamount eruption**. For instance, if we consider an extreme case with a tremor located 20 km away horizontally and a source depth of 10 km, with a waveform propagation velocity of 2.0 km/s, the travel time from the source to the station would be within 12.2 s. Subtracting ~12 s from the arrival time of all 1-minute tremor episodes would not affect our conclusion that these tremors initiated ~60 h before and continued during the eruption.

Given the challenges in picking the precise arrival times of each tremor burst signal and the poor constraints on source depth, we did not estimate the origin times, only retaining the arrival times for each 1-minute tremor episode for subsequent interpretations. Future efforts to extend the deployment of seismic stations southeast of the Axial caldera will improve our ability to better constrain both depths and origin times.

2. The authors use the S-wave velocity of 2 km/s. The signals from tremors should travel in solid above the LAB (Fermat first principle), which should be mainly consist of gabbro at these depths (See Arnulf et al., JGR 2018, also your Figure 4), which means the velocity they use is much lower than the real average crustal S- wave velocity, assuming that these tremors travel with S-wave velocity, not P- wave velocity, which would be much higher (>6km/s). Moreover, I do not understand why the tremors will travel with a S-wave velocity. They do perform some crude tests (Figure S8), but their test is not consistent with reality. They need to explain that what would be uncertainties in their location and origin time due to errors in velocity.

P-waves are present in volcanic tremors. However, identifying them is challenging due to their generally emergent and weak amplitude. They are often obscured by low-frequency noise and high-amplitude surface waves, as shown in Fig. 1C. **We confirm the detected waveforms are mainly associated with S-wave and validated the robustness of the 2 km/s as the wave propagation velocity** by:

1) performing particle motion analyses to confirm that the volcanic tremors are associated with S-waves. The results show that the amplitude of horizontal particle motion is more than three times that of the corresponding vertical particle motion, suggesting that the volcanic tremors are mainly associated with S-waves. The analysis and result have been added in [Text S1](#) and [Fig. S8](#) of the supplementary materials.

2) listing four related references on the S-wave velocity of gabbro within the crust around the Axial Seamount (Bell et al., 2016; Lee et al., 2024; Wang et al., 2025; Wang et al., 2013), to clarify that it is reasonable to set up the S-wave velocity searches around 0.5-4.0 km/s. The clarifications have been added in [Text S1](#) of the supplementary materials.

3) performing velocity searches throughout 0.5-4.0 km/s to validate the reasonableness of 2.0 km/s as the wave propagation velocity in the location process. The result shows that the velocity with the smallest average RMS value (AVG) is still 2.0 km/s. When the velocity is higher or lower than 2.0 km/s, the AVG becomes larger. The analysis and result have been added in [Text S1](#) and [Fig. S9](#) of the supplementary materials.

4) taking one 1-minute tremor episode located at the southeast of the off-axis region as a typical example to show the inferred locations varied with the wave propagation velocity and RMS arrival time residual distributions. The result shows that horizontal locations vary under different assumed velocities. When the assumed velocity is 2.0 km/s, the horizontal location of the 1-minute volcanic tremor is best constrained, as evidenced from having the smallest minimal RMS arrival time difference residual of 0.07 s. The analysis and result have been added in [Text S1](#) and [Fig. S10](#) of the supplementary materials.

Nevertheless, the uncertainties in velocity have minor effect on the spatial migration characteristic and the origin time of the tremor signals. We clarified it as follows:

1) The volcanic tremors show similar spatial migration characteristic along the northwest direction into the Axial caldera (Figs. 3A, S12), and demonstrate spatial overlap with the funnel-shaped AML|LAB under different assumed seismic wave propagation velocities from 1.0 km/s to 3.5 km/s.

2) In an extreme scenario, if a tremor signal is located 20 km away horizontally with a source depth of 10 km, the travel time to the station would be ~11.2 s at a propagation velocity of 2.0 km/s, and ~5.6 s at 4.0 km/s. Subtracting these values from the arrival times of all 1-minute tremor episodes would not significantly affect our main conclusion that these volcanic tremors occurred ~60 h before and continued during the eruption.

3. The 3D multi-channel seismic reflection image of Kent et al. (Nature2025) does not show the presence of any melt sills in the distal part of their location during Phase 1. The authors should acknowledge this lack of observation and provide explanation for the same.

We provided the possible explanations as follows:

1) When the tremor is close to station AXBA1, the other seven stations near the Axial caldera may record weak amplitudes, leading to large location uncertainties in the longitudinal direction.

2) The detected tremors are from the pre-eruption and eruption periods, while Kent et al. (Nature 2025)'s observations of magma bodies relate to a time that is four years after the eruption hence only reflect magma bodies with sufficient remnant/replenished melt. Given this time difference, it is understandable that the spatial locations might not perfectly align.

3) The 3D seismic profile from Kent et al. (Nature 2025) does not extend all the way to the southeasternmost tremors, hence may miss potential melt bodies in that region.

Considering Geology's character count limit for the main text, we briefly acknowledged this lack of observation and provided possible explanations in the revision as follow:

[Lines 208-211, Page 9]: the southeasternmost volcanic tremors do not fully overlap with the funnel-shaped AML|LAB structures, which could be due to the tremors' location uncertainties in the longitudinal direction (Fig. 3A) or the spatial limit and timing (~4 years after the eruption) of the active source survey (Kent et al., 2025).

4. They observe a quiescence period of 39 hours between Phase 1 and Phase 2. They should say few words about cause of such a quiescence.

In the revision, we listed several volcanos that also show hours of seismic quiescence before the eruption, and clarified the possible reasons of quiescence as below:

[Lines 124-127, Pages 5-6]: Hours of seismic quiescence have also been observed at other volcanoes before eruptions, e.g., Telica and Sierra Negra, and are linked to the sealing of magma conduits caused by mineral deposits, low-porosity magma transport, or crystallization during magma intrusion (Li et al., 2022; Roman et al., 2016).

5. Most importantly, Kent et., al. (2025) suggest that melt migrates along the LAB before the eruption, which the authors seem to suggest in their Figure 4, but their relative depth is much shallower at such a large distance.

In the revision, we revised the cartoon Figure 4 to make the AML|LAB deeper in the southeast region than previous version. We also note that the cartoon is not to scale.

6. In conclusion, the observation is interesting and interpretation is provocative but scientific support is limited.

We performed the following tests to strengthen the scientific support by:

1) performing particle motion analyses for the detected 1-minute tremor to confirm that the volcanic tremors are associated with S-waves. The analysis and result have been added in [Text S1](#) and [Fig. S8](#) of the supplementary materials.

2) validating the robustness of 2 km/s as the wave propagation velocity by:

[1] listing related references on the S-wave velocity of gabbro within the crust around Axial Seamount to verify that it is reasonable to set up the S-wave velocity searches around 0.5-4.0 km/s. The clarifications have been added in [Text S1](#) of the supplementary materials.

[2] conducting velocity searches throughout 0.5-4.0 km/s to validate the reasonableness of using 2.0 km/s as the wave propagation velocity in the location process. The analysis and result have been added in [Text S1](#) and [Fig. S9](#) of the supplementary materials.

[3] taking one 1-minute tremor episode located at the southeast of the off-axis region as an example to show the robustness of the location when using 2.0 km/s as the wave propagation velocity. The analysis and result have been added in [Text S1](#) and [Fig. S10](#) of the supplementary materials.

3) discussing the uncertainties associated with the depth to clarify that it only introduces minor uncertainties in the horizontal locations and origin time of the tremor signals relative to our main conclusions. The result has been added in [Fig. S11](#) of the supplementary materials.

4) discussing the uncertainties associated with the velocity to clarify that it only introduces minor effect on the spatial migration characteristic and the occurrence time of the tremor signals. The result has been added in [Fig. S12](#) of the supplementary materials.

7. Moreover, the melt body in the Axial region seem to widespread, and hence I would not use the word 'satellite' in the title. I would also recommend the authors to plot the seafloor bathymetry to make sure that the readers can correlate the seafloor geology with their locations.

In the revision, we have replaced the 'satellite' with 'distributed' in both the main text and supplementary materials to clarify that the detected tremors did not just originate from a single magma reservoir located directly beneath the volcano, and plotted the seafloor bathymetry in [Figs. 1A, 3A](#) of the main text, and [Figs. S12, S13, S14a](#) of the supplementary materials.

We benefited a lot from your comments and suggestions in revising the manuscript. Thank you again.

## Response to Reviewer #2 (Graham Kent)'s comments

1. The results presented in the provided manuscript are very exciting and I would argue transformation not only in terms of understanding the eruption dynamics at Axial Seamount, but more generally for other volcanos and potential magma migration from distant "satellite" bodies during eruptive sequences. As the lead author on the recent Nature article which highlights the amazing 3D imagery, including funnel-shaped surfaces (AML|LAB) that are located 10+ km southeast of Axial's caldera, it was quite shocking for our group to see the imagery and try to decipher what it really means? And yet, to see tremor migrate along these same surfaces during the 2015 eruption was not only exciting but I must say jaw-dropping. Together, both of these results really change what constitutes the "space" of what eruptive dynamics at Axial Seamount (and other less studied volcanos) might be. This eruption scenario was not on my "bingo card" just a few years back, not even close. This is really exciting stuff and I think Geology would be a great place to publish as I feel this content needs to be presented in a journal of high impact. Although I feel the content is fantastic, and worthy of publishing in Geology, I think the manuscript would benefit from some heavy editing (somewhere between minor and major) to help clarify points and bring the manuscript up-to-date.

Thank you for your comments. We have revised both the main text and supplementary materials based on your point-to-point edits or notes on the PDF provided manuscript and supplemental information.

2. I have included edits or notes on the PDF provided manuscript and supplemental information. I hope that helps and highlights some of the points below:

1) Line 15: are-> is.

Done.

2) Line 16: Need adds "in a larger magma domain."

Done.

3) Lines 18-19: 'these distributed melt bodies' connectivity with the main magma reservoirs and role during eruptions remain unclear.' -> 'the connectivity of these melt bodies within the magma domain and their role during eruptions remains unclear'.

Done.

4) Line20: replace 'and' with 'which or that'.

Done.

5) Line 24: I'd remove highlighted section "with previously imaged main magma reservoir, satellite magma reservoir" within the abstract and replace with: "spatial overlap with the funnel-shaped axial melt lenses/lithosphere-asthenosphere boundaries that comprise the magma domain. NOTE: the MMR and SMR are a much less correct version of magma chamber structure based on 2-D MCS profiles and 3-D tomography study with less than ideal coverage. The 3-D MCS data are much superior and provides the best estimate of structure to date (significant improvement).

Done.

5) Line 26: add “,or transport through,” after the “activation”.

Done.

6) Line 26: I'd say something like "over 10 km from the caldera" instead of “located many kilometers from the caldera”.

Done.

7) Line 35: Add “It was previously thought that Axial seamount was underlain ...” before the The Axial caldera.

Done.

8) Line 41: "that a much more accurate estimate of the spatial coverage of the complex magma domain that included funnel-shaped ..." Also, I would at this point refer to the updated imagery structures from Kent et al., 2025 as for example the SMR outline is just not correct and MMR is overly simplified.

Done.

9) Line 41: I might say axial melt lenses/ lithosphere-asthenosphere boundaries (AML|LAB) as the latter is used again in manuscript and makes it clearer instead of “axial melt lenses(AML)|lithosphere-asthenosphere boundaries (LAB)”.

Done.

10) Line 49: Replace ‘how these satellite melt bodies connect with the MMR’ with ‘how these bodies interconnect to provide melt to the caldera or along the rift zones’.

Done.

11) Line 62: missing comma before which.

Done.

12) Line 63. maybe add Sigmundsson 2016 reference here.

Done.

13) Line 105: please remove the “SMR” and replace with "AML|LAB Funnels C & D (Kent et al., 2025)". Again, the SMR is not an accurate representation of subsurface structure as it was based on widely spaced 2D data not 3D. Better to keep the narrative and associations with the best model or image to date.

Done.

14) Line 119: say "AML|LAB Funnel C" instead of SMR.

Done.

15) Line 123: add "along the southeastern extent of AML|LAB Funnels B & C) toward ..." after "migrating" northwest.

Done.

16) Line 125: "with" -> "showing".

Done.

17) Line 127: remove "SMR, and MMR"--it's redundant.

Done.

18) Line 128: replace "hence likely indicate" with "and are likely indicative of".

Done.

19) Lines 132-137: maybe this gets moved into Discussion and Conclusions as it's an interpretation.

In the revision, it has been moved into Discussion and Conclusions on [\[Lines 181-186, Page 8\]](#).

20) Lines 153: also add Sigmundsson GRL 2016 for magma domain; also add earlier in text when referring to magma domain.

In the revision, we have cited the GRL paper from Sigmundsson (2016) throughout the main text when referring to the magma domain.

21) Remove Lines 153-158, it's a repeat from the Intro starting Line 46.

Done.

22) Lines 158: Remove Nevertheless ... and maybe something like "Our high-quality database of tremor through time may provide insighting into the formation, connectivity," etc...

Done.

23) Lines 161-162: Remove "previous seismic reflection surveys resolved a MMR beneath the caldera, a SMR located ~5 km away from the eastern caldera (Arnulf et al., 2014; Arnulf et al., 2018)," as one doesn't want to highlight previous studies that are superseded by a much better one. So maybe say, "a high-quality 3D seismic reflection survey collected in 2019 provided a detail map of AML|LAB structure, including 3 funnel-shaped AML|LAB surfaces extending up to ~16 km southeast of the caldera.

Done.

24) Line 164: remove "the MMR, SMR, and".

Done.

25) Line 164: add surfaces B, C & D after funnel-shaped AML|LAB.

Done.

26) Line 168: remove “MMR’s”.

Done.

27) Line 169: replace “MMR” with “caldera”.

Done.

28) Figure 1: Can you label funnels A, B, C & D per Kent et al., 2025?

Done.

29) Line 343: Not sure that sentence ‘Red dashed polygons represent the MMR and SMR imaged in Arnulf et al. (2018)’ is necessary as the current model (and more accurate) is most appropriate.

In the revision, we have removed the symbols and sentences related to the MMR and SMR.

30) Lines 343-344: Remove “Red dashed polygons represent the MMR and SMR imaged in Arnulf et al. (2018)”.

Done.

31) Line 31 in SI. Maybe restate ‘the 8 OOI permanent stations’ vertical component seismic data,’ on ‘the vertical component of 8 permanent OOI seismic stations to generate ...’. get away from ‘stations’.

Done.

32) Line 109 in SI. Replace ‘the volcanic tremors’ migration’ with ‘the migration of volcanic tremor’.

Done.

33) Fig.S9 in SI. I'd remove the red polygons for MMR and SMR and leave the more accurate "Funnels".

Done.

34) Fig. S10 in SI. Same... remove MMR and SMR polygons.

Done.

35) Fig. S11. Remove redline outlining MMR in this figure.

Done.

3. I suspect most of the editing or changes would be in the Intro and Discussion & Conclusion sections. There some replication in prose that I point out, and one paragraph that needs to be moved to Discussion and Conclusions. Also, there may be too much reliance on "We" as many sentences, especially in the Supplemental section, where probably too many sentences start with "We". Not sure if Geology is OK with that style, but kinda too much of a good thing IMHO.

In the revision, replication in proses identified throughout the main text has been removed, and subsections about the mechanisms of tremors have been moved to the Discussion and Conclusion sections. Additionally, many sentences have been modified to reduce the use of "We" in both the main text and supplementary materials.

4. I think conversations with Bill Chadwick helped our group appreciate why the concept of a Magma Domain seems perfectly in sync with observations at Axial, so I would recommend using the Sigmundsson reference and ideas therein and incorporate them into your manuscript.

In the revision, we have cited the GRL paper from Sigmundsson (2016) throughout the main text.

5. Also, there's kinda a back 'n forth with the Arnulf et al. 2018 MMR and SMR framework and the Kent et al. (2025) AML|LAB funnels framework. As a co-author on the former, and lead author on the latter, it's probably best to introduce both, but move on from the MMR & SMR framework as the new 3D imagery is so much more accurate and parts of the MMR & SMR is just wrong for obvious reasons when one takes 2D data and makes a 3D model or surface. I've suggested a lot of edits in this regard; I think it will make the manuscript cleaner and less confusing if you stick to the much better model from 3D reflectivity data. And it better matches your interpretations.

In the revision, we have removed the comparisons of our results with MMR and SMR and only mentioned them once in the introduction section.

6. Also, I think the discussion of tremor and processing therein (other than the "We" issue) is pretty clean and straightforward. Also, for those interested, I'm not opposed to having Supplemental information as part of this manuscript.

Done.

We benefited a lot from your comments and suggestions in revising the manuscript. Thank you again.

## References

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