Comments to the authors
Journal: Seismica
Authors: Lamb *et al.*

The manuscript submitted by Dr. Lamb and the colleagues is an important work that well report the unrest with seismic swarms and deformation in May 2022 at Taupo caldera in New Zealand. Taupo is an active caldera that has a great social relevance, which makes the analysis of its seismic unrest quite important. I am happy to review this manuscript that shows comprehensive overview of the 2022-2023 unrest, including locations and temporal history of the seismic sequence. Their analysis and interpretation are basically reasonable and helpful. Also, I find that the manuscript has been already well written and organized.

There are still a few concerns mainly related to their moment tensor analysis and interpretation, but I do not find any fatal errors in this work. I recommend that this work is accepted for publication from Seismica after minor revision resolving several issues listed below. I refer to some previous studies, but I do not request cite all of them; please refer to them as you need. I hope my comments are useful.

[Major comments]
1. Isotropic and CLVD components in moment tensor
As a full moment tensor analysis (allowing $M_{11} + M_{22} + M_{33} \neq 0$) is used here, there should be a strong trade-off between vertical-CLVD and isotropic components. For shallow earthquakes, it is difficult to distinguish the isotropic (M_{11}:M_{22}:M_{33} = 1:1:1) and vertical-CLVD (M_{11}:M_{22}:M_{33} = –0.5:–0.5:1) components, as shown in many previous studies (Hejrani & Tkalčić, 2020; Kawakatsu, 1996). For example, Hejrani & Tkalčić (2020) showed that the resolvability between the isotropic and vertical-CLVD components exists even at frequencies as high as 0.15 Hz (see Section 3.3 of the paper), indicating that this problem may not be avoided in this case where a low frequency seismic data (0.02–0.04 Hz) is used. Although the authors have noticed this trade-off problem (line ~141), it is not appropriate to just interpret directly a large CLVD component as an isotropic component due to volumetric change, because a vertical-CLVD source in calderas is also possible due to ring-faulting mechanism (Ekström, 1994; Sandanbata et al., 2021; Shuler et al., 2013).

Hence, the authors are strongly recommended to discuss that how these two components are distinguished from this analysis (I guess they are not well-resolved). For example, it would be good to show two moment tensor analysis results obtained with or without the zero-trace assumption $M_{11}+M_{22}+M_{33}=0$) with waveform comparison; if the waveform fit is similar in both cases, this will demonstrate that these components are not distinguished.

Also, it would be better to mention somewhere the possible interpretation of vertical-CLVD component as ring faulting, instead of inflating source for isotropic component. (Since ring-faulting in calderas is usually due to pressurized magma, even vertical-CLVD source will support your conclusion that the unrest is associated with magma intrusion.)

2. Moment tensor solutions

Although you discuss that the solution of M_L 5.7 earthquake has a "significant isotropic component" in many parts (lines 21, 221, 254, and 354), it seems to be dominated by a double-couple component, representing a reverse-fault, with a minor non-double-couple component (if the isotropic is dominant, the solution should be like a mono-colored solution, not like a beach-ball). This indicates that the faulting mechanism is a dominant mechanism for the earthquake, rather than an inflation source. It should be more accurate to say, for example, "the solution is dominated by a double-couple component representing a reverse fault but contains a non-negligible non-double-couple component". Please consider revising the parts (lines 21, 221, 254, and 354), following this suggestion.

If you agree that the M_L 5.7 earthquake is a double-couple reverse faulting, a short discussion on possible causes of the difference between smaller events with a normal fault mechanism and the largest event with a reverse fault will be helpful for readers. (this is not a requirement, but just a suggestion.)

For evaluation and better understanding of the solutions, please consider providing a list of the moment tensor solutions shown in Figure 3, or at least that of the M_L 5.7 event, with exact values of M_{11}, M_{22}, M_{33}, M_{12}, M_{13}, and M_{23}, the seismic magnitudes, the locations, and the times.

[Minor comments]

<u>Abstract</u>

L. 18: *the largest magnitude earthquakes*

Please consider mentioning the specific seismic magnitude value, M_L 5.7, of the largest earthquake here.

L. 21: *Moment tensor inversion for the largest earthquake includes a significant inflationary isotropic* *component. We suggest the seismic unrest was caused by the reactivation of faults due to an intrusion of magma at depth.*

The reactivation of faults is not inferred from "inflationary isotropic component", but from a double-couple component. Looking at the solution of M_L 5.7 in Figure 3c, it includes the isotropic component but still dominated by a double-couple component. It should be better to argue here that the moment tensor is dominated by a double-couple component but with **non-negligible** isotropic component; then, this observation confirmatively suggests that the seismic unrests is doe to the reactivation of faults associated with an intrusion of magma at depth.

L. 70: Volcanic Alert Level

What is the highest level of VAL? This would be helpful information to know how dangerous VAL 1 is considered.

L. 73: *a small yet complex lake tsunami*

Could you give some information of the maximum tsunami amplitude?

L. 91:

Some parts of the methods of the seismic analysis are not clear. First, for earthquake relocation and moment tensor analysis, did you use the GeoNet seismic stations shown in Figure 1, or those in a broader region in NZ? Please clarify. In the latter case, a supplementary figure showing GeoNet seismic stations in New Zealand is required to know basic conditions of the station coverage and epicentral distance. Also, the overall epicentral distance should be mentioned in Main Text. Second, did you perform the moment tensor analysis for all events? If not, how did you decide which events to analyze (e.g., magnitude threshold)?

L. 213: *The second group was located approximately 5 km north of the first, forming a linear feature oriented NNW-SSE and roughly aligned with the -56 mGal residual gravity anomaly contour (Fig. 3c).*

(This is just a comment, which you do not have to incorporate into the revision.) It is interesting to me that, following the largest event on the southern side of the caldera, the seismicity on the northern side suddenly became high. This observation reminds me of a paper on Sierra Negra caldera (Gregg et al., 2022) suggesting that the stress change due to a faulting event on the southern side of Sierra Negra caldera may have induced a tensile failure on the northern side (please see Figure 4 of Gregg et al.

[2022]). I just speculate that the seismicity on the northern side in Phase C may have been similarly induced by the stress change due to the largest earthquake event on the south.

L. 245: *associated with at least one of the major caldera collapse events.*
=> associated with at least one of the major caldera collapse events in the past

Figure 3:
The moment tensor solutions, except for M_L 5.7 event, look purely double-couple mechanisms. Did you assume double-couple mechanisms for them? Is a non-double-couple component estimated only for the largest event?

L. 255: *Altogether, the earthquake and ground deformation may be interpreted as the opening of a sub-horizontal tensile crack*
The moment tensor of M5.7 event seems to contain large double-couple component with minor non-double-couple component (see my major comment 2). This character may not be explained by only a horizontal tensile crack mechanism and requires a faulting mechanism. This will support your suggested mechanism, "*the reactivation of faults triggered by inflation of a magmatic body"* (line 298) more strongly.

L. 258: *a 'trapdoor' faulting mechanism*
Before findings of trapdoor faulting in submarine calderas introduced here, a trapdoor faulting had been observed many times at Sierra Negra caldera (e.g., Amelung et al., 2000; Jónsson, 2009). I recommend citations of these related studies, since at Sierra Negra some faulting events led to caldera eruptions.

References

Amelung, F., Jónsson, S., Zebker, H., & Segall, P. (2000). Widespread uplift and 'trapdoor' faulting on Galápagos volcanoes observed with radar interferometry. *Nature*, *407*(6807), 993–996. https://doi.org/10.1038/35039604

Ekström, G. (1994). Anomalous earthquakes on volcano ring-fault structures. *Earth and Planetary Science Letters*, *128*(3–4), 707–712. https://doi.org/10.1016/0012-821x(94)90184-8

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Kawakatsu, H. (1996). Observability of the isotropic component of a moment tensor. *Geophysical Journal International*, *126*(2), 525–544. https://doi.org/10.1111/j.1365-246X.1996.tb05308.x

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Shuler, A., Ekström, G., & Nettles, M. (2013). Physical mechanisms for vertical-CLVD earthquakes at active volcanoes. *Journal of Geophysical Research, [Solid Earth]*, *118*(4), 1569–1586. https://doi.org/10.1002/jgrb.50131

In this paper, the authors investigate a recent unrest episode beneath Taupō Volcano in New Zealand through relative relocation of earthquakes and moment tensor inversion. Overall, I felt that it was well written and makes a useful contribution to the field. My comments below are largely minor, but will hopefully assist the authors in improving their manuscript.

Line 96: It's unclear what is meant by using all GeoNet phase picks (automatic and manual) without further modification. Aren't the manual picks based on the automatic picks, in which case are they not preferable? Or are there some automatic picks that are not manually refined (e.g. too small a magnitude), but if so, can they be relied upon?

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Lines 127-128: Perhaps a bit surprising that depth uncertainty is not larger than the horizontal uncertainty, even given the source-receiver geometry.

Figure 2: The installation of the two new broadband sensors in late November/early December 2022 doesn't appear to make much difference to the magnitude of completeness. Might be worth commenting on. It would also be useful if something more can be said about location uncertainty, or if it can be represented graphically in some way. I note that the event cross-sections max out at 0 km elevation, yet the caldera is up to ~1 km higher than this. Did nothing locate at very shallow depths, or did you get rid of very shallow events?

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With this manuscript, Lamb and other authors are describing an unrest episode at Taupo volcano, describing also some of the challenges related to monitoring a caldera volcano beneath a lake.

I found the paper well-written, easy to follow, and interesting in terms of the seismological analysis done.

There is only one point, that has not been discussed, and that I found interesting and probably needs a discussion. In Figure 3b I notice some sort of gap in the seismicity ("horizontally"), between 10 and 15 km. In Figure 4 there is another gap, way more visible, with an almost vertical extension. What can cause these aseismic zones? Could these two areas be connected somehow?
Maybe a plot in 3D (with any 3D visualization software) can help in visualizing the geometry of this aseismic zone.

I also suggest adding graphs regarding the error of localizations, like rms, distribution of the gap in degrees (to see how many data have lower gaps), and the errors in km on the horizontal and vertical hypocenter locations. This are all information that should be added in a paper like this, which will further explain how a geological/geographical setting like this can be challenging.

14 June 2024

Dear Editor**,**

On behalf of all the authors, I am pleased to submit a revised version of the manuscript entitled "Seismic characteristics of the 2022-23 unrest episode at Taupō volcano, Aotearoa New Zealand". You will find included a revised version of the manuscript, as well as a version with all the in-line changes marked. Below, you will find our point-by-point response to all the comments from each of the reviewers.

In summary, we have made the following changes to the manuscript: i) new text to support the moment tensor inversion, earthquake relocation methodology, and interpretation of the results, ii) six new supplementary figures to support our results, as well as a new supplementary file with details of all the moment tensors presented in this manuscript, and finally iii) minor changes to the text throughout the manuscript. We hope you will find our response to the reviewers comments satisfactory.

Thank you for your patience while we responded to the reviewers comments. We hope for a positive outcome for this manuscript in the very near future.

Best wishes,

Oliver Lamb

Te Pū Ao | GNS Science

Point-by-point response to reviewers

Lamb et al. 'Seismic characteristics of the 2022-2023 unrest episode at Taupō volcano, Aotearoa New Zealand'

Original reviewer comments are in normal text, author responses are in red. Line numbers refer to those in PDF without changes marked.

(Note that a summary of the changes made to the manuscript can be found at the end of this document)

Reviewer #1:

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Maybe a plot in 3D (with any 3D visualization software) can help in visualizing the geometry of this aseismic zone.

We acknowledge that there does appear to be some kind of 'aseismic' zone at 10 – 15 km depth in the N-S cross-section of Fig. 3b, however this zone becomes seismically active in phase C (Fig. 3c) so cannot be described as 'aseismic'. Furthermore, due to uncertainties in depths of our relocations (see "GeoNet Network and Methods" section, lines 122-136) we cannot be confident in assigning any region as 'aseismic'.

Nevertheless, we concur with the suggestion for a 3D plot so we have provided an additional supplementary figure with four different viewpoints of the data (Fig. S12). We must also note that additional NE-SW and NW-SE cross-sections are provided in supplementary figure Fig. S1.

I also suggest adding graphs regarding the error of localizations, like rms, distribution of the gap in degrees (to see how many data have lower gaps), and the errors in km on the horizontal and vertical hypocenter locations. This are all information that should be added in a paper like this, which will further explain how a geological/geographical setting like this can be challenging.

We have added a new supplementary figure to illustrate the uncertainties in the localizations (Fig. S4).

Reviewer #2:

The manuscript submitted by Dr. Lamb and the colleagues is an important work that well report the unrest with seismic swarms and deformation in May 2022 at Taupo caldera in New Zealand. Taupo is an active caldera that has a great social relevance, which makes the analysis of its seismic unrest quite important. I am happy to review this manuscript that shows comprehensive overview of the 2022-2023 unrest, including locations and temporal history of the seismic sequence. Their analysis and interpretation are basically reasonable and helpful. Also, I find that the manuscript has been already well written and organized.

There are still a few concerns mainly related to their moment tensor analysis and interpretation, but I do not find any fatal errors in this work. I recommend that this work is accepted for publication from Seismica after minor revision resolving several issues listed below. I refer to some previous studies, but I do not request cite all of them; please refer to them as you need. I hope my comments are useful.

[Major comments]

1. Isotropic and CLVD components in moment tensor

As a full moment tensor analysis (allowing $M11 + M22 + M33 \neq 0$) is used here, there should be a strong trade-off between vertical-CLVD and isotropic components. For shallow earthquakes, it is difficult to distinguish the isotropic (M11:M22:M33 = 1:1:1) and vertical-CLVD (M11:M22:M33 = –0.5:–0.5:1) components, as shown in many previous studies (Hejrani & Tkalčić, 2020; Kawakatsu, 1996). For example, Hejrani & Tkalčić (2020) showed that the resolvability between the isotropic and vertical-CLVD components exists even at frequencies as high as 0.15 Hz (see Section 3.3 of the paper), indicating that this problem may not be avoided in this case where a low frequency seismic data (0.02–0.04 Hz) is used. Although the authors have noticed this trade-off problem (line ~141), it is not appropriate to just interpret directly a large CLVD component as an isotropic component due to volumetric change, because a vertical-CLVD source in calderas is also possible due to ring-faulting mechanism (Ekström, 1994; Sandanbata et al., 2021; Shuler et al., 2013). Hence, the authors are strongly recommended to discuss that how these two components are distinguished from this analysis (I guess they are not well-resolved). For example, it would be good to show two moment tensor analysis results obtained with or without the zero-trace assumption $M11+M22+M33=0$) with waveform comparison; if the waveform fit is similar in both cases, this will demonstrate that these components are not distinguished.

Thank you for the suggestion. We have now included two new supplementary figures that illustrate the deviatoric and full moment tensor solutions, with waveform comparisons (Fig. S7, S8). We have also amended the text in the results and discussion section to highlight the different solutions and the implications these have for our interpretations (lines 230-235, 268-279).

Also, it would be better to mention somewhere the possible interpretation of vertical-CLVD component as ring faulting, instead of inflating source for isotropic component. (Since ring-faulting in calderas is usually due to pressurized magma, even vertical-CLVD source will support your conclusion that the unrest is associated with magma intrusion.)

We have amended the text in the discussion section to highlight that a normal fault is also consistent with the data (line 276).

2. Moment tensor solutions

Although you discuss that the solution of ML 5.7 earthquake has a "significant isotropic component" in many parts (lines 21, 221, 254, and 354), it seems to be dominated by a double-couple component, representing a reverse-fault, with a minor non-double-couple component (if the isotropic is dominant, the solution should be like a mono-colored solution, not like a beach-ball). This indicates that the faulting mechanism is a dominant mechanism for the earthquake, rather than an inflation source. It should be more accurate to say, for example, "the solution is dominated by a double-couple component representing a reverse fault but contains a non-negligible non-double-couple component". Please consider revising the parts (lines 21, 221, 254, and 354), following this suggestion.

Thank you for your suggestion. We have modified the text at each location to emphasise the non-double and isotropic components are non-negligible (now lines 21, 232, 271, and 382).

If you agree that the ML 5.7 earthquake is a double-couple reverse faulting, a short discussion on possible causes of the difference between smaller events with a normal fault mechanism and the largest event with a reverse fault will be helpful for readers. (this is not a requirement, but just a suggestion.)
We have added a few sentences into the discussion section regarding the normal faulting nature of most of the moment tensors (lines 250 - 253).

For evaluation and better understanding of the solutions, please consider providing a list of the moment tensor solutions shown in Figure 3, or at least that of the ML 5.7 event, with exact values of M11, M22, M33, M12, M13, and M23, the seismic magnitudes, the locations, and the times.

All moment tensor solutions are provided by via the GeoNet website (https://github.com/GeoNet/data/tree/main/moment-tensor). Nevertheless, we have now included a csv file of all the MTs plotted in Figure 3.

[Minor comments]
Abstract
L. 18: *the largest magnitude earthquakes*
Please consider mentioning the specific seismic magnitude value, ML 5.7, of the largest earthquake here.

Done.

L. 21: *Moment tensor inversion for the largest earthquake includes a significant inflationary isotropic component. We suggest the seismic unrest was caused by the reactivation of faults due to an intrusion of magma at depth.*
The reactivation of faults is not inferred from "inflationary isotropic component", but from a double-couple component. Looking at the solution of ML 5.7 in Figure 3c, it includes the isotropic component but still dominated by a double-couple component. It should be better to argue here that the moment tensor is dominated by a double-couple component but with **non-negligible** isotropic component; then, this observation confirmatively suggests that the seismic unrests is due to the reactivation of faults associated with an intrusion of magma at depth.

Thank you for the suggestion. I have amended the text in the abstract to note that the isotropic component was non-negligible.

L. 70: Volcanic Alert Level
What is the highest level of VAL? This would be helpful information to know how dangerous VAL 1 is considered.

I have added a note to state the scale runs from 0 to 5 (line 71).

L. 73: *a small yet complex lake tsunami*

Could you give some information of the maximum tsunami amplitude?

The maximum measured amplitude was approximately 20 cm. I have added a note to mention this value (line 74).

L. 91:
Some parts of the methods of the seismic analysis are not clear. First, for earthquake relocation and moment tensor analysis, did you use the GeoNet seismic stations shown in Figure 1, or those in a broader region in NZ? Please clarify. In the latter case, a supplementary figure showing GeoNet seismic stations in New Zealand is required to know basic conditions of the station coverage and epicentral distance. Also, the overall epicentral distance should be mentioned in Main Text.

Thank you for the suggestion. We have added a new supplementary figure (Fig. S2) showing locations of all GeoNet seismic stations in the North Island of New Zealand. For earthquake relocations, we predominantly used stations within 100 km of Lake Taupō, except for the largest M4+ events. For MT analysis, a selection of stations within across the North Island and top of South Island were used (e.g. Fig. S7). We have amended the text to make this clear to readers (lines 109, 147).

Second, did you perform the moment tensor analysis for all events? If not, how did you decide which events to analyze (e.g., magnitude threshold)?

No, moment tensor analysis was only conducted for events with $M_w \geq 3.5$. I have added a note to the text about this (line 143)

L. 213: *The second group was located approximately 5 km north of the first, forming a linear feature oriented NNW-SSE and roughly aligned with the -56 mGal residual gravity anomaly contour (Fig. 3c).*
(This is just a comment, which you do not have to incorporate into the revision.) It is interesting to me that, following the largest event on the southern side of the caldera, the seismicity on the northern side suddenly became high. This observation reminds me of a paper on Sierra Negra caldera (Gregg et al., 2022) suggesting that the stress change due to a faulting event on the southern side of Sierra Negra caldera may have induced a tensile failure on the northern side (please see Figure 4 of Gregg et al. [2022]). I just speculate that the seismicity on the northern side in Phase C may have been similarly induced by the stress change due to the largest earthquake event on the south.

Thank you for your interesting observation! We have added a note to the text by referring to the Sierra Negra study and speculating that the distinct earthquake clusters may have been generated in a similar manner (line 284- 286).

L. 245: *associated with at least one of the major caldera collapse events.*
=> associated with at least one of the major caldera collapse events in the past

Thank you. I have incorporated this suggested edit (now line 262).

Figure 3:
The moment tensor solutions, except for ML 5.7 event, look purely double-couple mechanisms. Did you assume double-couple mechanisms for them? Is a non-double-couple component estimated only for the largest event?

Yes, it was the only event in the whole unrest sequence that featured a significant non-double-couple component. I have added a note in the results section to make this clear (line 234).

L. 255: *Altogether, the earthquake and ground deformation may be interpreted as the opening of a subhorizontal tensile crack*
The moment tensor of M5.7 event seems to contain large double-couple component with minor nondouble-couple component (see my major comment 2). This character may not be explained by only a horizontal tensile crack mechanism and requires a faulting mechanism. This will support your suggested mechanism, "*the reactivation of faults triggered by inflation of a magmatic body"* (line 298) more strongly.

We have amended the text to include the faulting mechanism along with the movement of the sub-horizontal crack (line 276).

L. 258: *a 'trapdoor' faulting mechanism*
Before findings of trapdoor faulting in submarine calderas introduced here, a trapdoor faulting had been observed many times at Sierra Negra caldera (e.g., Amelung et al., 2000; Jónsson, 2009). I recommend citations of these related studies, since at Sierra Negra some faulting events led to caldera eruptions.

Thank you, I have added a mention of the trapdoor faulting at Sierra Negra along with citations of Amelung et al. and Jónsson (line 282).

Reviewer #3

In this paper, the authors investigate a recent unrest episode beneath Taupō Volcano in New Zealand through relative relocation of earthquakes and moment tensor inversion. Overall, I felt that it was well written and makes a useful contribution to the field. My comments below are largely minor, but will hopefully assist the authors in improving their manuscript.

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Yes, the reviewer is correct in stating that manual picks are preferable over automatic. Some automatic picks are kept unmodified if they have been reviewed and confirmed to be correctly made by the automatic system. We have added a note to the text to make this clear to the reader (line 96).

Line 107: 310 degrees appears to be a very generous azimuthal gap. 180 degrees is rather more common. If you have 5 stations recording an earthquake with an azimuthal gap of 310 degrees, location is going to be quite poor.

The 310 degrees value is for the maximum azimuthal gap. The median azimuthal gap was 71 degrees with a standard deviation of 36 degrees; only 7 events had azimuthal gaps greater than 220 degrees.

We have made a note of this in the text and added a supplementary figure to illustrate the azimuthal gaps (Fig. S3).

Lines 127-128: Perhaps a bit surprising that depth uncertainty is not larger than the horizontal uncertainty, even given the source-receiver geometry.

We should point out that the horizontal uncertainties stated here are more minimum/maximum values, whereas the vertical is a median. Nevertheless, we have now included a supplementary figure to illustrate the distribution of uncertainties in our earthquake relocations (Fig. S4).

Figure 2: The installation of the two new broadband sensors in late November/early December 2022 doesn't appear to make much difference to the magnitude of completeness. Might be worth commenting on.

We already made a note in the discussion section regarding the differences caused by adding the two new stations (lines 352 - 357). To summarise, we saw an increase in depth resolution but no difference in the number of earthquakes detected.

It would also be useful if something more can be said about location uncertainty, or if it can be represented graphically in some way.

In response to another reviewer's comment, we have added a supplementary figure illustrating the uncertainties in the relocations (Fig. S4).

I note that the event cross-sections max out at 0 km elevation, yet the caldera is up to ~1 km higher than this. Did nothing locate at very shallow depths, or did you get rid of very shallow events?

We did not remove any shallow events from the catalogue. We must note that the 1 km elevation is only applicable for a peak (named Pihanga) located south of the lake (see Fig. 1) and not within the lines of the cross-sections in Figure 3. The max elevation of the lake is 360 m, with lake depths reaching 186 m. Nevertheless, we see very few events located at depths <1 km.

Lines 253-254: It would be nice to get a bit more detail about the source mechanism of the magnitude 5.7 event, in particular the uncertainty in the solution. It is claimed earlier that an F-test was undertaken to ensure that the non-double (isotropic) component is statistically significant – how about showing some numbers? I find it a little odd that all other earthquakes are clearly double couple, but this one – the largest by far – happens to have an apparently significant isotropic component (and is located quite deep).

Thank you for your suggestion. We have added more details on the F-test conducted for the moment tensor solution for the M5.7 event (lines 233)

Lines 270-271: Again, I would recommend providing information on the uncertainty associated with the moment tensor solutions, so readers can better understand whether this lack of alignment is real.

See answer to previous comment.

Line 323: But it seems that depth uncertainties are no worse than horizontal uncertainties based on earlier analysis in the paper.

See answer to above comment.