

Reply to comment on egusphere-2024-166, Referee #1 on earthquakes triggered by the subsurface undrained response to reservoir-impoundment at Irapé, EGU-Solid Earth, 2024

1-514: The manuscript discusses the impact of reservoir filling on induced seismicity and concludes, that the undrained response of the subsurface rather than pore pressure diffusion is triggering mechanism. Field, lab and modelling techniques are used to reach this conclusion. Recommendations on how to prevent future induced earthquakes through reservoir impoundment strategies are given.

The scientific significance of the manuscript is high with the topic remaining urgent and unresolved. The presentation quality is superb as the manuscript is very well structured and filled with visually pleasing and comprehensible figures. The use of the English language is impeccable throughout most parts; however, two sections fall below standard and need thorough revision. The list of references also needs revision as consistency is lacking. The scientific quality is high as well. Abundant and relevant references are included, established methods are applied, results are discussed and put into context, and recommendations for reservoir management strategies are given.

Author's response: We extend our thanks to the reviewer for his/her careful consideration and positive assessment of the paper. We have addressed the comments of the reviewers, which have served to clarify some of our assumptions and, as a result, we feel that the quality of the manuscript has improved.

13: At what frequency? It sounds like it is always the case.

Author's response: Yes, seismicity is triggered in almost all cases. Generally, microearthquakes are observed soon after or during the reservoir impoundment, which corresponds to the initial undrained response. In some cases, larger earthquakes occur many years later, in what is so called delayed response. RTS cases with a magnitude $M > 3.0$ are typically a concern. In the early 1960s, several cases of reservoir-triggered seismicity (RTS) with magnitudes of 6 or more were recorded (lines 52-59).

18: Great!

Author's response: Thanks!

21: Delete comma

Author's response: Deleted.

22: Numbers until twelve in letters?

Author's response: We have corrected.

23: Wording too complicated. Maybe "above the bottom threshold".

Author's response: We have reworded a bit the sentence. Now it reads "Only three out of the eleven tested samples present permeability above the lowest measurable value of the apparatus".

29: Traditionally I expect all effective stresses to decrease when pore pressure increases. Please make difference clearer in this sentence.

Author's response: We appreciate the reviewer's insightful comments. Indeed, the coupled hydro-mechanical response of the subsurface to reservoir loading is counterintuitive. The reason for the vertical effective stress to increase is that the loading caused by the reservoir filling is higher than the consequent pore pressure increase caused by the undrained response of the low-permeability rock to compaction. We have modified a bit this sentence in an attempt to highlight this fact.

50: Great introduction

Author's response: We thank the reviewer for these positive assessment.

52: I'm confused by the variation in abbreviations: Mw, ~M and M. All the same?

Author's response: We use abbreviation "M" to refer to the magnitude of seismic occurrences; they most likely did not use the magnitude of the moment Mw. Nowadays, moment magnitude is the best representation of earthquake energy, but it cannot be used for all occurrences, hence we use M for all other types, which often employ body wave magnitude mb. As per very first RTS recorded, Lake Mead at the Hoover dam (United States) in the mid-1930s is associated with an approximate magnitude, we have used the symbol "~", i.e., "(~M) 4.0" to indicate that the value of the magnitude is approximately this value. This estimation is based on historical records, which showing some points of ambiguity regarding the precise magnitude of the events, as mentioned by Carder (1945). Apart from this, the subscript w is used when the magnitude refers to the local magnitude.

59: Great

65: Thanks for the examples

68: What is the aim of the manuscript? It reads as if it was the forecasting of RTS hazard by interaction and analysis of drained and undrained responses.

Author's response: We have modified this sentence to highlight that the aim is to understand the causes of RTS. Now, it reads "The interactions and comprehensive analysis of these two responses are key to understand the causes of RTS cases and eventually improve the forecasting and mitigation of RTS hazard".

77: Great reading flow

Author's response: We thank the reviewer for these positive words.

85: Great position of this paragraph

93: that = it

Author's response: We have corrected this in the revised manuscript.

92: that = the

Author's response: We have corrected this in the revised manuscript.

96: I really like the traditional structure of the manuscript

106: Language issues? Word order?

Author's response: Word order and correction have been made in the revised manuscript.

104: Reference?

Author's response: We have inserted the reference in the revised manuscript.

105: ..sedimentation processes of passive margins associated with the deposition.. Language issues? Stands out against all other sentences.

Author's response: We have rephrased this sentence.

108: Blue colour doesn't match well in image/legend

Author's response: We have made changes to the legend (blue colour) to match that of the image and have replaced the figure in the revised manuscript.

108: What indicates the line at the top left?

Author's response: The top left line and the one in the middle of the Chapada Acauã formation indicate a fault or compressed shear zone, as explained in the legend.

114: Number = word?

Author's response: We have changed this in the revised manuscript.

124: Maybe word it more carefully? "This leads us to investigate a causative relationship/hypothesis"

Author's response: We have incorporated this suggestion.

132: Space in reference missing

Author's response: We have corrected this typo.

147: Is this also true for the depth of the event (3.88km)? Maybe add information on faulting regime data source and depth.

Author's response: Yes, it is true, Chimpliganond et al., 2007 assume that the stress regime does not vary within the first kilometres. Unfortunately, focal mechanisms could not be

inferred from the seismic data, as explained in the text in the following sentence, which makes it impossible to assess the stress regime at depth.

155: Why is this differently spelled? km vs. -km. It occurs several times throughout the manuscript.

Author's response: When there are three nouns, the first two are hyphenized. For example, we write "long-term storage". For the case of "4.8-km thick" we could alternatively write "a thickness of 4.8 km". When km is followed by a noun, a hyphen should be included between the number and the units. This is why we write "4.8-km thick".

182: Maybe stay in present tense here, like everywhere else.

Author's response: Corrected.

188: Delete second "an"

Author's response: Deleted.

220: ..in these samples. I find this btw already an interesting result!

Author's response: It is true that there are several correlations to estimate permeability based on porosity. Nonetheless, permeability depends on the pore connectivity rather than the total volume of the pores. This is a good example that highlights this physical process.

233: Maybe elaborate a little on the similarity of the rocks to make this argument more convincing for the reader.

Author's response: We have mentioned a common similarity in the mineralogy between these two rock types to make the argument more convincing.

276: I don't associate highly metamorphosed rock with good porosity. It reads as if the authors do. Maybe contrast better: "despite high porosity, the rock has low permeability. Therefore, ..."

Author's response: We thank the reviewer for this suggestion. We have incorporated it in the revised manuscript.

278: I like the idea with the integrated outcrop picture. However, I don't find the figure intuitive to an amateur reader: Is this a side view or a top view? What does the irregular trapezium indicate? Are the angles of the sides relevant? What do the yellow circles indicate? Where do the arrows point? Where does the crystalline rock start? Why is the figure in this irregular box?

Author's response: We thank the reviewer for this idea. The diagram shows a vertical cross-section of the rock, with the reservoir in perspective. The irregular trapezium at depth illustrates how fault slips and RTS occurs due to the weight of the reservoir water volume. There is no relation to side angles; it is shown schematically. The yellow circles indicate the main earthquake. According to the local velocity model, the crystalline rocks start at a depth of 4.2 km. We have modified this figure to make it more understandable.

290: What is the problem? Please specify.

Author's response: The problem is that knowledge of the physics of the triggering mechanisms is required. To this end, the properties of the rock should be known. We now specify this in the revised manuscript.

289: "Potential reservoir site". Make it more obviously a recommendation and summary.

289 cont.: These are conclusions and recommendations rather than discussion. Move to correct section please.

Author's response: We have clarified this recommendation and moved it to the conclusion in the revised manuscript.

296: In the Irapé case the dam is already built and poro-perm measurements have been taken. Please make the distinction clearer between the existing project and potential future projects.

Author's response: Yes, the dam is already built, but the porosity-permeability measurements have not been made until several years later after the filling of the reservoir. To the best of our knowledge, this is the first time that poro-perm measurements are made. We have made this distinction clearer in the revised manuscript.

299-309: PARAGRAPH IS POORLY WRITTEN, PLEASE REWRITE. Vocabulary is insufficient and words seem to be missing. While the rest of the manuscript is carefully and beautifully composed, this paragraph seems to lack structure, aim and, frankly, language skills.

Author's response: We re-written the paragraph.

299: Is being employed or should be employed? Above, conditional tense is used, here not. Please adjust.

302: "effort have begun"? Maybe: Efforts have been made regarding... "infrastructure harm"? Maybe: damages... "loss and damages" of what?

300-302: Please rewrite. TLP does not initiate light and is not an approach or point. Maybe: According to the TLP green light permits operations without restriction, yellow light demands mitigation measures and red light appeals for regulatory intervention.

304: ensure??

305: can be revolved around??

307: promising what?

Author's response: We thank to the reviewer for these recommendations to improve the text. We have re-written the paragraph in the revised manuscript.

311: The figure is insufficiently included and introduced in the paragraph.

Author's response: We have re-written the paragraph in the revised manuscript and better introduce the figure now.

313-318: The description is great.

Author's response: We thank the reviewer for these positive assessment.

335: Manipulation of reservoir loading refers to the impoundment. Mind that the study also suggests mitigation and management strategies for risk of RTS (289-323) which is not mentioned here. Add?

Author's response: We have rewritten the last sentence of the Conclusions in the revised manuscript.

359-513: LIST OF REFERENCES IS INCONSISTENT AND CONTAINS ERRORS, PLEASE REWRITE. - points missing - spaces missing - pages differently abbreviated - DOIs differently inserted - links inconsistently used - some spelling errors

Author's response: We have corrected and improved the errors in the revised manuscript.