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Reply on RC1

Patrick Oswald et al.

Author comment on "Magnitude and source area estimations of severe prehistoric earthquakes in the western Austrian Alps" by Patrick Oswald et al., Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2021-281-AC1, 2022

Point to Point Response to the Reviewer's comments

Anonymous Reviewer 1

The paper summarizes the paleoseismic record of 3 lakes situated in the western Austrian Alps, an area currently experiencing moderate seismicity with a few larger historic earthquakes. Sedimentary horizons indicating earthquake induced deformation were identified throughout the 3 lake records in seismic reflection and core data. The lacustrine record spans the entire Holocene and Late Pleistocene since deglaciation of the area about 15,000 – 17,000 years ago. This long record allows for some statistical analysis of earthquake recurrence intervals. A strength of the paper is the integration of the 3 lake records to determine the timing and extent of earthquake-induced deformation. This leads to an estimate of paleo-magnitudes and source areas for prehistoric events and the presentation of shakemaps for 4 larger prehistoric events. These shake scenarios can provide important input into seismic hazard maps for western Austria as well as neighboring Germany and Switzerland and are the most important message of the paper.

The paper is well suited for publication in "Natural Hazards and Earth System Sciences". However, I would suggest a few modifications to further highlight the strengths of the paper.

We thank the reviewer for the insightful review and comments. We have revised the manuscript following the reviewer's suggestions and comments and provide a detailed reply to each comment below.

- The paper seems to serve two purposes, a presentation of the Late Pleistocene sediment and earthquake record for two of the lakes and the integration of the Holocene and Late Pleistocene records of all three lakes to determine characteristics of paleoearthquakes. While the Holocene lake sediments and related earthquake horizons are probably presented in detail in earlier papers by Oswald et al., the criteria for assigning an earthquake origin to certain horizons is not well explained or cited in this manuscript. Several terms such as multiple MTD (mass transport deposit) horizons, SSDS (soft sediment deformation structures) are used throughout the text but I think there needs to be a short introduction to these features earlier in the text similar to the distinction of flood-generated and mass movement related turbidites presented in section 4.1.1.

We addressed this comment in the revised manuscript by explaining the principles of lake paleoseismology in Lines 35-38 and 132-135, and by adding a paragraph about the earthquake imprints (multiple MTDS, SSDS) in the investigated lakes in Lines 104-110.

- It seems that event scaling for Holocene earthquake horizons uses similar principles for the Holocene and Late Pleistocene record. I am wondering if the Late Pleistocene sediments are different enough to exhibit different thresholds for deformation (I am thinking of organic matter content, sedimentation rates etc.). Can you explain more?

We fully agree with the reviewer that within a postglacial lake record the susceptibility of subaquatic slope failures is potentially higher in Late Glacial (glaciolacustrine) sediments compared to Holocene lacustrine sediments due to an increased sedimentation rate. For example, Thresholds as low as V-V1/2 were inferred for current-day proglacial lakes in Alaska (Praet et al. 2017; Van Daele et al., 2020). On the one hand, this could lead to a slightly decreased intensity threshold for recording earthquakes in our lakes. On the other hand, this different proglacial sedimentation style could cause an underestimation of the number of events within the paleoseismic record, because relatively thin earthquake-related turbidites might not be distinguishable from thick clastic varves or other types of turbidites without a multi-proxy analysis of each layer (Vandekerkhove et al. 2020). In any case, the Holocene lacustrine sedimentation of Plansee and Achensee is influenced by detrital clastic input, and thus does not vary much from the former glaciolacustrine sedimentation in these lakes. Moreover, the organic matter content is very little in the lacustrine sediments and therefore neglectable for potentially altering the susceptibility of slope failure. We addressed this comment by indicating the glaciolacustrine and lacustrine sedimentation in the new figures 3, 4 and 5 and its caption, and by adding a discussion in Lines 443-447, that event scaling might not be fully comparable from glaciolacustrine to lacustrine sediments within a record.

References:

Praet, N., Moernaut, J., van Daele, M., Boes, E., Haeussler, P. J., Strupler, M., et al. (2017). Paleoseismic potential of sublacustrine landslide records in a high-seismicity setting (south-central Alaska). Mar. Geol. 384, 103–119. doi:10.1016/j.margeo.2016.05.004.

Vandekerkhove, E., Van Daele, M., Praet, N., Cnudde, V., Haeussler, P. J., and De Batist, M. (2020). Flood□triggered versus earthquake□triggered turbidites: A sedimentological study in clastic lake sediments (Eklutna Lake, Alaska). Sedimentology 67, 364–389. doi:10.1111/sed.12646.

Van Daele, M., Haeussler, P. J., Witter, R. C., Praet, N., and De Batist, M. (2019). The sedimentary record of the 2018 Anchorage earthquake in Eklutna Lake, Alaska: Calibrating the lacustrine seismograph. Seismol. Res. Lett. 91, 126–141. doi:10.1785/0220190204.

- I think it would help to describe the lake sediments more and to point out similarities and/or differences between the Holocene and Late Pleistocene sequence. Adding a section summarizing the sedimentology of the lake deposits as well as the associated deformation features (see above) might work.

We added a paragraph better explaining the lake sedimentation in Late Glacial to Holocene times following the comment of the reviewer in Lines 98-104.

- I think a little rearranging could make the manuscript flow better.

Following the other minor comments of the reviewer below, we have rearranged and added paragraphs about lake formation, sedimentation types and sedimentation rates to the section 2 setting and added an additional new figure 2 to the seismotectonic setting.

Detailed comments

Title: and elsewhere. I am wondering if there is a better term for "western Eastern Alps"? Could you say western Austrian Alps?

We changed the term to western Austrian Alps in the title and the whole manuscript following the reviewer's suggestion.

Abstract:

Line 9-16: This seems a little lengthy and repeats in the introduction. Maybe shorten.

The beginning of the abstract describes the rationale of this study why there is need for paleoseismic records and is crucial to understand the results demonstrated in the abstract.

I would add a sentence on the methods used.

The applied methodologies relevant for the main research topic are outlined in different sentences in the abstract, as in Lines 12-17. Moreover, we added ", which comprises multiple mass-transport deposits on reflection seismic profiles, and turbidites and soft-sediment deformation structures in sediment cores" in Lines 18-19 to show on which data the paleoseismic records were build.

Introduction

Line 54: here and throughout text: please translate abbreviations when first introduced.

The abbreviation IPE is introduced in Line 52. We also checked the few other abbreviations, which are also explained at the first occurrence in the text.

Figure 1

Can you enlarge the inset map and show adjacent country boundaries? I would also label countries.

We have revised the figure 1 following the reviewer's suggestion.

Settings

Line 75-78: I think the seismicity of the region has to be described in more detail e.g. the size/impact of historic events. Otherwise, it is quite difficult to compare the paleoearthquakes to the more recent events later on.

We revised the manuscript by adding a paragraph about the impact of the historical events and seismotectonics in Lines 79-90 and an additional new figure 2 showing the affected region of the Namlos earthquake in 1930. This earthquake is the only historical event for which enough data (IDPs) is available to generate an isoseismal map, which can be compared with the computed paleo-earthquake shakemaps.

I think here is an opportunity to add a paragraph and describe lake formation, lake sedimentology, Holocene versus Late Pleistocene sediments, age model etc. Some of the information in the next paragraph would fit nicely here.

We added a paragraph about lake formation and the different types of sedimentation in Lines 98-104 following the reviewer's suggestion.

Methods

I am wondering if you could briefly give an idea of your data base, such as extent of reflection seismic data, number of cores etc.

We address this comment by adding a description of the available data sets in Line 91-97 and added a supplementary table S4.

Before going into the event scaling, there should be an explanation of how event horizons look like. Please translate abbreviations and maybe add a short explanation of SSDS, multiple MTD, turbidites etc. Otherwise, it is quite difficult to follow the scaling arguments.

We expanded the explanation of earthquake related event horizons at the end of the section 2 in Lines 104-110. Abbreviations of SSDS and MTD are described at first use in the text in Lines 106 and 109, respectively.

Line 112 and following: I am wondering if not only the slope and basin areas but also differences in lake sediments, the slope itself etc. influence the size of event layers. Maybe you can explain further why slope and basin area ratios are sufficient. Also is there a difference between the Holocene and Late Pleistocene record?

We proposed the relative imprint size scaling method to make events and their relative sedimentary imprint sizes comparable within different lakes. The main driving force of slope failures is the slope angle itself: the size and amount of MTDs that fail during seismic shaking might be controlled by the slope gradient (Moernaut et al. 2019) and is investigated in ongoing and future research. In our investigated lakes, the subaqueous slopes have a wide range of slope angles and the slopes compose of different sediment types with different strength characteristics (delta, hemipelagic, mixed hemipelagic-delta), which altogether can result in a complete paleoseismic record, i.e. at each period in time, there probably was a slope segment in a near-critical situation that would fail when severely shaken. The determination of the difference of failure susceptibility between Holocene and Late Glacial slopes is one of the big outstanding questions in lacustrine paleoseismology and would require in-situ geotechnical measurements (CPT) at each lake (see e.g. Strupler et al. 2017) and should also be conducted on modern proglacial lakes settings (as analogue for the Late Glacial period in our lakes), which would be a research project in itself. The aim of our method is to make earthquake imprints comparable with standard state-of-the-art limnogeological techniques (bathymetry, seismics, core data) to make it also applicable, where no additional geotechnical measurements are conducted.

Results

Line 192: Maybe better then “extension of..”: The paleoseismic record of Tyrol Lakes. I would include a quick summary on the Piburger See in this paragraph.

We keep the section title “Extension of the paleoseismic records at Plansee and Achensee”, because this section is only about two lakes of Tyrol (Achensee and Plansee) and most of these paleoseismic archives are already published and this section is only about to extend these archives.

199-205: This information might be better earlier under lake setting. Please add reference for homogeneous turbidite formation.

We now provide an overview about the sedimentation types in the investigated lakes earlier in the manuscript in lines 98-104. However, the specific information about the interpretation of graded turbidites is only required in this section to extend the paleoseismic record of Plansee. Therefore, we keep the lines 229-235

in this section 4.

Figure 2: b and c are hard to see. Maybe show 2b and c earlier when explaining event horizon characteristics.

Now Figure 3: We have addressed this comment by slightly stretching and enlarging the core images of Figures 2b and c for a better visibility.

Figure 3: The age constraints for the lower record seem a little rough but probably the best available.

Now Figure 4: Unfortunately, none of the lake sequences in the study area has been cored to its real base and thus, the lake initiation age could only be inferred from regional chronological investigations for the start of the glacial retreat (~17-15 ka BP; Ivy-Ochs et al., 2008).

Reference:

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., et al. (2008). Chronology of the last glacial cycle in the European Alps. J. Quat. Sci. 23(6–7), 559–573.

Line 265: if there is a magnitude range for "severe" maybe this can be specified here or earlier

We added an explanation of the use of severe shaking / earthquakes to the section 2 Setting describing that the magnitudes of the earthquakes are only moderate but have a severe infrastructural impact due to their relatively shallow depth of 5-10 km in Line 79-82. Severe shaking is defined at a Modified Mercali Intensity of VIII according to the USGS

https://www.usgs.gov/programs/earthquake-hazards/modified-mercalli-intensity-scale

Line 269-270: I am not clear about this sentence.

We revised the sentence and further clarified the uncertainty of interpretation overlapping event ages from different paleoseismic sites in Lines 301-303.

Fig. 4: add and explain grey solid and dashed line in legend. Mention that numbers indicate timing of event.

Now Figure 5. We addressed this comment by revising the figure caption.

Line 273 and following: All these lakes seem to be outside of Figure 1. Could they be added?

The reviewer is correct that Figure 1 is not large enough to cover all the Swiss, German and Italian lakes used in the investigation for overlapping event ages. Adding these lakes to figure 1 would require a scale enhancement and thus loss in detail. However, we added all these surrounding lakes in the new Figure 6a and referred to this figure after the listing of these lakes in Lines 305-308.

Line 297: maybe better: Paleoearthquake scenarios

We have revised the section title to "Paleoearthquake scenarios" following the reviewer's suggestion in Line 329.

Line 308: Mention Figure 5a first

Now Figure 6a: We have addressed this comment by mentioning this figure 6a in the previous section in Line 307.

Line 312: violet triangles are hard to see. M 5.7/5.8 seems very close to the threshold for lake sediments to show traces. I find it interesting that you found deformation. Maybe you can discuss this somewhere?

We have improved the visibility of the triangles in the new Figure 6.

Regarding the second part of the reviewer's comment: It is important to note that it is not about the magnitude that controls whether the threshold of the lake sediments to record the earthquake is exceeded or not. The main controlling factor for generating an earthquake related sedimentary imprint is shaking intensity at the specific lake site (e.g. Monecke et al. 2004; Moernaut et al. 2014). Recent and ongoing research investigates the relationship of peak ground acceleration (PGA) with the lake specific threshold or investigates the influence of other earthquake parameters such as bracketed duration, low frequency content of seismic shaking or directivity of well-known, recent earthquakes (e.g. Avşar et al. 2016, Molenaar et al. 2021). However, for the historical earthquakes there is no information on these earthquake parameters available, and the translation from documented shaking intensity from nearby villages to PGA at the lake site would add more uncertainty. Moreover, there are historical examples of a moment magnitude 5.8 (and even lower) earthquake causing sedimentary imprints: i) The M_W ~5.3 Namlos earthquake at CE 1930 left a sedimentary imprint in Plansee (Oswald et al. 2021); ii) the M_W ~5.8 earthquake in Unterwalden (Switzerland) at CE 1601 (AHEAD database), which caused a tremendous sedimentary imprint in the form of multiple mass wasting in lake Lucerne (Schnellmann et al., 2006).

References:

AHEAD Database entry for CE 1601 Unterwalden earthquake:

https://www.emidius.eu/AHEAD/event/16010918_0145_000

Avşar, U., Jónsson, S., Avşar, Ö., and Schmidt, S. (2016). Earthquake-induced soft-sediment deformations and seismically amplified erosion rates recorded in varved sediments of Köyceğiz Lake (SW Turkey). ***J. Geophys. Res. Solid Earth*** **121, 4767–4779. doi:10.1002/2016JB012820.**

Moernaut, J., van Daele, M., Heirman, K., Fontijn, K., Strasser, M., Pino, M., et al. (2014). Lacustrine turbidites as a tool for quantitative earthquake reconstruction: New evidence for a variable rupture mode in south central Chile. J. Geophys. Res. Solid Earth 119, 1607–1633. doi:10.1002/2013JB010738.

Molenaar, A., Van Daele, M., Vandorpe, T., Degenhart, G., De Batist, M., Urrutia, R., et al. (2021). What controls the remobilization and deformation of surficial sediment by seismic shaking? Linking lacustrine slope stratigraphy to great earthquakes in South–Central Chile. Sedimentology. doi:10.1111/sed.12856.

Monecke, K., Anselmetti, F. S., Becker, A., Sturm, M., and Giardini, D. (2004). The record of historic earthquakes in lake sediments of Central Switzerland. Tectonophysics 394, 21–40. doi:10.1016/j.tecto.2004.07.053.

Oswald, P., Strasser, M., Hammerl, C., and Moernaut, J. (2021). Seismic control of large prehistoric rockslides in the Eastern Alps. Nat. Commun. doi:10.1038/s41467-021-21327-9.

Schnellmann, M., Anselmetti, F. S., Giardini, D., and Mckenzie, J. A. (2006). 15,000 Years of mass-movement history in Lake Lucerne: Implications for seismic and tsunami hazards. Eclogae Geol. Helv. 99, 409–428. doi:10.1007/s00015-006-1196-7.

Figure 6: I really like these shakemaps – very important information for hazard assessment.

Thank you for this positive feedback!

Discussion:

Line 400: Maybe say: Late Pleistocene paleoseismic record. Also, I would put this whole section 5.1. earlier.

Within the previously glaciated Alps and perialpine regions, the term 'Late Glacial' is widely used and well defined for the time period between the deglaciation at the certain lake site (<21 to 16 ka BP) and the begin of the Holocene (11.7 ka BP). The use of the term 'Late Pleistocene' would be less accurate as it covers the last 120 kyrs until the begin of the Holocene.

The whole section 5.1 is meant as a discussion of the own results with literature and also includes interpretation. Thus, we refrain to move this section to the results.

Line 427 and following: This paragraph might also fit better earlier in the text, maybe under event scaling?

Section 5.2 contains a discussion about the used intensity values for the calculation of paleo-earthquake scenarios with literature and is therefore not suitable for the results section. Moreover, we go into process-based discussions such as "…long-lasting interplay of hydromechanical and seismic preconditioning weakening the rock slope stability". We try to separate results from discussion as good as possible.

Line 480 and following: This seems a little tentative with just three events that are spaced far apart. Maybe leave out?

We fully agree with the reviewer that an earthquake migration pattern is and will probably always be tentative for earthquakes in the Alps because there are only a few events recurring every 1000-2000 years on potentially different fault systems. We have revised the manuscript in Lines 512-514 and the caption of (now) Figure 8 to improve the clarity that this earthquake pattern is only tentative. The number of paleoevents around this fault system will most likely not become substantially more by investigating more archives, as the Fernpass-Loisach fault system is already well covered by the Plansee and Piburgersee record. Therefore, we want to keep this tentative information in the manuscript, as it probably could be supportive for future research observing a similar earthquake pattern in other Alpine regions and could form the starting point of physics-based earthquake simulations to verify whether such a pattern is feasible or not.

Conclusions

Line 548: maybe rephrase: "….indicated by the regional paleo-earthquake catalogue"

We addressed this comment by rephrasing the sentence to '…indicated by the lacustrine paleoseismic archives' in Line 581.

References not checked, sorry.