CC BY

Quantitative paleoseismology in Carinthia, Eastern Alps: Calibrating the lacustrine sedimentary record with historical earthquake data

Christoph Daxer[1], Christa Hammerl[2], Maria del Puy Papi-Isaba[2], Stefano Fabbri[3], Patrick Oswald[1], Jyh-Jaan Steven Huang[1], Michael Strasser[1], Jasper Moernaut[1]

[1]University of Innsbruck, Austria; [2]ZAMG -Central Institute for Meteorology, Vienna, Austria; [3]Institute of Geological Sciences, University of Bern, Switzerland

Introduction

The state of Carinthia (southern Austria, bordering Italy and Slovenia; Fig. 1) has experienced several well-documented historical earthquakes in a wide intensity range (V-IX, EMS-98) in 1201, 1348, 1690, 1857 and 1976, with the 1348 event considered to be the strongest historical earthquake in the Alps with an estimated M_w of ~7. We compare these temporally well-spaced earthquakes and the associated lacustrine sedimentary imprints in Wörthersee and Millstättersee to calibrate our methodology, i.e. we explore relationships between seismic intensity and the type and size of mass transport deposits (MTDs), turbidites and sediment deformations.

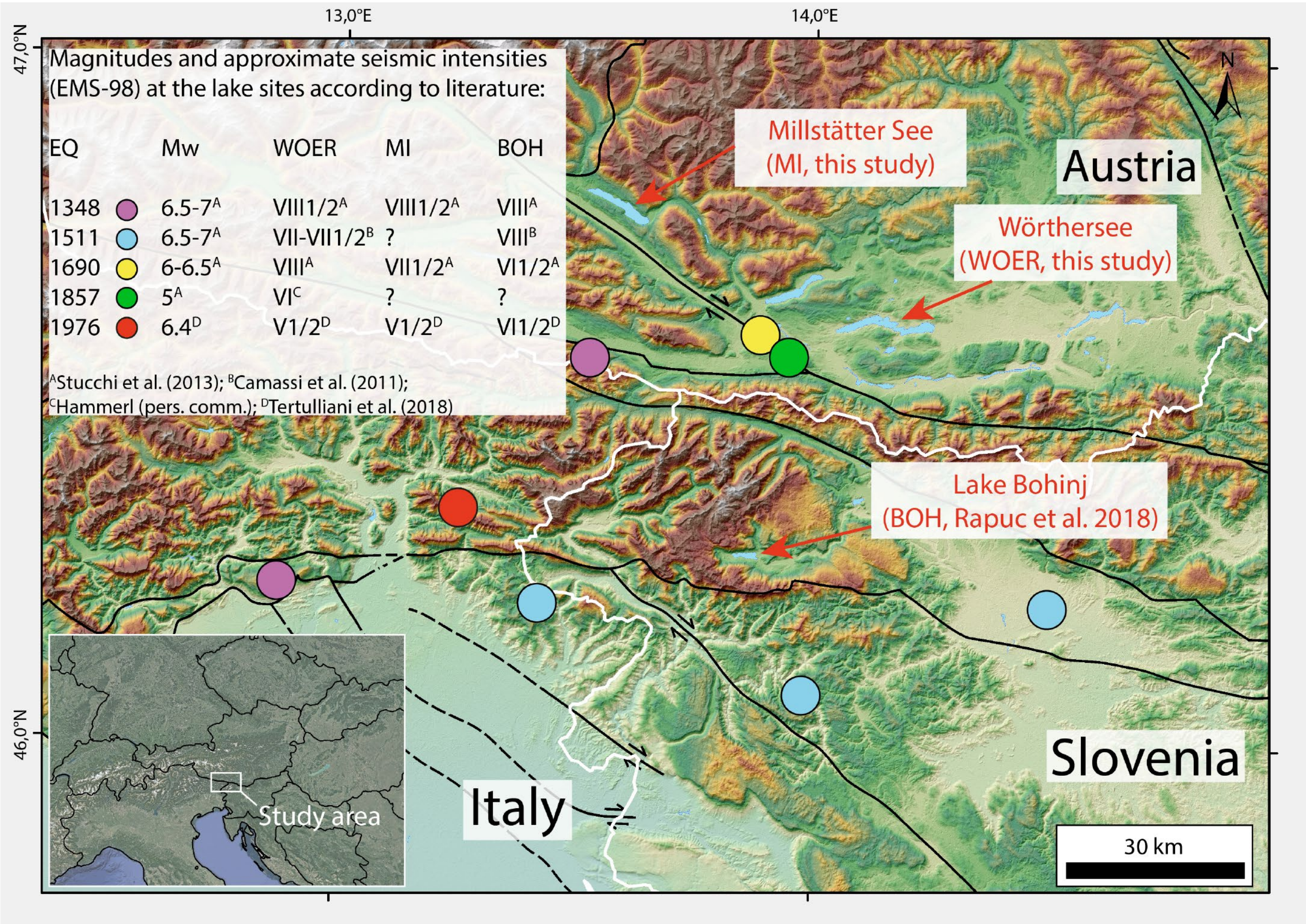


Fig. 1: Overview map of the investigated lakes and epicentres (dots) of strong earthquakes. Where more than one dot is shown, the epicentre is still debated. Black lines depict faults according to Schmid et al. (2004).

Lacustrine paleoseismology - scientific approach

Lakes can archive strong seismic shaking in a variety of ways: as (1) fractured, plastically-deformed or liquefied sediments (Monecke et al. 2004; Avsar et al., 2016); (2) failures of subaquatic slopes, leading to mass transport deposits and turbidites on the basin floor (e.g. Strasser et al., 2013); (3) remobilization of a thin veneer of surficial slope sediment (Moernaut et al., 2017); (4) elevated fluvial sediment fluxes during the years following the earthquake due to onshore landslides (Howarth et al. 2015).

We use bathymetric data and high-resolution seismic data (2D line spacing ~ 100 m) to investigate the sedimentary infill of the lakes. This allows us to identify and map landslide deposits and to determine suitable coring sites. Short (~1.5 m) and long (~11 m) sediment cores are retrieved and investigated for potentially seismically-induced features such as turbidites and in-situ deformation, aided by X-ray CT and measurements of geophysical, geochemical and sedimentological properties. Radiocarbon dating and varve (yearly lamination) counting allow for very accurate dating of event deposits. By comparing our lake record with historical earthquake data (e.g. Hammerl, 2017), we can investigate the relationship between seismic intensity and the type and size of sedimentary imprint in the lake.

FWF Der Wissenschaftsfonds. Interreg Italia-Österreich European Regional Development Fund EUROPEAN UNION universität innsbruck

Multiple coeval mass movements in both lakes

In both Millstätter See and Wörthersee, multibeam bathymetry revealed extensive sublacustrine mass transport deposits and associated megaturbidites. Dense seismic surveys allow us 1) to accurately map these deposits and determine their volume and 2) to assess coevality of landslides - an indication of a seismic trigger mechanism (e.g. Schnellmann et al., 2002; Strasser et al., 2013; Kremer et al., 2017).

Seismic profile from Millstätter See

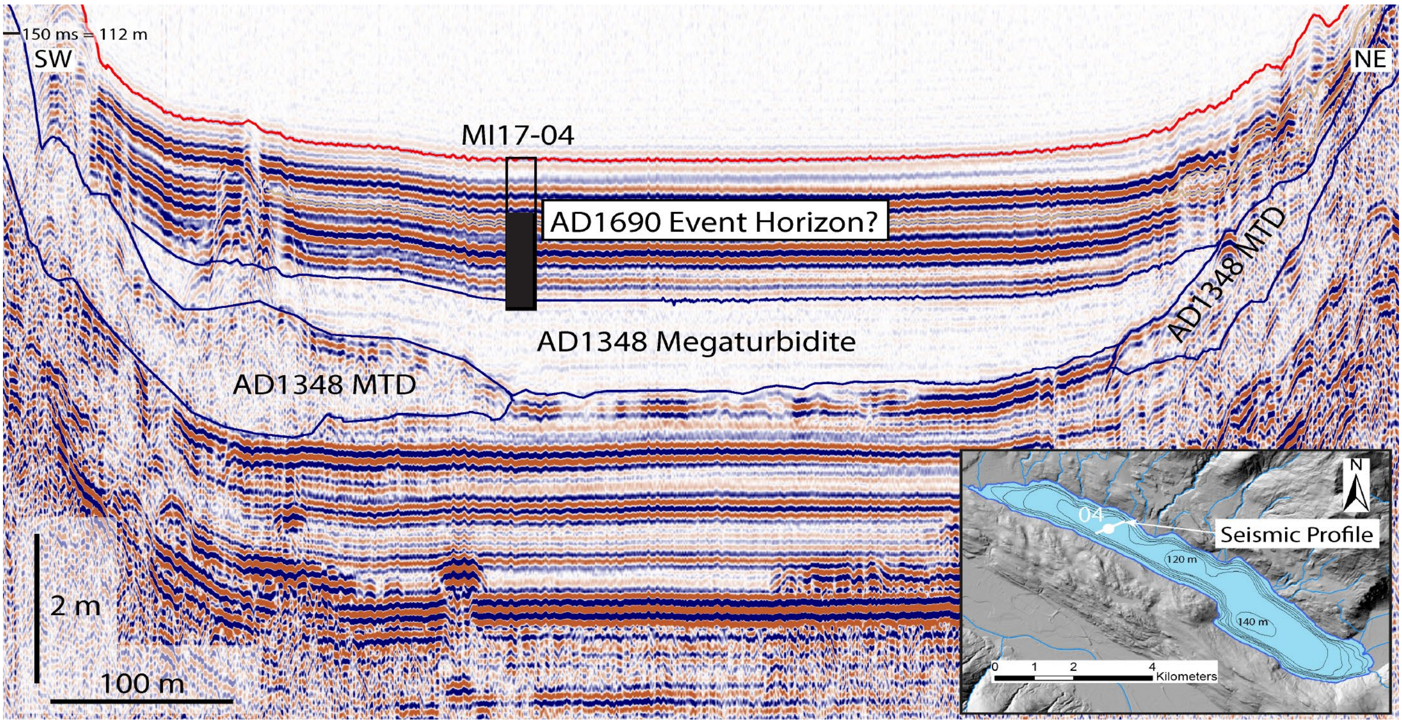


Fig. 2: 3.5 kHz seismic profile from Millstätter See. The AD1348 event is recorded as ubiquitous landslides and an associated m-thick megaturbidite. Another - younger - horizon shows multiple landslides as well and is related to the AD1690 earthquake.

Thickness maps of the landslide deposits related to the AD1348 earthquake

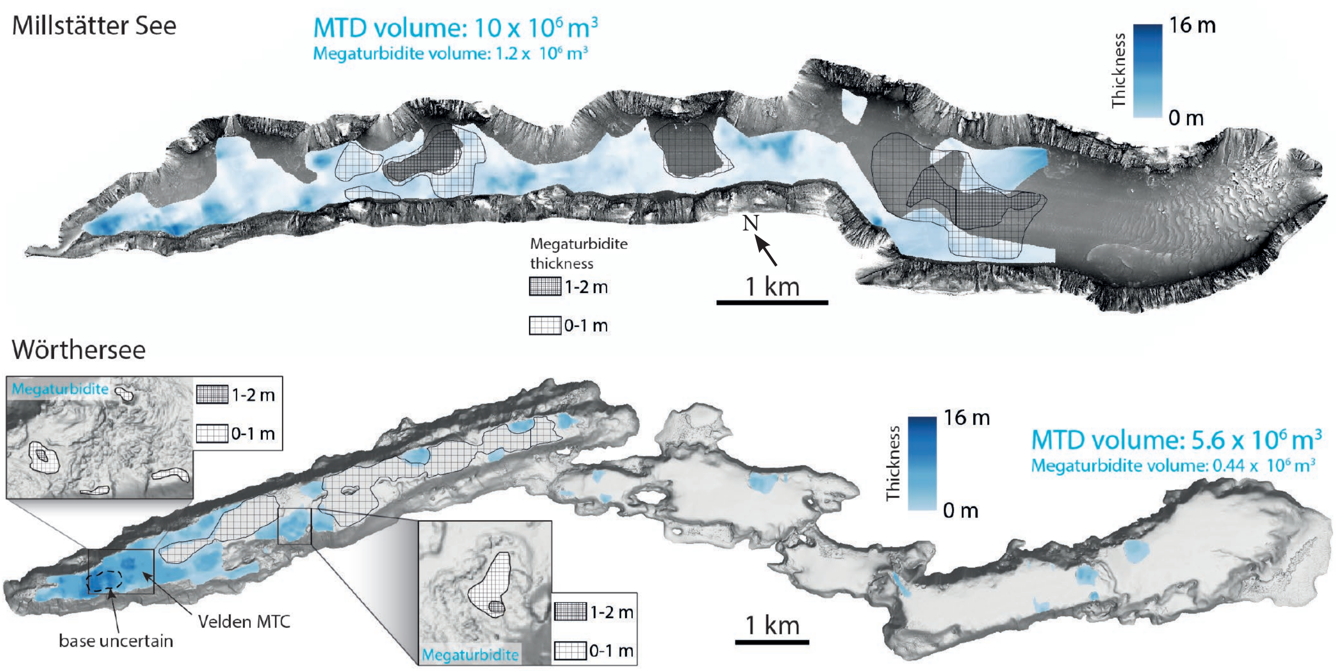


Fig. 3: The AD1348 earthquake led to extensive landsliding in both Millstätter See and Wörthersee (Daxer et al., 2019). For time-to-depth conversion, a velocity of 1500 m/s was assumed.

CC BY

The turbidites related to these MTDs can be well dated: a varve chronology from Millstätter See

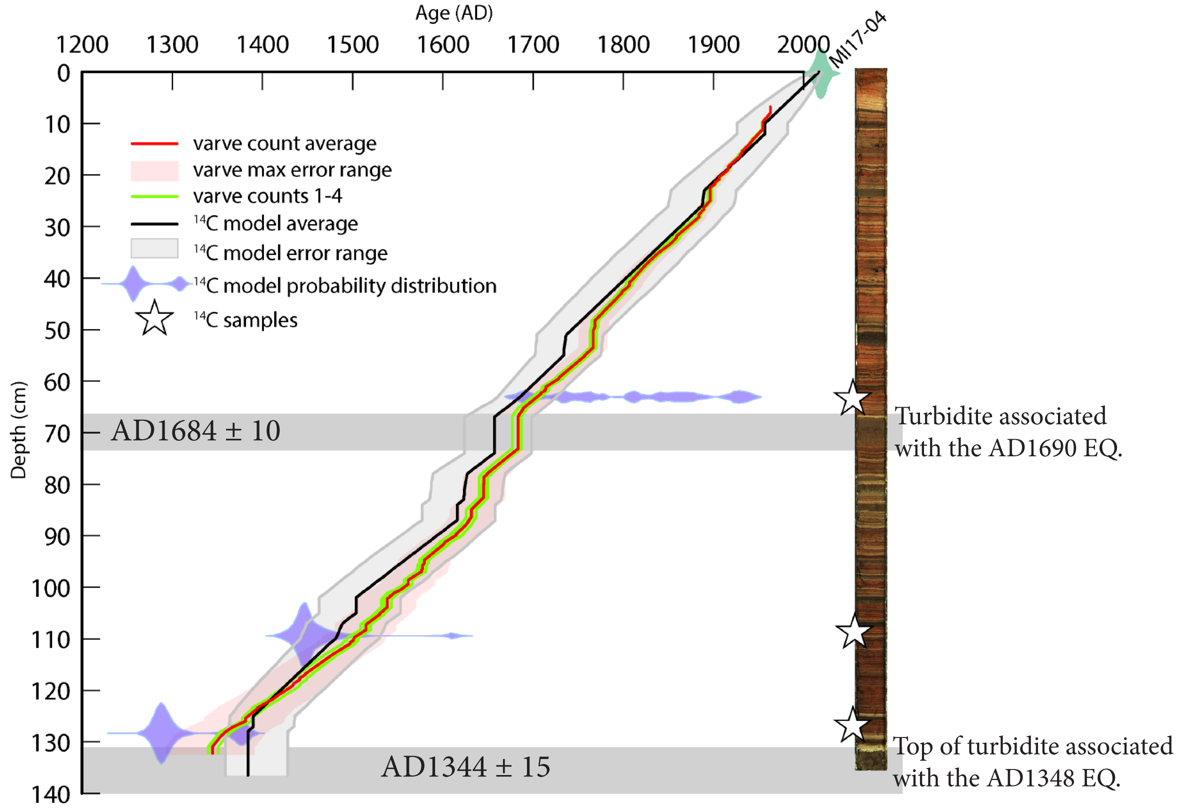


Fig. 4: Chronology of a short core from Millstätter See. In the lake basins, the earthquake events are archived as turbidites. Exceptional preservation of yearly lamination allows us to very precisely date these deposits. In Millstätter See, only the AD1348 and the AD1690 earthquakes are archived as a combination of major landslides and turbidites.

Short core correlation from Wörthersee

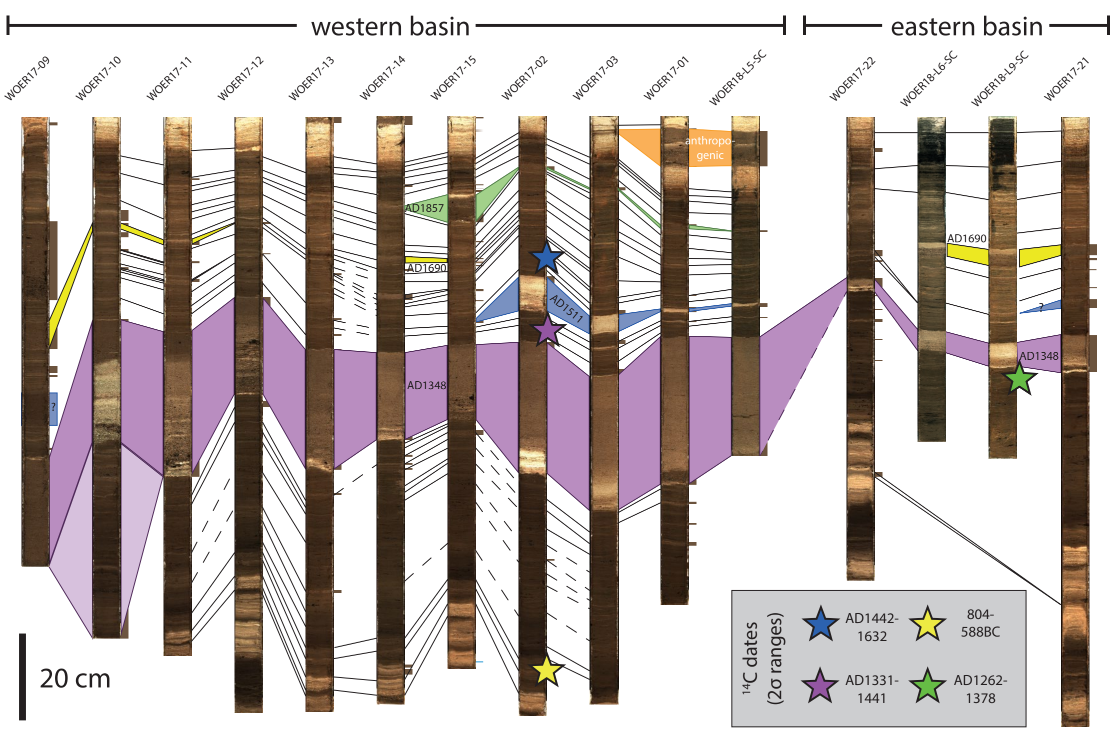


Fig. 5: Numerous short cores enable us to trace the turbidite deposits related to earthquake-induced landsliding over both lake basins. The AD1348 EQ is recorded over the whole lake, whereas the AD1511, AD1690 and AD1857 are present as smaller trubidites. The AD1976 is missing completely in the sedimentary record, therefore defining a earthquake-sensitivity threshold.

cc BY

Determining the most likely fault sources - a probabilistic approach
preliminary data

Because the evidence of past earthquakes found in lakes cannot be readily linked to a certain fault rupture, determining the fault source that caused this evidence is a difficult task. Former studies (Strasser et al., 2006; Kremer et al., 2017) used a reverse application of intensity-prediction equations (IPEs) based on the grid-search approach of Bakun and Wentworth (1997) to determine possible source areas and magnitudes. However, this method 1) does not take IPE uncertainties into account and 2) is strongly dependent on the definition of threshold values for both positive and negative evidence.

Therefore, Vanneste et al. (2018) proposed a different method, based on probabilistic seismic hazard assessment. Following this approach, we are currently evaluating the potential of lacustrine deposits to determine the most likely fault source to have caused the evidence (negative or positive) of shaking observed in the lakes. **This is work in progress, any suggestions and remarks are highly welcome.**

We use the OpenQuake Engine (Pagani et al., 2014) to model individual earthquake rupture scenarios and compute the probability of (non)exceeding a certain intensity threshold at the lake sites, depending on whether earthquake-related MTDs are present.
The fault sources and their parameters are based on the European Database of Seismogenic Faults (EDSF13, Basilic et al., 2013) and literature (Reiter et al., 2018). We divided the potential seismogenic faults in segments of **1.75 km** in length. These segments are then combined to lengths of 1, 2, 3, 4, 5, 6, 8, 13, 21, 33, 53 and 77 times the single segment length. Using an aspect ratio of 1 (the maximum depth of the fault is provided in the EDSF13 and usually ~12 km), this yields magnitudes between 4.5 and 7.2, according to magnitude-area relationships defined by Wells and Coppersmith (1994).
To add a sort of epistemic uncertainty, we use two different intensity prediction equations suitable for our setting, weighting them equally: 1) a local Austrian prediction equation (Papí Isaba et al., 2020) and 2) a Swiss prediction equation developed for the Swiss Alps (Appendix E of Fäh et al., 2011). Both IPEs are normally distributed and have a standard deviation of 0.5.

At the moment, our fault model does not allow crossing of steps and/or gaps. In the near future, however, we will implement this possibility due to the presence of several small (<5 km) steps and gaps (Fig. 6).

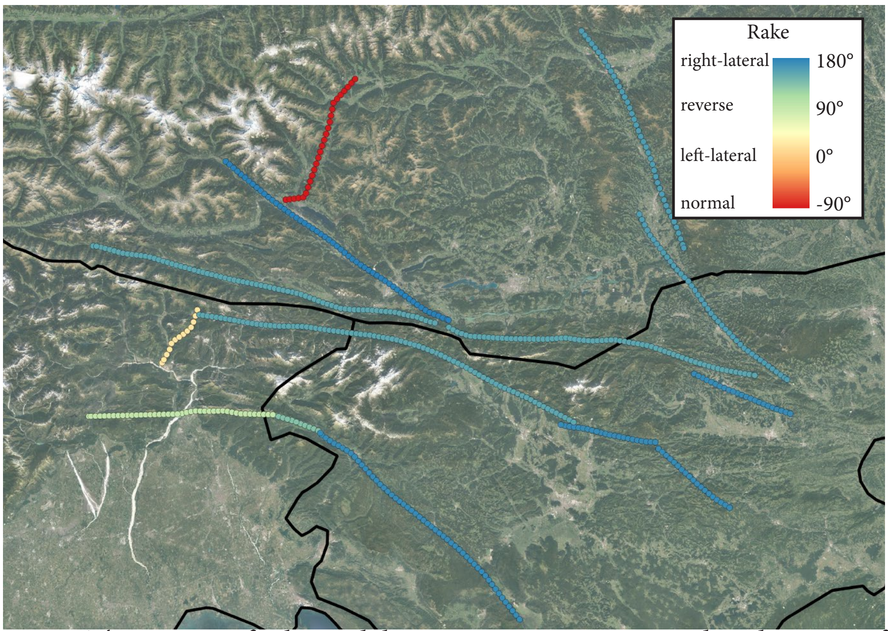


Fig. 6: The current fault model. Dots represent start and end points of minimum length sections, their colour denotes the rake of the fault.

FWF Der Wissenschaftsfonds.

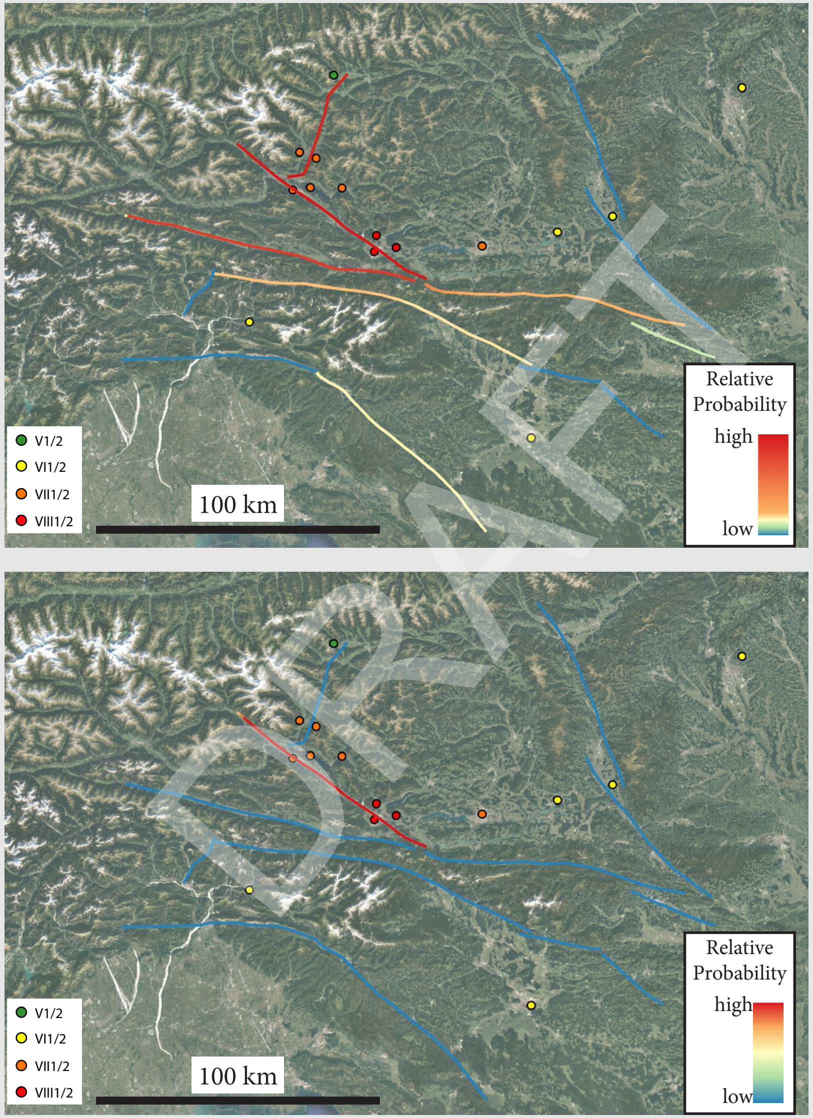
CC BY

universität innsbruck

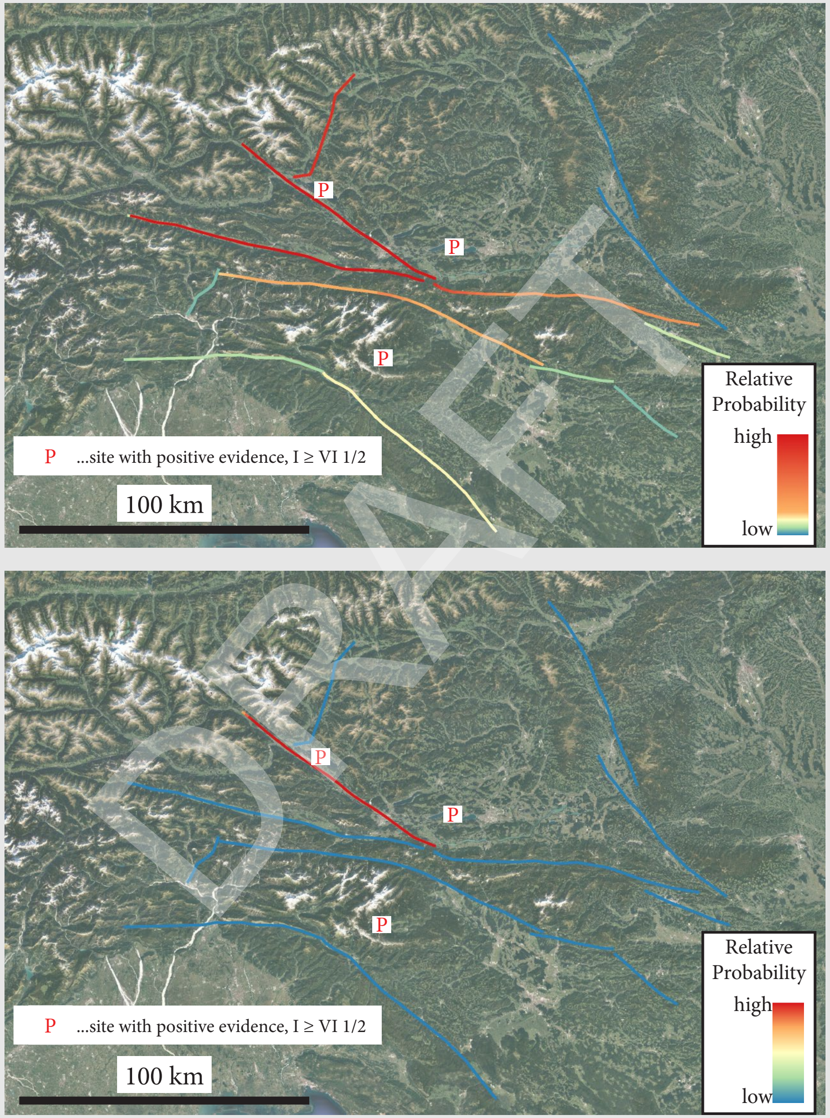
Determining the most likely fault source - example of the AD1690 earthquake

In order to use the probabilistic approach for events dating into prehistoric times, we need to ensure that our lake records provide sufficient information to conclusively determine the most likely fault source and magnitude. In a first test, we tested the lacustrine evidence of the AD1690 earthquake against the intensity data points provided by historical records. Although all three considered lake sites are categorized as positive evidence (and thus no upper bound on the magnitude is given), the modelling results from the lake record are strikingly similar to the results obtained by the model including several intensity data points. The lower figures show the same data, but plotted differently (notice the scale bar).

Intensity data points from historical records



Evidence of seismic shaking from lake record



CC BY

Conclusions & Outlook

Detailed investigation of the lacustrine archives via bathymetric/seismic surveys and sediment cores revealed that:

1. The AD1976 earthquake (I = V1/2 at the lake sites) is not recorded in the lakes, therefore defining a lower earthquake-sensitivity threshold of our archive
2. The AD1348 is by far the most prominent event in both lakes, which is in agreement with the intensity estimations from historical records
3. This enables us to deduce intensities and - via combination of several independent lake records - magnitudes of prehistoric earthquakes, by studying long sediment cores reaching back into the Late Glacial
4. Modelling of the most likely fault rupture is only in a preliminary stage, but first attempts are very promising. We will refine our methods and carry out sensitivity tests to further corroborate the approach.

This work is funded by the Austrian Science Fund (FWF), project number P30285-N34, and the Interreg V- Italy-Austria project *ARMONIA* (ITAT-301 6).

References

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

Bakun, W.H. & Wentworth, C.M. 1997. Estimating earthquake location and magnitude from seismic intensity data. Bulletin of the Seismological Society of America, 87, 1502–1521.

Basilic, R., Kastelic, V., Demircioglu, M. B., Garcia Moreno, D., Nemser, E. S., Petricca, P., Sboras, S. P., Besana-Ostman, G. M., Cabral, J., Camelbeeck, T., Caputo, R., Danciu, L., Domac, H., Fonseca, J., García-Mayordomo, J., Giardini, D., Glavatovic, B., Gulen, L., Ince, Y., Pavlides, S., Sesetyan, K., Tarabusi, G., Tiberti, M. M., Utkucu, M., Valensise, G., Vanneste, K., Vilanova, S., Wössner, J. (2013): The European Database of Seismogenic Faults (EDSF) compiled in the framework of the Project SHARE, (Share - The European Database of Seismogenic Faults).

Camassi, R., Hector, C., Castelli, V. & Slejko, D. 2011. The 1511 Eastern Alps earthquakes : a critical update and comparison of existing macroseismic datasets. 191–213, https://doi.org/10.1007/s10950-010-9220-9.

Daxer, C., Sammartini, M., Molenaar, A., Piechl, T., Strasser, M. & Moernaut, J. 2019. Morphology and Spatio-Temporal Distribution of Lacustrine Mass-Transport Deposits in Wörthersee, Eastern Alps, Austria., https://doi.org/10.1144/SP500-2019-179.

Fäh, D., Giardini, D., et al. 2011. ECOS-09 earthquake catalogue of Switzerland release 2011 report and database. Public catalogue, 17. 4. 2011. Swiss Seismological Service ETH Zurich. Risk, 1–42.

Hammerl, C. 2017. Historical earthquake research in Austria. Geoscience Letters, 4, 7, https://doi.org/10.1186/s40562-017-0073-8.

Howarth, J.D., Fitzsimons, S.J., Norris, R.J. & Jacobsen, G.E. 2014. Lake sediments record high intensity shaking that provides insight into the location and rupture length of large earthquakes on the Alpine Fault, New Zealand. Earth and Planetary Science Letters, 403, 340–351, https://doi.org/10.1016/j.epsl.2014.07.008.

Kremer, K., Wirth, S.B., et al. 2017. Lake-sediment based paleoseismology: Limitations and perspectives from the Swiss Alps. Quaternary Science Reviews, 168, 1–18, https://doi.org/10.1016/j.quascirev.2017.04.026.

Moernaut, J., Van Daele, M., et al. 2017. Lacustrine turbidites produced by surficial slope sediment remobilization: A mechanism for continuous and sensitive turbidite paleoseismic records. Marine Geology, 384, 159–176, https://doi.org/10.1016/j.margeo.2015.10.009.

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

Pagani, M., Monelli, D., et al. 2014. Openquake engine: An open hazard (and risk) software for the global earthquake model. Seismological Research Letters, 85, 692–702, https://doi.org/10.1785/0220130087.

del Puy Papí Isaba, M., Weginger, S., Apoloner, M., Jia, Y. & Hausmann, H. 2020. Intensity Prediction Equation for Austria : Applications and analysis. 7683.

Rapuc, W., Sabatier, P., et al. 2018. 6600 years of earthquake record in the Julian Alps (Lake Bohinj, Slovenia) Manville, V. (ed.). Sedimentology, 65, 1777–1799, https://doi.org/10.1111/sed.12446.

Reiter, F., Freudenthaler, C., Hausmann, H., Ortner, H., Lenhardt, W. & Brandner, R. 2018. Active seismotectonic deformation in front of the Dolomites indenter, Eastern Alps. Tectonics, 1–30, https://doi.org/10.1029/2017TC004867.

Schmid, S.M., Fügenschuh, B., Kissling, E. & Schuster, R. 2004. Tectonic map and overall architecture of the Alpine orogen. Eclogae Geologicae Helvetiae, 97, 93–117, https://doi.org/10.1007/s00015-004-1113-x.

Schnellmann, M., Anselmetti, F.S., Giardini, D., McKenzie, J.A. & Ward, S.N. 2002. Prehistoric earthquake history revealed by lacustrine slump deposits. Geology, 30, 1131, https://doi.org/10.1130/0091-7613(2002)030<1131:PEHRBL>2.0.CO;2.

Strasser, M., Anselmetti, F.S., Fäh, D., Giardini, D. & Schnellmann, M. 2006. Magnitudes and source areas of large prehistoric northern Alpine earthquakes revealed by slope failures in lakes. Geology, 34, 1005, https://doi.org/10.1130/G22784A.1.

Strasser, M., Monecke, K., Schnellmann, M. & Anselmetti, F.S. 2013. Lake sediments as natural seismographs: A compiled record of Late Quaternary earthquakes in Central Switzerland and its implication for Alpine deformation Weissurt, H. (ed.). Sedimentology, 60, 319–341, https://doi.org/10.1111/sed.12003.

Stucchi, M., Rovida, A., et al. 2013. The SHARE European Earthquake Catalogue (SHEEC) 1000–1899. Journal of Seismology, 17, 523–544, https://doi.org/10.1007/s10950-012-9335-2.

Tertulliani, A., Cecić, I., Meurers, R., Sović, I., Kaiser, D., Grünthal, G., Pazdírková, J., Sira, C., Guterch, B., Kysel, R., Camelbeeck, T., Lecocq, T., Szanyi, G. (2018): The 6 May 1976 Friuli earthquake: re-evaluating and consolidating transnational macroseismic data. - Bollettino di Geofisica Teorica ed Applicata, 59, 4, 417-444.

Vanneste, K., Wils, K. & Van Daele, M. 2018. Probabilistic evaluation of fault sources based on paleoseismic evidence from mass-transport deposits: the example of Aysén Fjord, Chile. Journal of Geophysical Research: Solid Earth, https://doi.org/10.1029/2018JB016289.

Wells, D.L. & Coppersmith, K.J. 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin - Seismological Society of America, 84, 974–1002.

FWF Der Wissenschaftsfonds. Interreg Italia-Österreich European Regional Development Fund EUROPEAN UNION ARMONIA universität innsbruck