

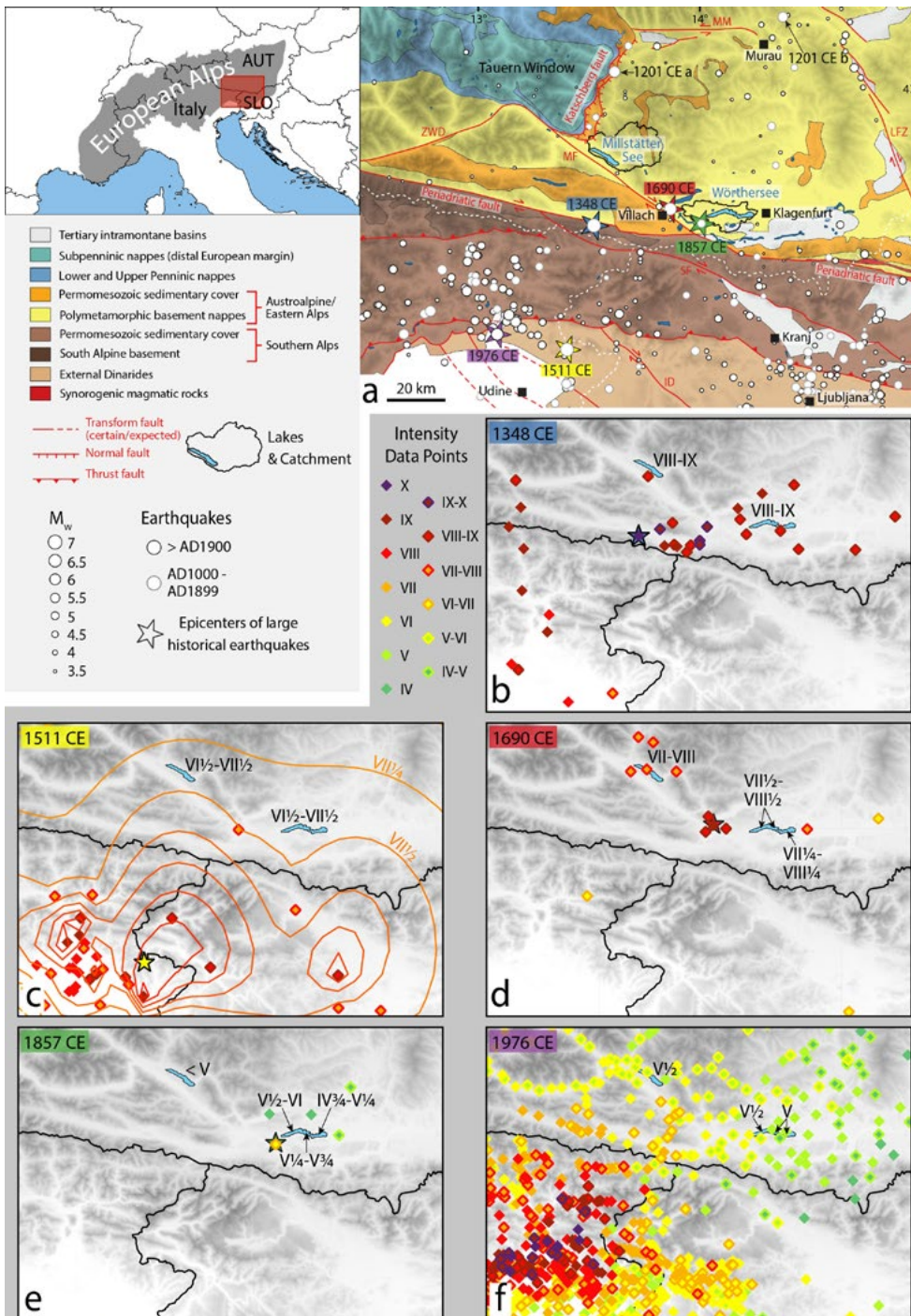
# Calibrated long term lacustrine paleoseismic records from Carinthia (Austria): implications for earthquake hazard in the south-eastern Alps

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## Introduction - Historical earthquakes in Carinthia



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  $\sim 7$ . 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) and turbidites.

Fig. 1. (a) General seismotectonic setting of the study area (simplified from Reinecker & Lenhardt 1999; Schmid et al. 2004; Reiter et al. 2018). ID: Idrija fault, LFZ: Lavanttal fault zone, MF: Mölltal fault, MM: Mur-Mürz fault, SF: Sava fault. Earthquake epicenters and magnitudes were compiled from SHEEC 1000-1899 (Stucchi et al. 2013), SHEEC 1900-2006 (Grünthal et al. 2013) and the Austrian earthquake catalogue (ZAMG). For the 1201 CE earthquake, two possible epicenters given in literature are plotted: close to the Katschberg fault (1201 CE a; Hammerl 1995) and near Murau (1201 CE b; Alexandre 1990). (b) - (f) Historically reported macroseismic intensity data points (IDPs; EMS-98 scale) of large earthquakes that affected our study area. IDPs for the 1348 CE and the 1690 CE earthquake are provided by the SHEEC 1000-1899 catalogue (Stucchi et al. 2013). To calculate possible macroseismic intensities at our lake sites for the 1511 CE event, the IDPs given by Camassi et al. 2011 were interpolated (section 4.1). For the 1857 CE earthquake, we derived macroseismic intensities from historical reports. The vast amount of IDPs for the 1976 CE earthquake is provided by Tertulliani et al. (2018).

## Studied lakes and methods

We use bathymetric data and high-resolution seismic data (2D line spacing  $\sim 100$  m) to investigate the sedimentary infill of the lakes Wörthersee, Millstätter See and Klopeiner See. This allows us to identify and map landslide deposits related to earthquakes and to determine suitable coring sites. Short ( $\sim 1.5$  m; white dots) and long ( $\sim 11$  m; red dots) sediment cores are retrieved and investigated for potentially seismically-induced features such as turbidites, 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.

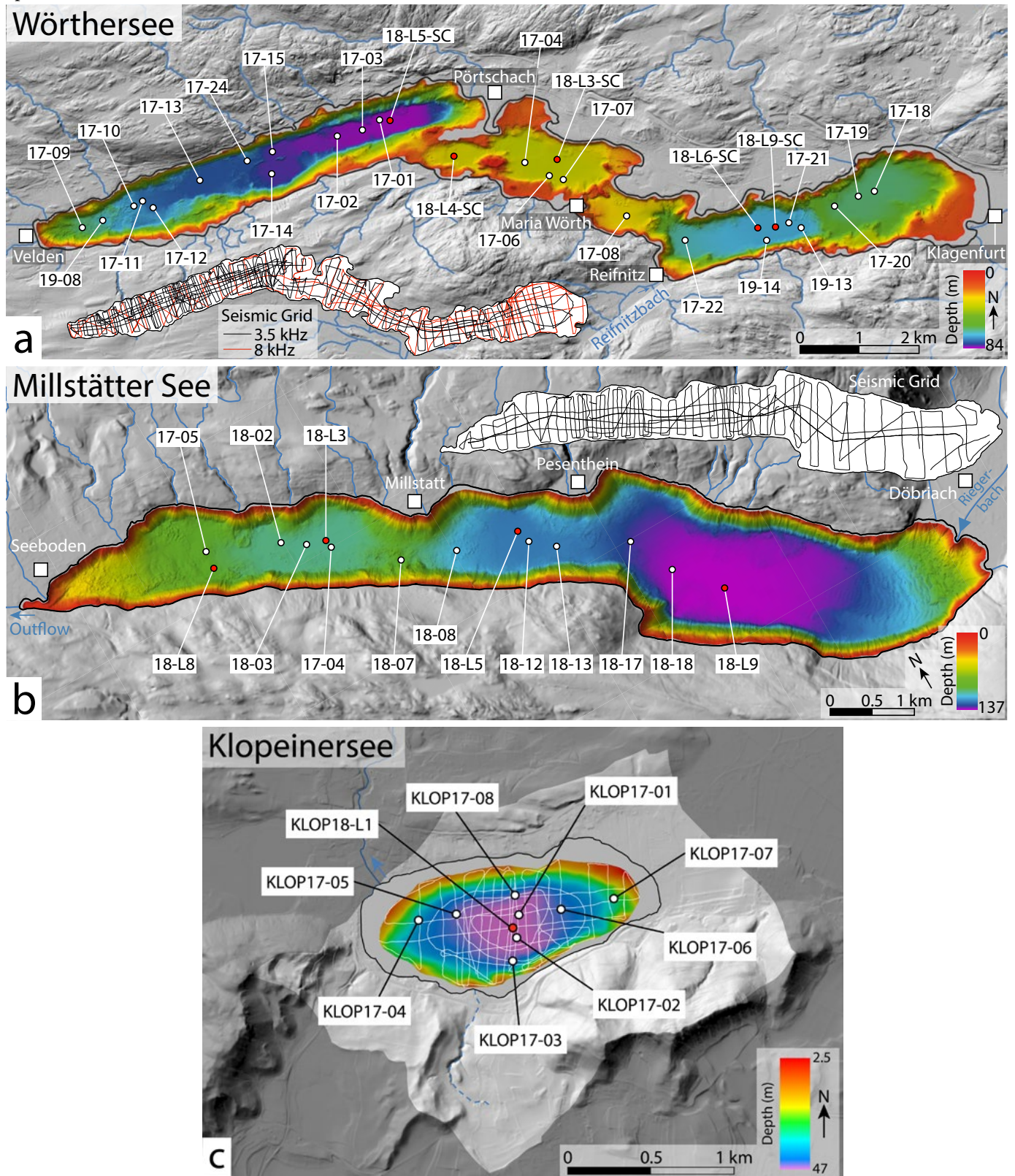
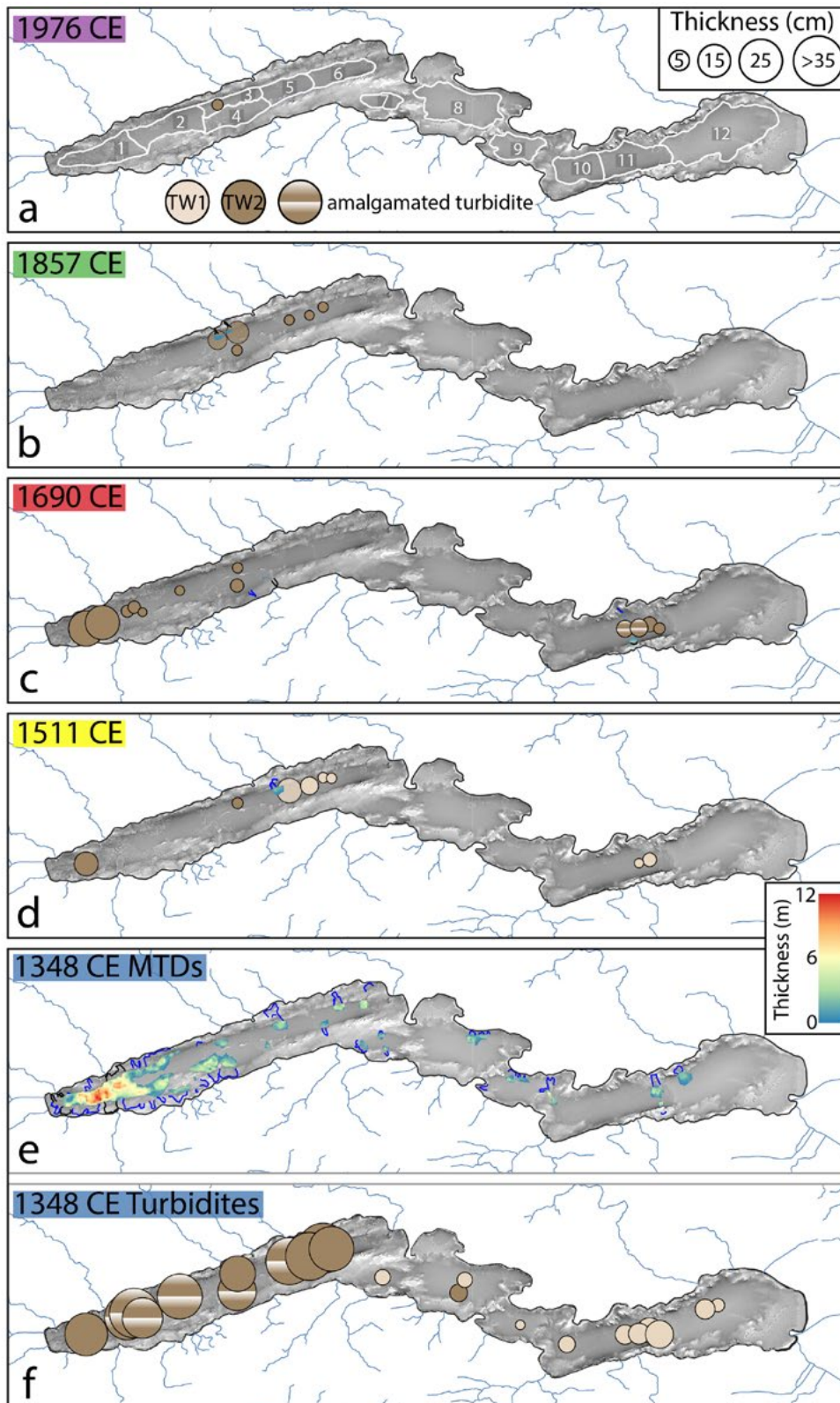


Fig. 2: The studied lakes Wörthersee (a), Millstätter See (b) and Klopeiner See (c). Red dots indicate long ( $\sim 11$  m) sediment cores, white dots indicate short ( $\sim 1.5$  m) sediment cores.

## Calibration of the sedimentary imprint



The large, historically reported earthquakes led to mass-transport deposits and associated turbidites in the studied lakes. Failures of deltas are present in our lakes from intensities of  $\sim V\frac{1}{2}$  onwards. Hemipelagic slopes start to fail at intensities ranging from VI to VII. This is in agreement with findings from multi-core studies of recent and historical earthquakes in Chile (Moernaut et al. 2014; Van Daele et al. 2015), Alaska (Van Daele et al. 2019), Switzerland (Monecke et al. 2004) and France (Wilhelm et al. 2016).

Fig. 3a-f: Spatial Imprint of large earthquakes in Wörthersee. Circles indicate turbidite thicknesses of different turbidite types (TW 1 = calcite-rich turbidites; TW2 = clastic-organic-rich turbidites). Source areas of MTDs are denoted as black (delta failures) or blue (hemipelagic slope failures) lines.

## Size-scaling relationships

By comparing the seismic intensities at the lake site with the sedimentary imprint, we are able to derive size-scaling relationships. Both the number of mappable mass-transport deposits as well as their volume increases logarithmically with seismic intensity.

Our data supports the findings of van Daele et al. (2015) that turbidites are more likely to be recorded in basins surrounded by sedimentary slopes if the seismic shaking strength is high. Furthermore, cumulative turbidite thickness increases with intensity. We apply these size-scaling relationships for the poorly documented historical 1201 CE earthquake and derive intensities of  $\sim$ VII at Millstätter See.

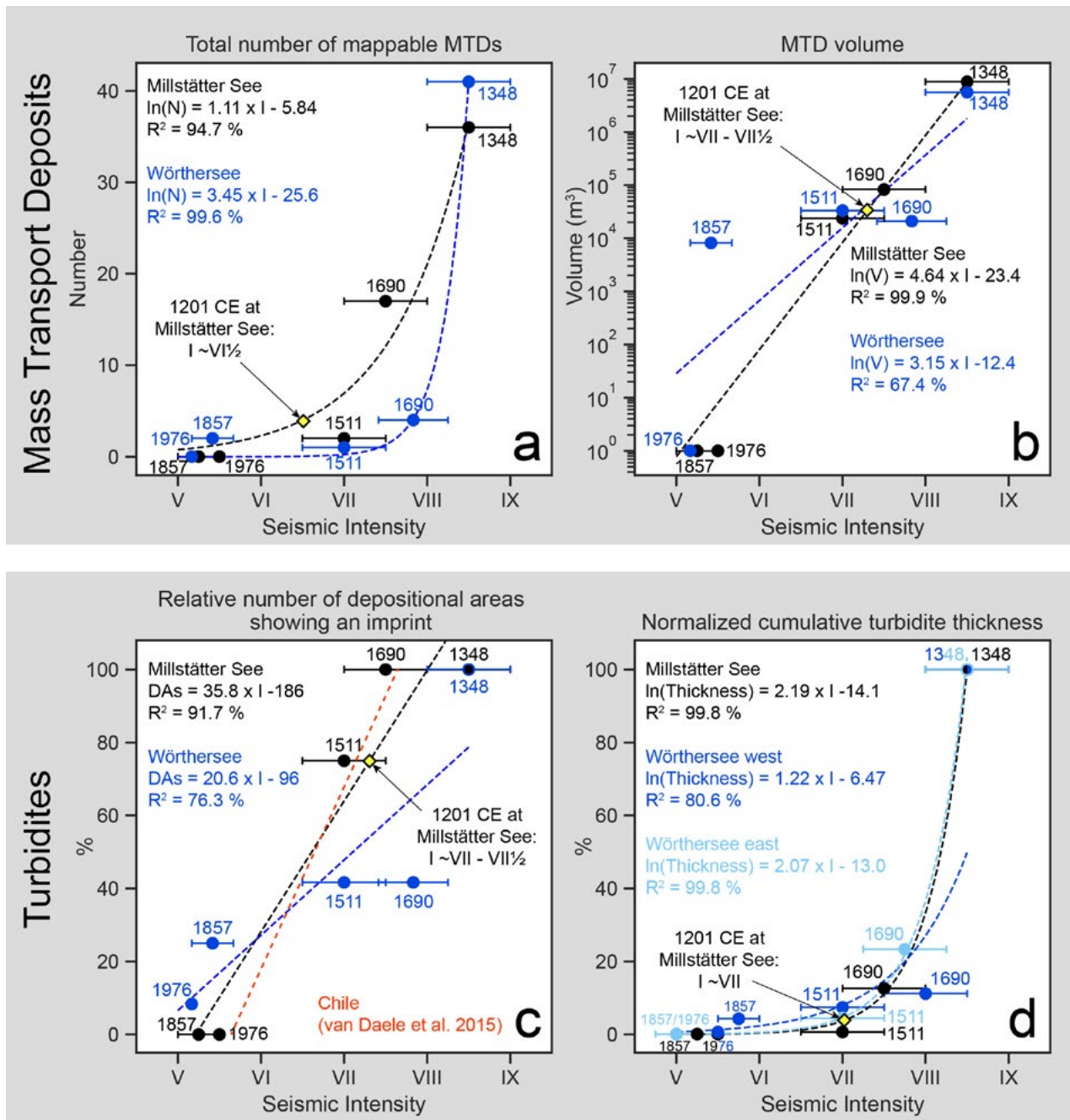


Fig. 4: Size-scaling relationships of earthquake imprint vs. seismic intensity. a) Seismic intensity vs. total number of mappable MTDs (in bathymetric data and/or seismic data). The total number of mappable MTDs increases with seismic intensity. b) Seismic intensity vs. MTD volume. The volume of remobilized sediment increases exponentially with seismic intensity. c) Seismic intensity vs. relative number of depositional areas in a lake that record an earthquake. The higher the seismic intensity, the more depositional areas show an earthquake imprint. From intensities  $\sim$ VII $\frac{1}{2}$  to VIII, seismic shaking is recorded in all areas. This agrees with findings from Chile (dashed red line; van Daele et al., 2015). d) Seismic intensity vs. normalized cumulative turbidite thickness (= the cumulated mean turbidite thicknesses per depositional area, normalized to the thickness of the AD1348 (mega-)turbidite). Cumulative turbidite thickness increases exponentially with seismic intensity.

## Multiple long calibrated records & implications for the regional seismicity

Eventually, we aim at applying the size-scaling on the multiple long records, reaching back into the Late Glacial. The MTDs and turbidites linked to prehistorical earthquakes indicate that the 1348 CE earthquake was the largest earthquake in the area during the Holocene. Generally, the lake records suggest increased seismic activity in the last ~1000 years, around 3000 - 4000 years BP and in the Late Glacial.

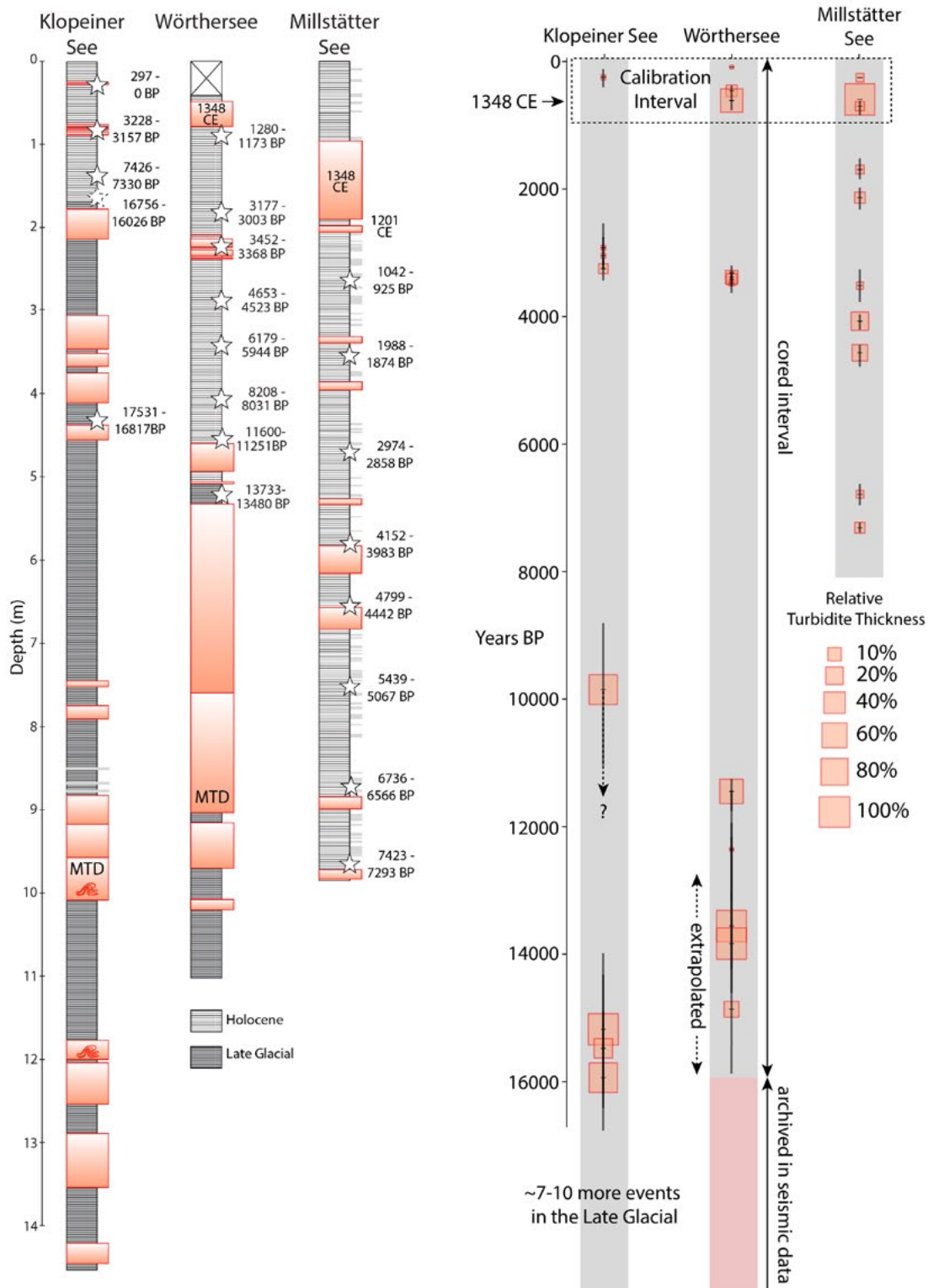


Fig. 5: In Klopeiner See and Wörthersee, the long sediment cores extend the paleoseismic record into the Late Glacial. In Millstätter See, the last ~8000 years of earthquake history could be revealed.

## Conclusions & Outlook

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

1. It is possible to derive scaling-relationships between seismic intensity and MTD volume/number as well as turbidite thickness in the Carinthian lakes.
2. The AD1348 is by far the most prominent event during the Holocene in our 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. Some of the Late Glacial events have a very large imprint. Because the sedimentational regime during that time differed strongly from Holocene conditions, however, the historical calibration might not be applicable for these earthquakes.

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Der Wissenschaftsfonds.



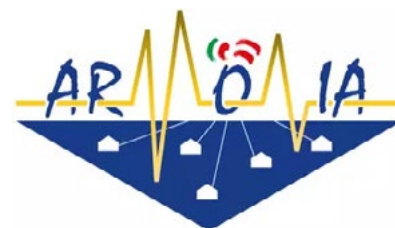
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