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7000 years of earthquake record in Julian Alps (Lake Bohinj, Slovenia)

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INTRODUCTION

- Julian Alps are characterised by a moderate to high seismic activity that has included several destructive earthquakes, such as the 1511 AD "Idrija" earthquake (MSK = X). Accurate assessment of the seismic hazard is required to reduce the high vulnerability of this region.
- Earthquake shaking may destabilise previously deposited sediment, which slides to the bottom of the lake and formed seismically induced mass wasting deposits (MWD), such as turbidites or homogenites.

MATERIALS & METHODS

- This study focused on Lake Bohinj (Fig. 1), in the Julian Alps (Slovenia). During the Quaternary, this area was affected by major NW-SE striking faults (Camassi et al., 2011).
- To reconstruct the earthquake chronicle, Lake Bohinj sediments were mapped with seismic reflection survey and cored in 2012 to provide a 12-m-long sedimentary record.
- A multiproxy analysis associating sedimentological and geochemical measurements was performed to reconstruct the long-term earthquake record.

FIG. 1

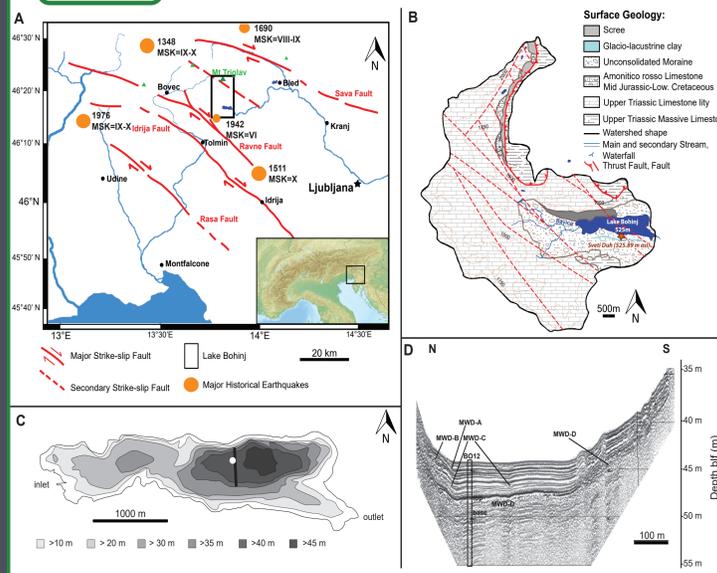


Fig. 1- General presentation of the study site. (A) Location of the study area with the major strike-slip faults and major historical earthquakes, modified from Moulin et al., 2014. (B) Geological map of the Lake Bohinj watershed. (C) Bathymetric map of Lake Bohinj. (D) Seismic profile oriented across the eastern basin showing the coring site location and four generations of mass wasting deposits (MWD).

RESULTS

- 4 generations of MWDs are identified across eastern sub-basin (Fig. 1D) at the edges of the subaqueous slopes. MWDs evolved laterally into transparent acoustic facies developing onlaps, typical signature for muddy turbidites or homogenites.
- Lake Bohinj sediment core is subdivided into 7 different sedimentary units. Most of the sedimentary record is Unit IV (443-998 cm, Fig. 2) composed of a coarse sandy thick erosive base overlaid by a homogeneous silty facies and a clayey cap.
- The upper part of the sedimentary record (0-443 cm) is interbedded by two types of graded-beds:
 - Type I is composed of (i) a coarse sandy base (Fig. 3), (ii) a central part with homogeneous silt, (iii) a thin light clayey cap. Typical characteristics of Homogenite-type deposits, confirmed by higher values of Foliation (Chapron et al., 2016).
 - Type II is characterized by a gray graded bed with a coarse and erosive silty base becoming slightly finer until a white clayey cap (Fig. 4). Characteristic of turbidite-type deposits (Sturm and Matter, 1978)
- The age depth model was created associating short-lived radionuclides profiles and 21 calibrated ¹⁴C ages. 7 outliers were unused because sampled in instantaneous deposits (Fig. 5).

FIG. 2

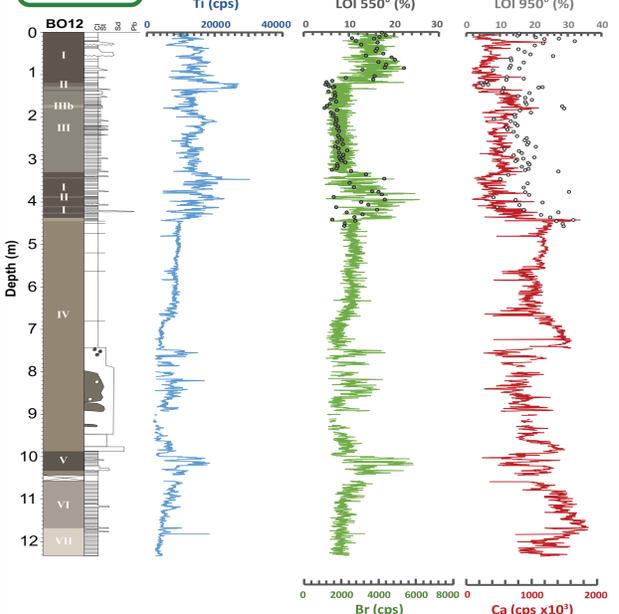


Fig. 2- Main sedimentological and geochemical results. Lithological and geochemical results (TI, Br and Ca contents) associated with the BO12 sequence. Lost On Ignition (LOI) 550° (dark-gray dots) and LOI 950° (light-gray dots).

FIG. 3

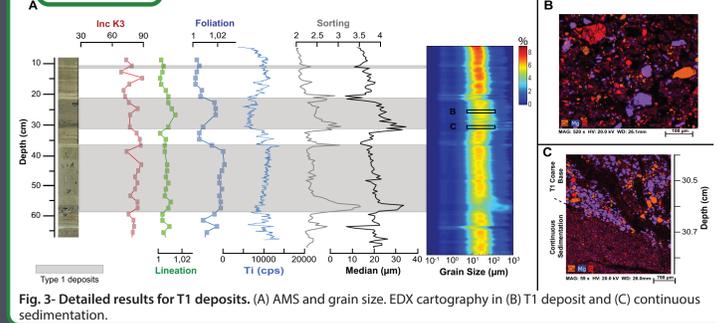


Fig. 3- Detailed results for T1 deposits. (A) AMS and grain size. EDX cartography in (B) T1 deposit and (C) continuous sedimentation.

FIG. 4

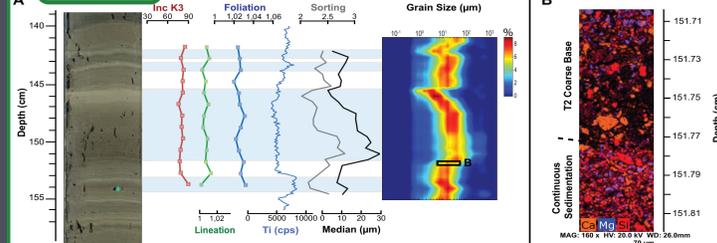


Fig. 4- Detailed results for T2 deposits. (A) AMS results, Ti content and grain size. (B) EDX cartography at the boundary of a T2 deposit and continuous sedimentation.

FIG. 5

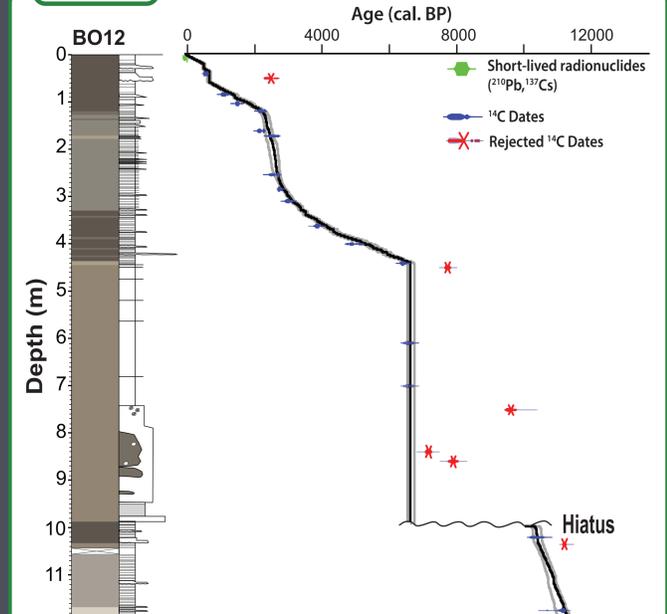


Fig. 5- Age-depth models from radiocarbon and short-lived radionuclide dates.

DISCUSSION

- Several mechanisms can trigger MWDs: e.g., earthquakes, spontaneous delta collapses, and considerable lake-level changes. The 15-m-high moraine ridge (Fig. 1) prevents sediment contribution of hyperpycnal flow from the delta and delta collapses to reach the coring location.
- Earthquakes record by MWDs depends on the sensitivity of a lake to record a seismic event. To characterize the sensitivity of Lake Bohinj, earthquake-sensitivity threshold Index (ESTI) method was applied (Fig. 6; Wilhelm et al., 2016).
- Seismic trigger hypothesis for the three distinct types of deposits:
 - Three most recent T1 correspond to three strong historic earthquakes (Fig. 6, 1348, 1511 and 1690 AD earthquake)
 - Between 3500 and 2000 yr cal BP major destabilizations occur in the watershed by human activities (Fig. 7) that led to increases in sedimentation rate and thus increase ESTI (more earthquakes should have been recorded). High T2 deposits number identified could be the consequence of sensitivity increase.
 - Unit IV occurred coevally with geomorphological changes in the area (Bovec Terrace, Fig. 1, Marjanac et al., 2001)
- The Bohinj earthquake chronicle presents several time intervals with no local seismic activity recorded by homogenite-type deposits. These periods could be linked to the lack of major seismic events or to ESTI decrease

FIG. 6

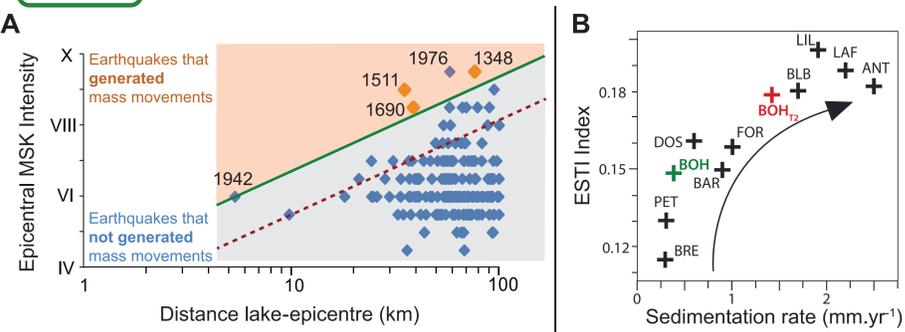


Fig. 6- ESTI estimation for Lake Bohinj. (A) Lake Bohinj sequence results associated with CPT15 data. Green line represents the limit of lake Bohinj sensitivity to earthquakes calculated for the historical period. The red dotted line represents the hypothetical limit of lake Bohinj sensitivity with an ESTI of 0.18 calculated for the mean sedimentation rate over the period of 3500 to 2000 yr cal BP, unique period with T2 deposits. (B) The ESTI versus sedimentation rate for Lake Bohinj (green) over the last centuries with previous results (black) from Wilhelm et al. (2016). The red cross corresponds to the ESTI and sedimentation rate for the period of T2 deposits (3500 to 2000 yr cal BP). This diagram suggests that a significant increase (decrease) of the sedimentation rate appears to be the dominant factor resulting in an increase (decrease) of earthquake deposits in the lake (Wilhelm et al., 2017).

CONCLUSION

- This is the first earthquake chronicle over the last 7000 years in the Julian Alps with 29 homogenite-type deposits.
- The regional seismic activity recorded by a lake is highly connected to earthquake settings, distance and the lake's sensitivity to recording a seismic event (ESTI), which is related to the sedimentation rate.
- When sedimentary sequence presents a variable ESTI, it should be prohibited to present a mean return period for seismic activity recorded by the lake system.

FIG. 7

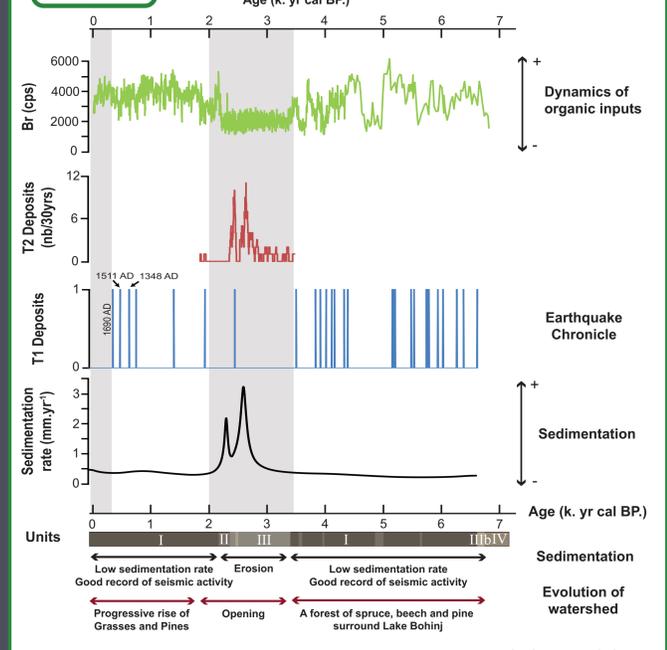


Fig. 7- Lake Bohinj earthquake chronicle. Comparison between the organic input dynamic (Br, T2 and T1 frequency) with major historical earthquakes and the mean sedimentation rate. Gray shadings correspond to intervals with potential higher ESTI.

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