1960 Valdivia earthquake tsunami deposits from two coastal lakes and preliminary results for an extended paleotsunami record of South-Central Chile

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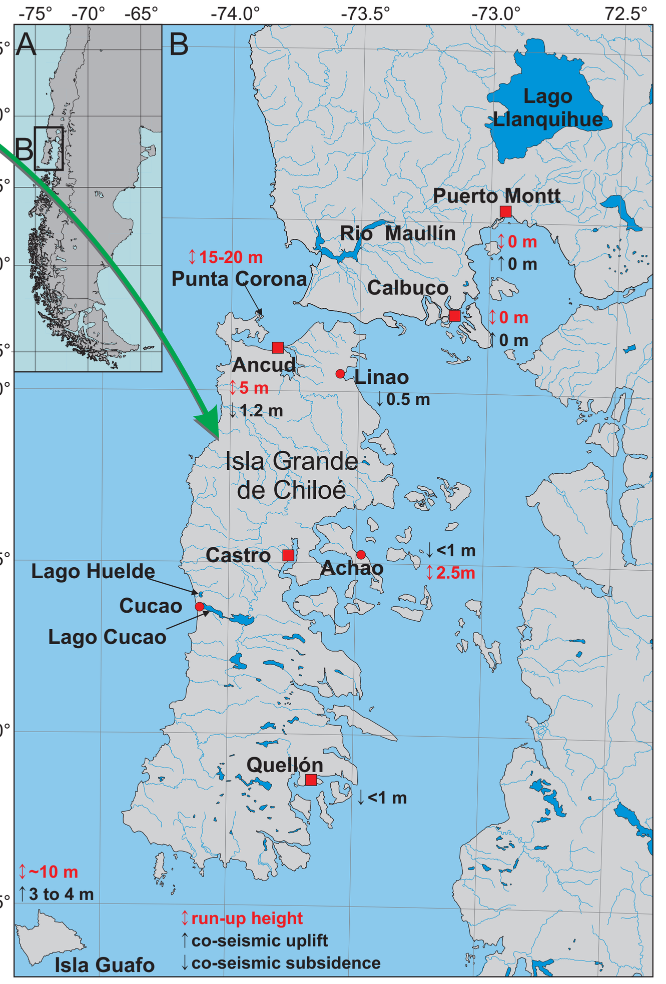
Introduction

The study area lies on La Isla Grande de Chiloé (fig. 1). Chiloé lies within the ~1000 km long Valdivia seismic segment, which violently ruptured in 1960 with the highest magnitude earthquake ever instrumentally recorded (Mw: 9.5). Two to four tsunami waves hit Chiloé with 10 to 20 m maximum wave height (Sievers et al., 1963). From the 52 houses comprising the village of Cucao at the time, 27 were heavily damaged or completely removed from their foundation and three people died (Weisner, 2003). The same wave hit the entire South-Central Chilean coast and caused damage and death in Hawaii and Japan, too.

From a geo-risks perspective it is crucial to know **(1)** how tsunami waves behave, when they cross onshore areas and **(2)** how often these giant tsunamis recur.

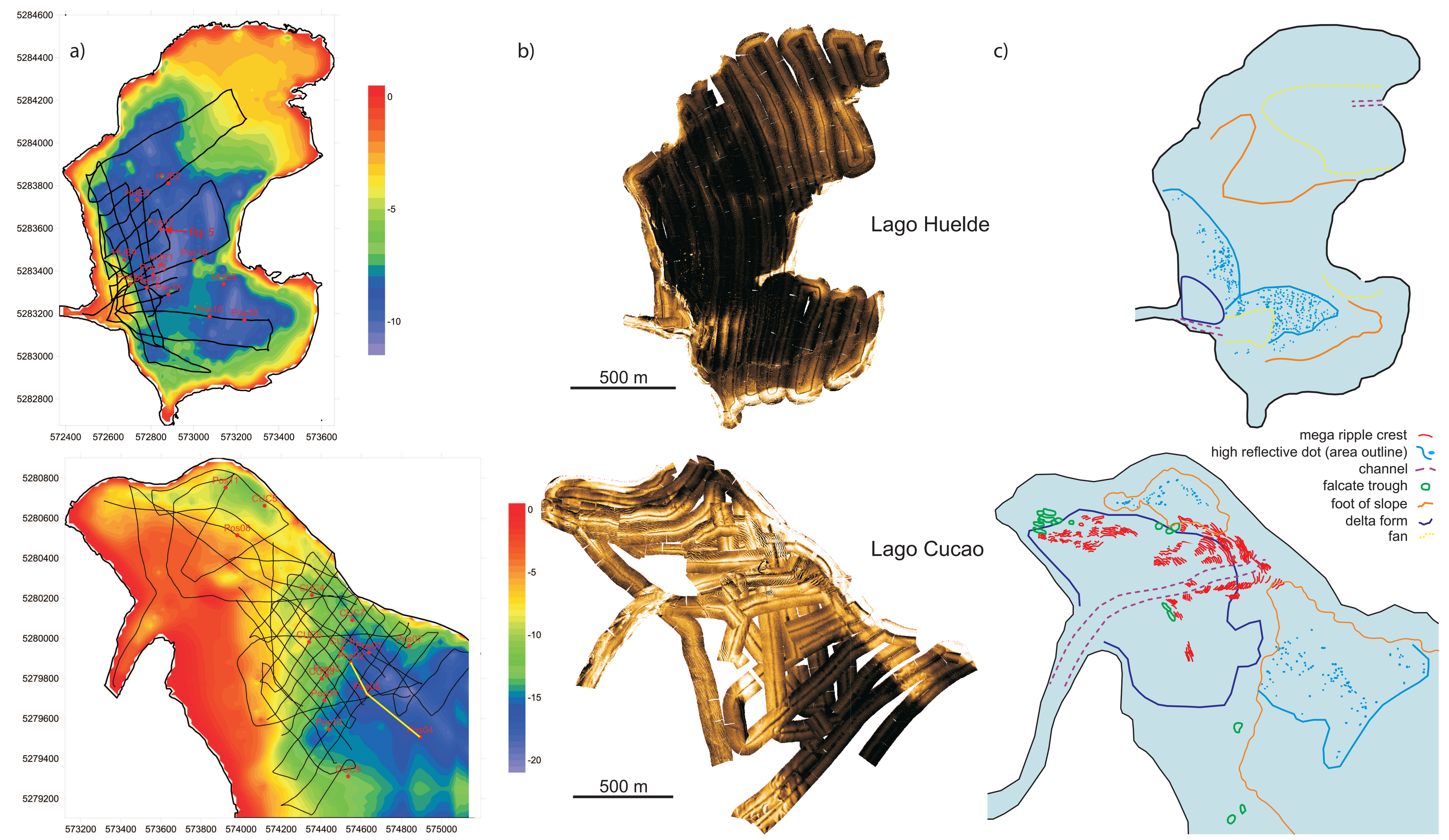
Question **(1)** will be addressed with a detailed sedimentological analysis on tsunami deposits, i.e. sedimentologic description, grain size analysis, physical property measurements, x-rays and ct-scans.

Question **(2)** will be approached by confirming or challenging the existing paleo-tsunami record for the Valdivia seismic segment from the Rio Maullín estuary by Cisternas et al. (2005) and extending the same record further back in time.



► **Figure 1:** Overview map of the research area. All locations that are written in green in the yellow text boxes are displayed on this map. The numbers in red show reported maximum run-up heights of the 1960 Valdivia earthquake tsunami. The numbers in black show measured co-seismic uplift (upward arrows) and co-seismic subsidence (downwards arrow) for the same event.

▼ **Figure 2:** a) bathymetry map based on the side-scan survey (SSS) bottomtrack with the sub-bottom profile lines in black, the core sites in red and the profile from figure 6 indicated in yellow; b) non-gain-controlled reflectivity map of the SSS data; c) interpretation map based on the knowledge gained from maps a) and b).



Acoustic data

The bottomtracks from the side-scan sonar (SSS) data from both lakes were extracted to produce crude overview maps of the lakes' bathymetry. In the SSS data soft basin sediment can be easily differentiated from acoustically harder sediment above the wave base of the lakes. On both lakes a delta-like plateau is located adjacent to the outlet of the lakes. Lago Cucao was observed to be in the intertidal zone during fieldwork, i.e. the outlet becomes an inlet during high tides, which explains the delta-like morphology. Lago Huelde was not observed to be in the intertidal zone. However, with the dynamic vertical displacement history at the Chilean coast it is expected that Lago Huelde has been in the intertidal zone in the past and that the same mechanism caused the delta-like morphology in Lago Huelde, too. In both lakes the plateau is crosscut by a channel. In Lago Huelde this channel can be identified as the major sediment source of a fan of acoustically harder surface sediments on the SSS reflectivity map (fig. 2b and c). There are small spots of higher reflectivity in the otherwise weakly reflective (dark) basins. These are interpreted as patches of large semi-intact terrestrial plant debris, which was unrooted by the tsunami, however, it was not possibly to collect a sample for ground truthing.

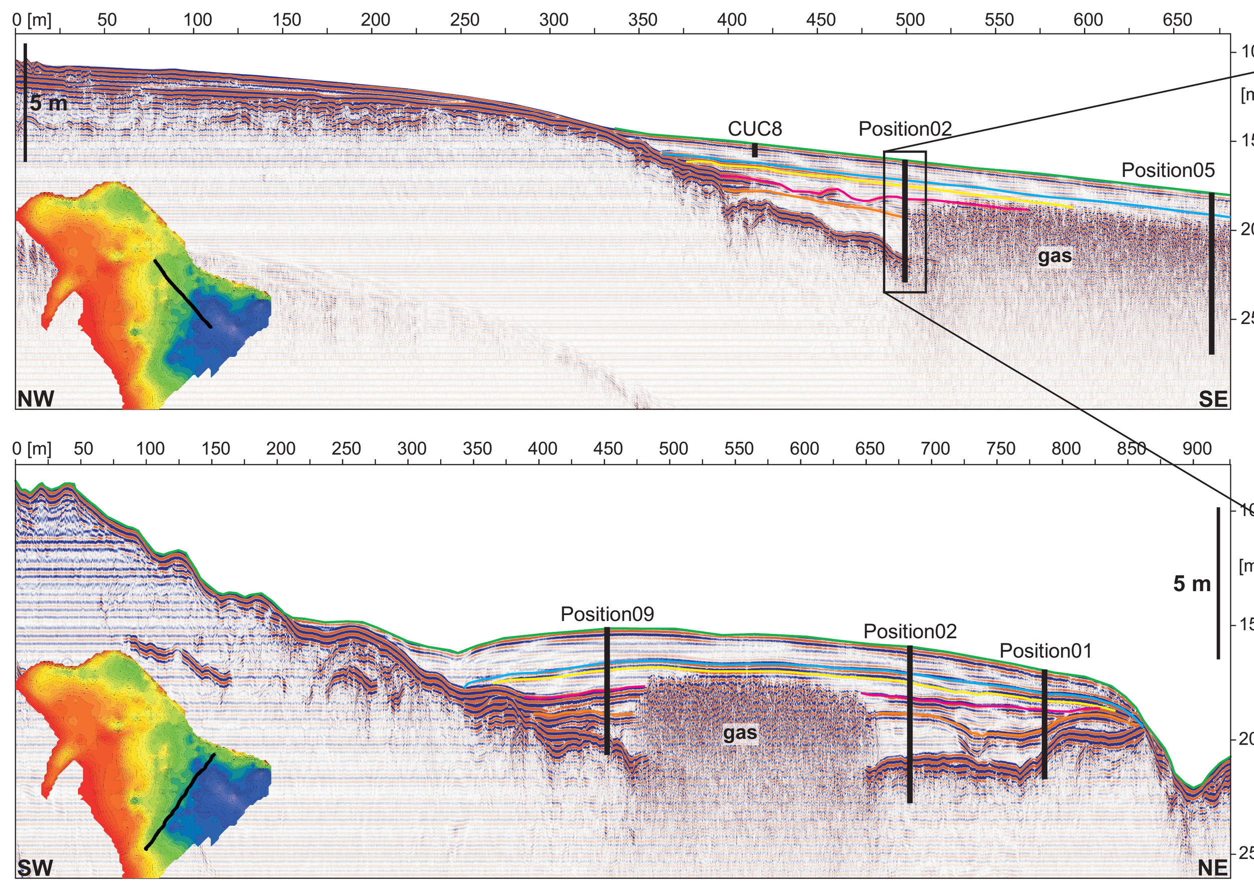
The sub-bottom profiles from both Lago Cucao and Lago Huelde have similar appearances. Acoustic penetration is highest on the slopes and close to the foot of the slope. Towards the basin gas masks the entire signal and penetration is limited to the uppermost reflector. Strong reflections can be correlated from the seismics to the cores, and the core-to-core correlation in areas where the masking prevents insight into the sedimentary architecture is possible in most cases, too.

Core analysis

The cores in this study are composite cores, where each core segment was approx. 3 m long (e.g. fig. 8). On each core site the topmost core segment is a gravity core with typically short sediment penetration of around 75 cm. In almost each core taken in both lakes were deposits of the 1960 Valdivia earthquake tsunami. These deposits typically contain sands or coarse silts, which produce high gamma ray density and high magnetic susceptibility values in comparison to the background sediment. An example of a common tsunami deposit is given in figure 5 (for location see fig. 2a).

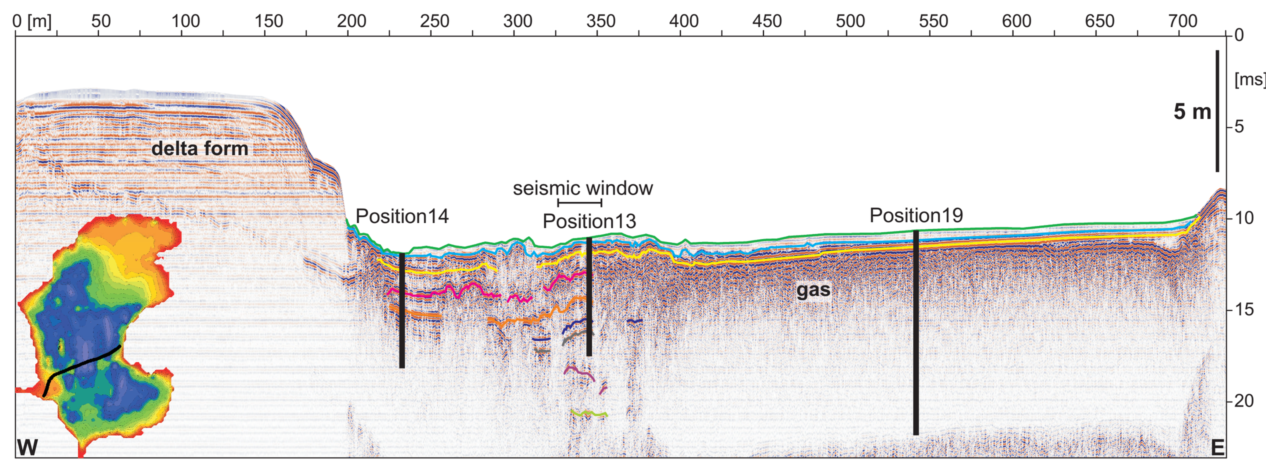
The existence of many event deposits with multiple sand layers with erosional lower contacts, multiple fining upwards cycles, mud drapes, traction carpets and mud rip-up clasts (fig. 7) makes a strong argument for these event deposits to be a product of tsunami inundations into the lake, especially considering the tsunami history of the South-Central Chilean coast.

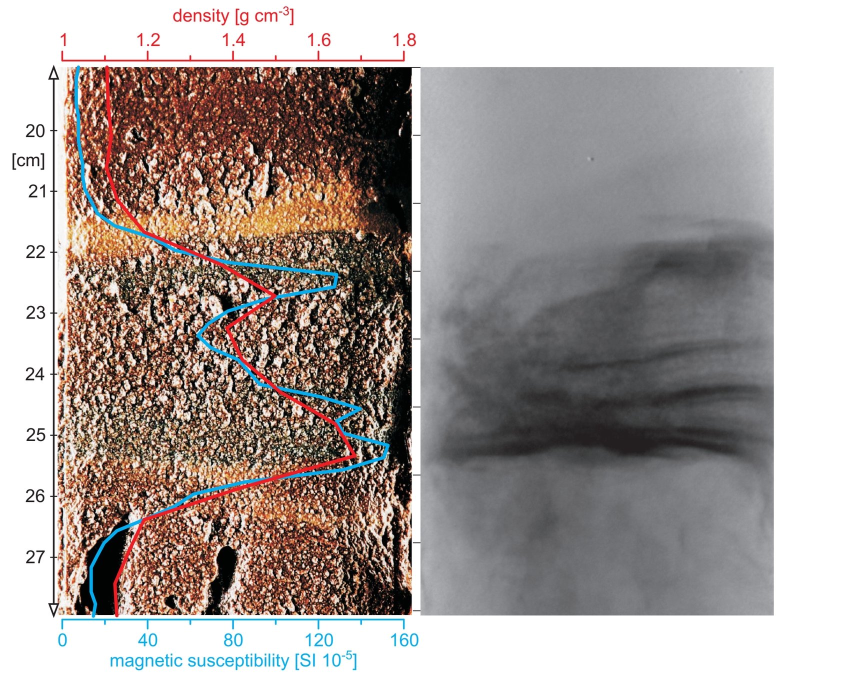
The most promising core record from Lago Huelde contains 18 coupled excursions of gamma ray attenuation density and magnetic susceptibility with correlating sandy and silty deposits over a range of 3930 ± 80 cal. years BP (fig. 8). So far the age control is not detailed enough for definite conclusions as to when each sand layer was deposited, however, averaging over the entire time span of the recovered sediment results in a recurrence time of about 220 years for tsunami inundations into Lago Huelde. This is longer than the historical recurrence time of ca. 128 years for large earthquakes during the last ~450 years (Lomnitz, 2004), but significantly shorter than the recurrence time for tsunamis of 285 years calculated from the sedimentary record at Rio Maullín (Cisternas et al., 2005). Averaged between each radiocarbon date the recurrence time is shown to have changed in time.



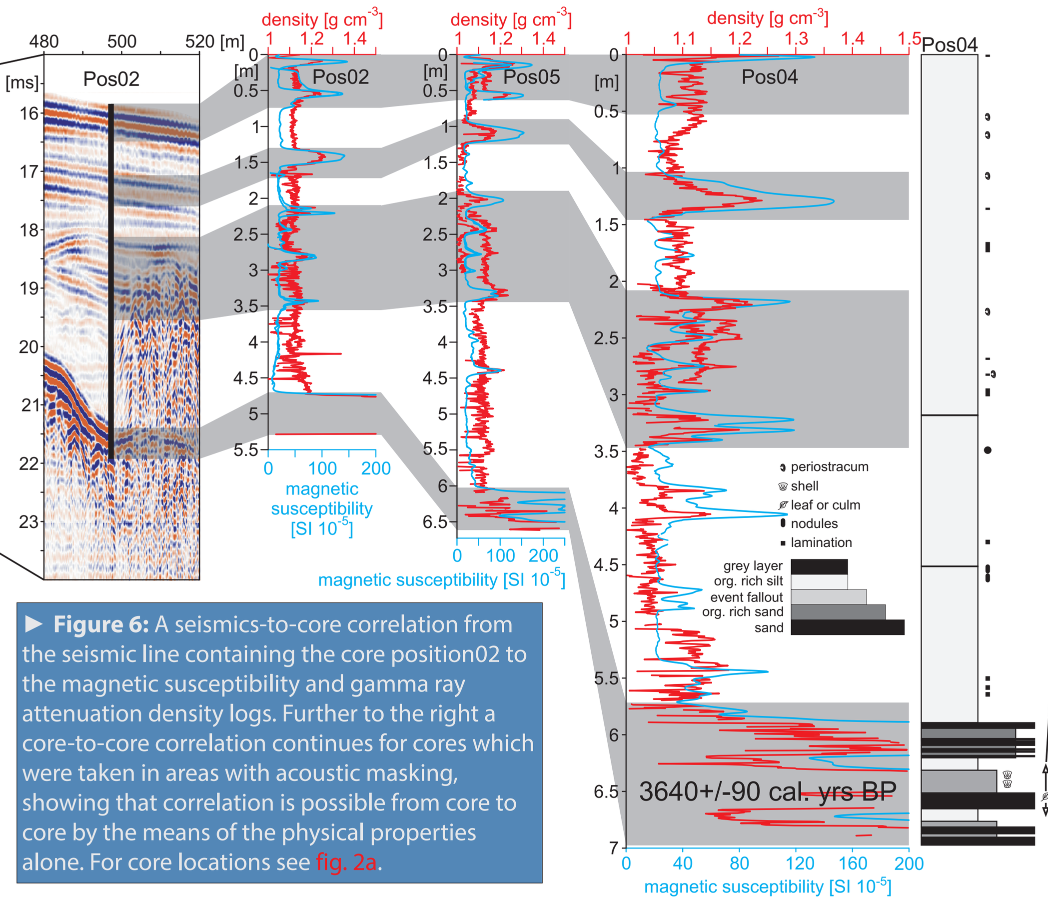
▲ **Figure 3:** Two seismic lines from Lago Cucao, one along (a) and one across (b) the lake's long axis. Cores are displayed according to their recovered penetration depth. There is only a narrow seismic window between the shallow area of the lake and the basin, where gas masking effects prevent the view into the sediment. The crossline hits this seismic window, with very little masking effects. The core at position02 is used in figure 6 for seismics-to-core correlation.

▼ **Figure 4:** A seismic line in Lago Huelde where the core sites are marked by a black bar, which corresponds in length with the recovered penetration depth. The masking effects by the gas are almost ubiquitious, except for a few seismic windows, e.g. at core position13, close to the outlet. In these seismic windows multiple strong reflections are interpreted as tsunami sand sheet reflections.



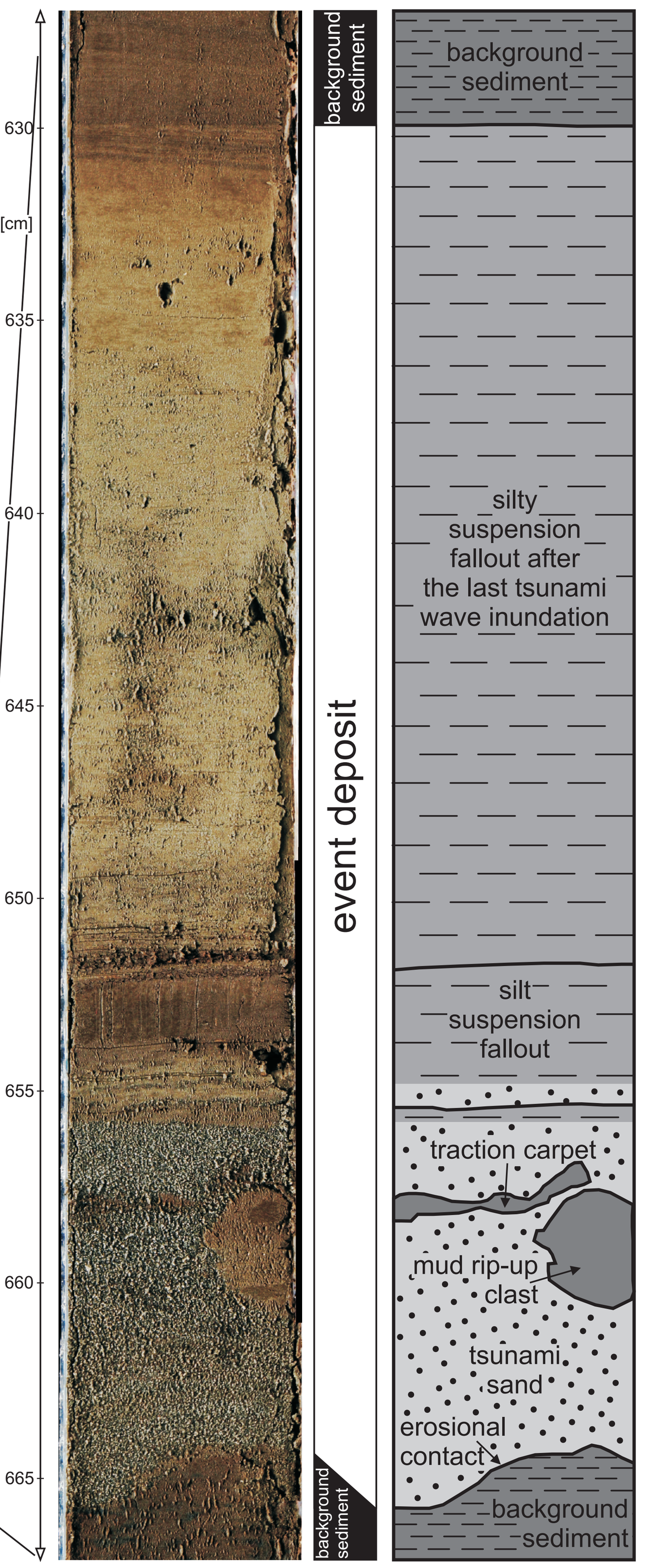


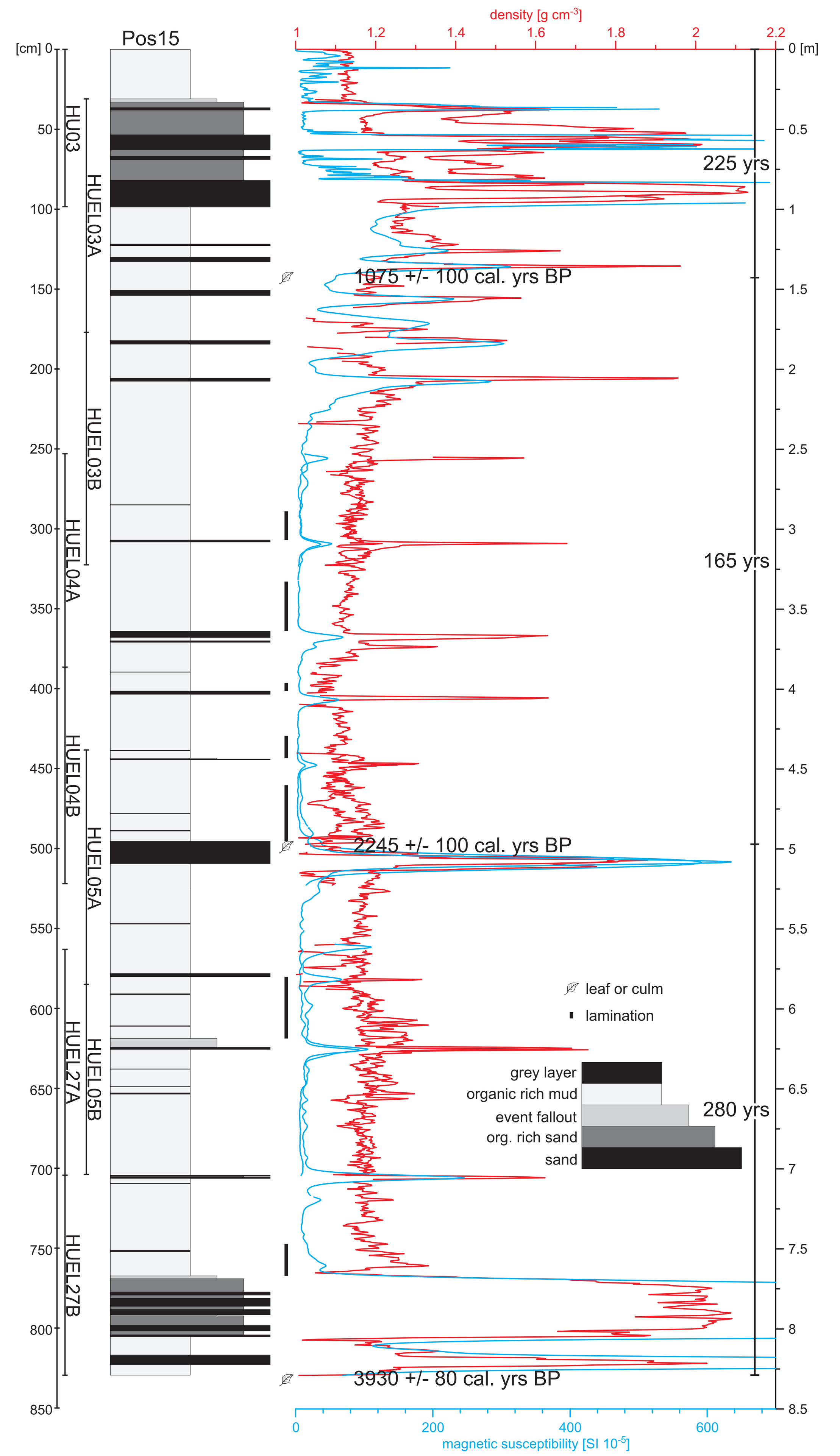
▲ **Figure 5:** A colour enhanced split core picture of a short core taken at position17 in Lago Huelde (fig. 2a) to the left with the gamma ray attenuation density (red) and the magnetic susceptibilty (blue) plotted ontop of the image. To the right is an x-radiography of exactly the same core section (the darker the denser). While the identification of an event deposit is easily done from the split core surface's look, it is necessary to include helpful tools like the magnetic susceptibility or even better the x-radiography for differentiation of the three layers within the event deposit. This particular event layer was deposited during the 1960 Valdivia earthquake tsunami.



► **Figure 6:** A seismics-to-core correlation from the seismic line containing the core position02 to the magnetic susceptibility and gamma ray attenuation density logs. Further to the right a core-to-core correlation continues for cores which were taken in areas with acoustic masking, showing that correlation is possible from core to core by the means of the physical properties alone. For core locations see fig. 2a.

▼ **Figure 7:** A split core picture of a core section from Lago Cucao to the left. The entire core log is shown in figure 6. The interpretationto the core seection is on the right. This section comprises almost the entire range of sedimentary units, structures and other features that are recorded among the tsunami deposits from Lago Huelde and Lago Cucao. However, usually tsunami deposits from the two lakes are simpler.





▲ **Figure 8:** Core log of the composite core at position15 in Lago Huelde. From left to right there are: i) the log of core sections with the core section ID indicated within their depth range; ii) the sedimentary core log with fossils found and fine lamination indicated; iii) the gamma ray density (red) and magnetic susceptibility (blue) core logs; iv) calibrated radiocarbon dates at their sample depth; and v) the average recurrence time of the tsunami deposits for each of the three time windows enframed by the three radiocarbon dates, using an age of -62 years BP at 0 cm depth. In total 18 excursions of gamma ray density and magnetic susceptibility are coupled with sandy deposits, all of which are interpreted as tsunami deposits.

Conclusions and outlook

There are two aspects to this study. One **(1)** is the detailed description of the range of the sedimentary characteristics and features in coastal lake tsunami deposits. The other **(2)** is the complementation and extension of the existing paleo-tsunami record of the Valdivia seismic segment.

Ad **(1)**: In practically all cores from Lago Huelde and Lago Cucao are event deposits with high density and high magnetic susceptibility buried underneath 20 to 40 cm of background sediment. These layers are multilayered and have three, possibly four fining upward cycles (fig. 5 and 7), matching the number of observed high tsunami waves around the study area in 1960.

The next steps are to make more x-radiographies and include ct-scanning and micro ct-scanning to the analysis to identify microstructures, e.g. ripples or mud rip-up clast imbrication. These analyses will help to improve the description of the physical environment during deposition of the tsunami sediments.

Ad **(2)**: So far the age control is not good enough to confirm or challenge the existing paleo-tsunami record. However, crude average recurrence times of 225, 165 and 280 years (fig. 8) show that the recurrence time of tsunamigenic earthquakes is probably changing significantly over time within the same seismic segment. Eighteen tsunami sand layers were identified on a single core site, reaching back in time to 3930 years BP.

During the comming year an extended seismics-to-core and core-to-core correlation as shown in figures 3, 4 and 6 will be coupled with extensive radiocarbon dating for a good age control throughout the core from both lakes. The aim is to confine each sand layer with a minimum and maximum age. The paleo-tsunami record from both lakes will be combined to establish a solid, detailed and long paleo-tsunami record from Chiloé for the Valdivia seismic segment.

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