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Lacustrine turbidites in Chile: why do they form continuous, sensitive and quantitative paleoseismic records?

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Abstract. Turbidite paleoseismology is a relatively new method used to obtain long records of past earthquakes. Despite its worldwide application, only few studies are dedicated on assessing the reliability of turbidite paleoseismic records. Here, we apply a multiproxy analysis of lacustrine turbidites produced by the 1960 Chile earthquake (Mw 9.5) in order to determine the processes that formed these earthquake-triggered turbidity currents. We show that the turbidites in four lakes result from failure of a thin veneer (~5 cm) of slope sediments and do not result from disintegration of subaquatic landslides. Therefore, slope-recharging processes do not significantly affect the turbidite records, and hence the patterns found are inferred to be related to earthquake recurrence and the macroseismic intensities associated.

Keywords: Turbidites, earthquakes, paleoseismology, lake sediments

1 Turbidite paleoseismology

Turbidite records at ocean margins and in lakes are getting increasingly used for paleoseismological purposes. In many areas this method is justified as the turbidites were found to correlate one-to-one with historical earthquakes. The correlation is especially clear when seismic intensity at the source region of the turbidity currents exceeded a value of VI to VII (Van Daele et al., in press).

In South-Central Chilean lakes, the 2010 Maule earthquake (Mw 8.8) and the 1960 Valdivia earthquake (Mw 9.5) deposited turbidites in all suitable lacustrine basins which are located near the rupture zones (Van Daele et al., in press). Moreover, it even seems that turbidite volumes in these lakes can be used to estimate the seismic intensity of historical and prehistorical events (Moernaut et al., 2014). Therefore, turbidite records can be regarded as natural seismographs that can help in extending the historical earthquake record back in time for several thousands of years (Strasser et al., 2013). Such an extended –and calibrated– earthquake record is indispensable to characterize the recurrence patterns of great and giant earthquakes in Chile, and update seismic hazard maps.
In some regions turbidite records do not fully represent the recurrence of strong earthquakes, and thus their paleoseismic relevance is limited (Sumner et al., 2013). In order to assess the consistency of turbidite paleoseismic records, it is therefore crucial to gain a better understanding of the slope failure processes that formed the earthquake-related turbidity currents. Most studies assume that turbidity currents evolve from subaquatic landslides via progressive dilution of the sliding mass and flow transformation. Surprisingly, virtually no process-related studies exist in order to validate this assumption, and thus it remains debated which processes underlie the turbidite records used in paleoseismology.

In our study, we analyse the sedimentary imprint of the giant 1960 AD Chile earthquake in four South-Central Chilean lakes (Villarrica, Calafquén, Panguipulli, Riñihue; Fig. 1A) and use this data to gain a better understanding about the processes of turbidity current generation in these lakes.

2 Analysis of turbidites and mass-transport deposits

We combined 2D seismic-reflection data, multibeam bathymetry data (Lake Villarrica) and more in-depth analyses of short sediment cores. We put these results in a temporal perspective using a long piston core in Lake Riñihue covering 5.2 kyrs of turbidite depositional events.

2.1 Geophysical data

Seismic-reflection data and multibeam bathymetry allowed the mapping of relatively recent mass-transport deposits ("landslides") in the sedimentary infill of the lakes. Moreover, it allows identifying the scarps these mass movements left further upslope. Volume calculations showed that most of the remobilized mass on the slopes is contained in the mass-transport deposits in the basins.

Therefore, only minor volumes of sediment may have been transported as turbidity currents derived from these "landslide-style" slope failures.

2.2 Sediment core analyses

Turbidite identification was mainly done visually as the homogeneous and fining-upwards characteristics of the turbidites clearly contrasts with the millimeter-scale laminations of the background sediments. Age information for short cores was taken from Moernaut et al. (2014) in which age models were made using radionuclides and varve-counting. In this way we could clearly determine which mass-transport deposits (MTDs) and turbidites were generated by the 1960 earthquake. Facies description of the MTDs (Fig. 1B) show that their internal structure remained largely intact, indicating minor dilution of the downslope moving mass, as was already indicated by the volume balances.

In order to identify the stratigraphic depth from which sediment was remobilized and transported as turbidity currents, we compared the composition of turbidites with background sediments at various stratigraphic depths. For this, we determined organic matter content, radionuclide content and sediment lightness. For most of the analysed turbidites, sediment lightness revealed that the material within the turbidites corresponds to the upper ~5 cm of the stratigraphic column (Fig. 1C). This indicates that the turbidites are produced by surficial slope failure and do not result from typical subaquatic landslides in which sequences of several meters thick get remobilized.

We analyzed a new long sedimentary record which contains up to 34 turbidites in Lake Riñihue (Fig. 1D). Radiocarbon dating shows that this record covers the last ~5200 years. As we wish to understand the significance of different variables and how they relate to the magnitude of a turbidity current, we ran a suite of statistical analyses on the inferred turbidite thicknesses and inter-event times obtained on the long record. This analysis shows that there is no correlation between inter-event times and the volumes of the turbidites (Fig. 1E). Hence, the generation and volume of turbidites is not governed by the amount of time in which the slopes could accumulate sediments since a previous turbidite event took place.

3 Implications for turbidite paleoseismology

The surficial slope failure mechanism and independence of slope recharging times means that the main slope preconditioning processes associated to subaquatic landslides do not affect the initiation of turbidity currents in the Chilean lakes. This allowed us to re-evaluate the factors that predispose a margin for being suitable for turbidite paleoseismology and let us conclude that the surficial failure process can lead to turbidite paleoseismic records of excellent continuity, high sensitivity, and which can provide information about paleo-earthquake intensities. In this way, we now have a conceptual model that explains why we can apply quantitative paleoseismology based on lacustrine turbidites in Chile. It is now of the utmost importance to further investigate the geotechnical details of the surficial slope failure process and evaluate if it can be applied worldwide.

Additionally, the combined long turbidite records of two South-Central Chilean lakes (Calafquén and Riñihue) will provide a first glimpse in the variability in earthquake recurrence times for both giant (M>9) and great earthquakes (M>8), which will aid in a better characterization of the seismic hazard in this region.

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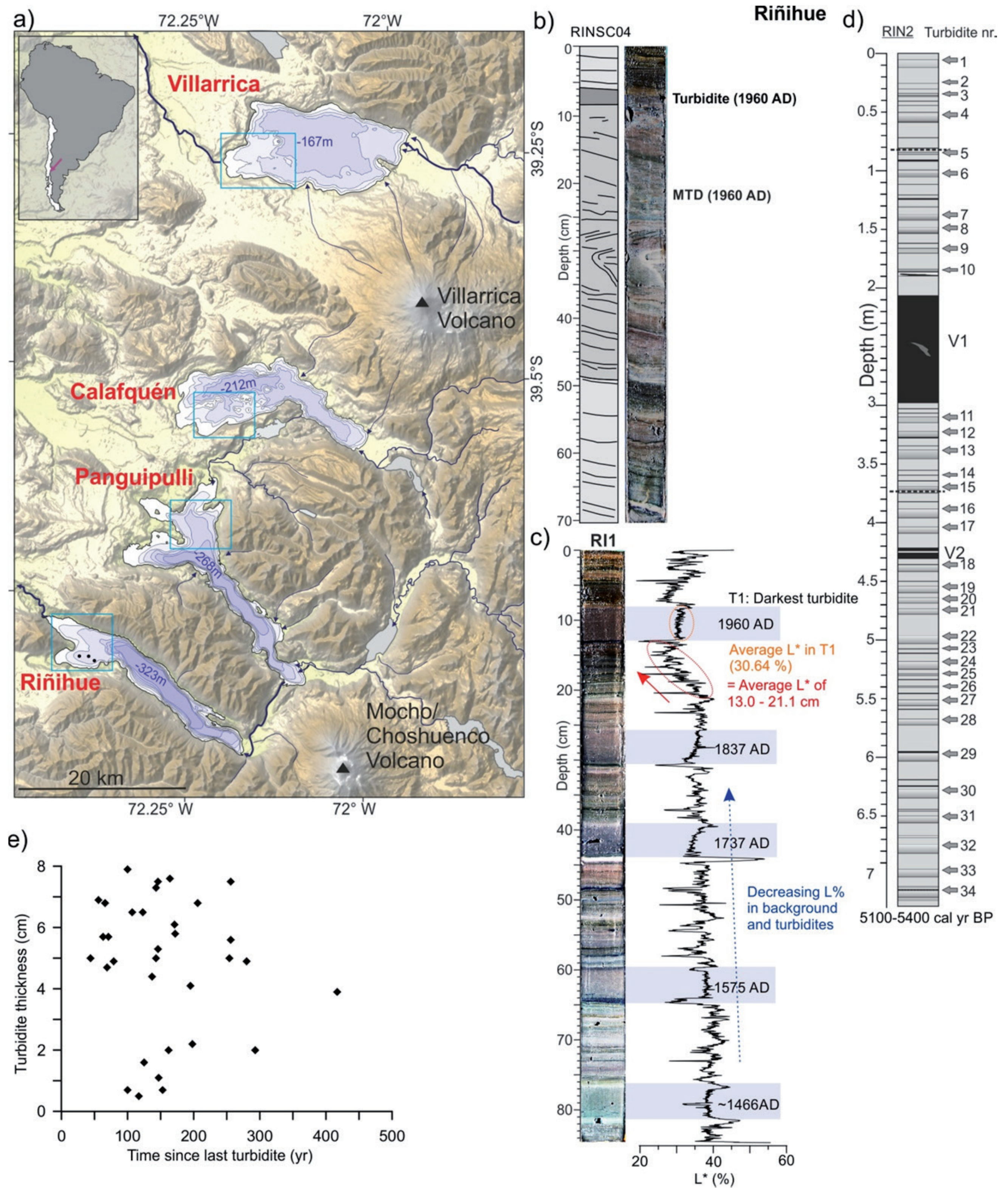

Figure 1. a) Setting of the four studied lakes and studied sub-basins. b) Sedimentary facies of mass-transport deposits (MTD). c) Determination of stratitigraphic failure depth based on sediment lightness. d) Long turbidite record in Lake Riñihue. e) Comparison of turbidite thickness and time since the last turbidite showing that there is no apparent correlation.