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Coastal lake sediments reveal 5500 years of tsunami history in south central Chile

Philipp Kempf [a, *], Jasper Moernaut [b, c], Maarten Van Daele [a], Willem Vandoorne [a], Mario Pino [c], Roberto Urrutia [d, e], Marc De Batist [a]

[a] Renard Centre of Marine Geology, Ghent University, Ghent, Belgium
[b] Institute of Geology, University of Innsbruck, Innsbruck, Austria
[c] Institute of Earth Sciences, Universidad Austral de Chile, Valdivia, Chile
[d] Centro EULA, Universidad de Concepcion, Concepcion, Chile
[e] Centro CRHIAM, Universidad de Concepción, Concepción, Chile

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A B S T R A C T

We present an exceptionally long and continuous coastal lacustrine record of ~5500 years from Lake Huelde on the west coast of Chiloé Island in south central Chile. The study area is located within the rupture zone of the giant 1960 CE Great Chilean Earthquake (M_W 9.5). The subsequent earthquake-induced tsunami inundated Lake Huelde and deposited mud rip-up clasts, massive sand and a mud cap in the lake. Long sediment cores from 8 core sites within Lake Huelde reveal 16 additional sandy layers in the 5500 year long record. The sandy layers share sedimentological similarities with the deposit of the 1960 CE tsunami and other coastal lake tsunami deposits elsewhere. On the basis of general and site-specific criteria we interpret the sandy layers as tsunami deposits. Age-control is provided by four different methods, 1) ^{210}Pb-dating, 2) the identification of the ^{137}Cs-peak, 3) an infrared stimulated luminescence (IRSL) date and 4) 22 radiocarbon dates. The ages of each tsunami deposit are modelled using the Bayesian statistic tools of OxCal and Bacon. The record from Lake Huelde matches the 8 regionally known tsunami deposits from documented history and geological evidence from the last ~2000 years without over- or underrepresentation. We extend the existing tsunami history by 9 tsunami deposits. We discuss the advantages and disadvantages of various sedimentary environments for tsunami deposition and preservation, e.g. we find that Lake Huelde is 2–3 times less sensitive to relative sea-level change in comparison to coastal marshes in the same region.

1. Introduction

The timespan of tsunami records is often limited to a couple centuries, which is the primary cause for underestimation of tsunami risk (e.g. Kagan and Jackson, 2013). Ideal sources of information about tsunamis are continuous and direct physical measurements of the wave and inundation, e.g. pressure sensors at the ocean floor, tidal gauges at the coast, videometric analyses of the inundation etc. (e.g. Fritz et al., 2012). These instrumental records provide highly detailed information on tsunami flow characteristics. The earliest instrumental records are tide gauge records, but they only exist since the mid-19th century (Scheffers and Kelletat, 2003). Historical records are the next best source of information in terms of both timing and size of tsunamis. Some historical records around the eastern Mediterranean Sea give evidence of a tsunami as early as ~1500 BCE (Antonopoulos, 1979), however, the longest continuous historical record from a subduction zone coastline is from Japan and covers 1300 years (Ando, 1975). This is contrasted by the relatively short historical records of the rest of the coastal areas around the Pacific and along the Sunda Trench, which cover fewer than 500 years or have large time gaps (e.g. Dominey-Howes et al., 2007; Lomnitz, 2004, 1970). With respect to the centennial- or even millennial-scale of recurrence times of earthquake-induced tsunamis most local historical records only report three or fewer tsunamis.

Onshore sedimentary records have proven useful on coasts of the Pacific (Atwater, 1987; Cisternas et al., 2017, 2005; Garrett et al., 2016; Sawai et al., 2009) and the Sunda Arc (Jankaew et al., 2008) to extend the tsunami history further back in time. The catalogue of

* Corresponding author.

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known tsunamis has been expanded widely with the now firmly established method of trench-digging and gouge-coring in coastal marshes (e.g. Nelson et al., 2015) or beach swales (e.g. Brill et al., 2011). However, the sedimentary environment of swales and marshes is very dynamic. Post-depositional processes may alter or erode tsunami deposits and marshes and beach swales often lack accommodation space, which can affect tsunami deposit preservation (Szczuciński, 2012). In comparison, coastal lakes are not restricted in accommodation space and the post-depositional processes are limited (Sugawara et al., 2008). Suitable lacustrine records are rare, but lacustrine sedimentary archives can reliably record tsunami inundations for several millennia and provide excellent material for paleotsunami research (e.g. Kelsey et al., 2005). The relatively stable sedimentation rates in lakes improve the accuracy of age-depth models, which improves age control of tsunami deposits.

Here, we present the sedimentary record from coastal Lake Huelde in south central Chile, containing 17 well-dated sandy layers, which we interpret as tsunami deposits. We discuss the correlation of the tsunami deposits to regionally known tsunamis and extend the regional tsunami history by ~3500 years, i.e. 9 previously not documented tsunami deposits, back to ~5500 cal years BP.

2. Setting

The study area is located on the southern west coast of South America. This is one of the most tsunami-prone regions on Earth, because of the seismicity associated with the Peru-Chile Subduction Zone (PCSZ). In the PCSZ the oceanic Nazca Plate is being subducted underneath the overriding South America Plate (Angermann et al., 1999). The on-going subduction process results in strong seismic activity and in a major volcanic arc system, the Southern Volcanic Zone (Fig. 1).

Lake Huelde (74.11° E, 42.59° S) is a small (1.49 km^2) coastal lake on the west coast of Chiloé Island in south central Chile (Fig. 1). It is located 1.1 km inland from the Pacific Ocean and separated by beach, dunes and freshwater marshes. The lake basin is surrounded by glaciofluvial terraces at ~45 m altitude. Like most purely freshwater lakes on Chiloé Island, Lake Huelde is a humic lake (cf. Villalobos et al., 2003). It is polymictic and does not freeze over in winter.

Lake Huelde is located in the central part of the rupture zone of the 1960 CE Great Chilean Earthquake (M_W 9.5) (Fig. 1) (Moreno et al., 2009). The earthquake induced a large tsunami (Sievers et al., 1963), which inundated Lake Huelde through the outlet river channel and by spilling over the barrier (Kempf et al., 2015). Beyond the 1960 CE earthquake, the historical record in south central Chile reports strong earthquakes in 1837 CE, 1737 CE and 1575 CE (Cisternas et al., 2005; Lomnitz, 2004, 1970), for which the 1737 CE event has neither written nor geological evidence of a tsunami. Multiple studies extend the sedimentary record by two large-scale earthquakes and tsunamis in 1319 CE ± 9 and 1127 CE ± 44 (Cisternas et al., 2017, 2005; Garrett et al., 2015; Moernaut et al., 2014). A record from Maullín (Fig. 1) of co-seismic subsidence and tsunami deposits introduces four additional, otherwise not described events from AD 1 to 1127 CE and infers a mean recurrence time of ~285 years (Cisternas et al., 2005).

3. Methods

3.1. Acoustic imaging

Cores of lake sediments only become meaningful in their

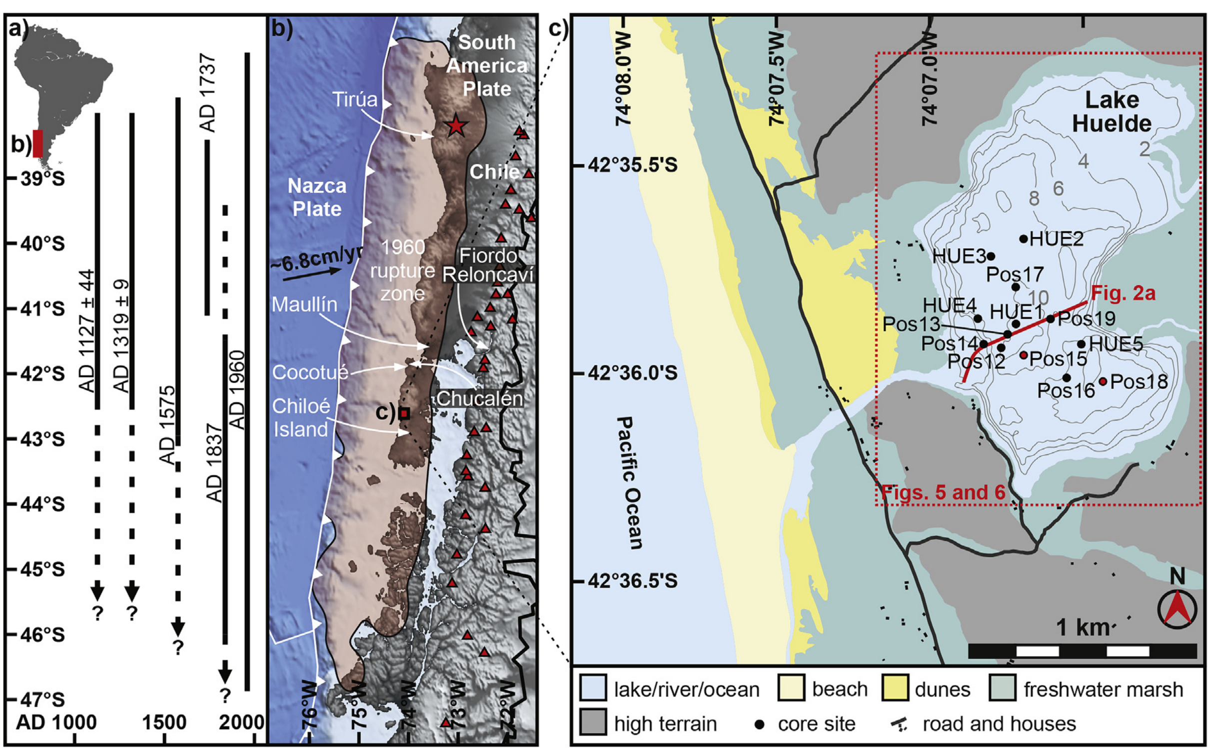

Fig. 1. a) Overview map of the study area with rupture lengths of past megathrust earthquakes. b) The 1960 CE earthquake rupture zone (>1 m slip contour) is represented by a red semi-transparent overlay (Moreno et al., 2009) and the epicentre as a red star. Volcanoes are represented by red triangles. The direction and rate of tectonic convergence are indicated by the black arrow after Angermann et al. (1999). The digital elevation model is an ETOPO1 dataset (Amante and Eakins, 2009). c) Physiographic map of the study area with core locations (black dots) from Lake Huelde. The cores used for the master core are highlighted (red dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)