Title

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

Authors

Philipp Kempf 1, Jasper Moernaut 2,3, Maarten Van Daele 1, Willem Vandoorne 1, Mario Pino 3, Roberto Urrutia 4,5 Marc De Batist 1

- 1) Renard Centre of Marine Geology, Ghent University, Ghent, Belgium
- 2) Institute of Geology, University of Innsbruck, Innsbruck, Austria
- 3) Institute of Earth Sciences, Universidad Austral de Chile, Valdivia, Chile
- 4) Centro EULA, Universidad de Concepcion, Concepcion, Chile
- 5) Centro CRHIAM, Universidad de Concepción, Concepción, Chile

Abstract

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 AD 1960 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 AD 1960 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 to 3 times less sensitive to relative sea-level change in comparison to coastal marshes in the same region.

Keywords

Holocene; Natural Hazards; Tsunami; Sea Level Changes; South America; Chile; Sedimentology, lakes, lagoons & swamps; age-depth modelling;

Contributions

All authors have read, contributed to and approved the final version of this manuscript. The respective role of the authors is as follows:

PK, JM, MDB and MVD wrote the manuscript. JM, MDB and PK developed the scientific concept. PK, JM, WV and MVD conducted fieldwork. PK did lab work on sediment, analysed all data and made figures. RU and MP contributed their expertise to improve the manuscript and facilitated fieldwork.

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 BC (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 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 km²) 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 AD 1960 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 AD 1960 earthquake, the historical record in south central Chile reports strong earthquakes in AD 1837, AD 1737 and AD 1575 (Cisternas et al., 2005; Lomnitz, 2004, 1970), for which the AD 1737 event has neither written nor geological evidence of a tsunami. Multiple studies extend the sedimentary record by two large-scale earthquakes and tsunamis in AD 1319 ± 9 and AD 1127 ± 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 AD 1127 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 sedimentary context. To understand this context we collected high-resolution reflection seismic and side scan sonar data from Lake Huelde.

High-resolution seismic reflection profiles were acquired, using a 3.5 kHz GeoAcoustics GeoPulse sub-bottom profiler. In total, 31 seismic lines (total length: ~20 km) were shot with a line spacing of 150-200 m. These seismic data image the stratigraphy of the lacustrine sediment infill at a vertical resolution of 10 to 20 cm. Profiles were processed (bandpass filtering) and interpreted using IHS Kingdom Suite v. 8.8.

The side scan sonar map, which covers the entire lake, was acquired using a Klein3000 side scan sonar, which utilizes frequencies of 100 and 500 kHz and was set to produce a 50 m wide swath. The resulting horizontal resolution is 8 to 40 cm, depending on the swath angle. Positioning was recorded with a Garmin GPS antenna with a 3 m horizontal error. Navigation line smoothening, slant range correction, mosaic selection and bottom-track extraction for a bathymetric map were performed with the SonarWiz.Map v. 4 software (Fig. 2).

3.2 Sediment analysis

In total 40 sediment cores at 13 different core sites recovered in total ~75 m of lake sediment at up to 9 m depth. Each core consists of a Swiss gravity core section at the top for an undisturbed sediment sample of the soft lake floor. Master sequences of long cores are achieved by overlapping 3-m-long UWITEC piston hammer cores that are correlated with the help of distinctive sedimentary patterns (e.g. tephra layers). The inner core diameter of both gravity and piston hammer cores is 6.0 cm. All cores were analysed with a Geotek multi sensor core logger (MSCL) measuring γ -ray attenuation density and magnetic susceptibility at 2 mm sampling intervals. High-resolution split core surface images were taken with a line scan camera mounted on the MSCL. Several cores were CT-scanned with a Siemens Flash medical CT-Scanner with a voxel size of $\sim 0.15 \text{ mm} \times 0.15 \text{ mm} \times 0.6 \text{ mm}$ (xyz). To define sedimentary facies, the sediment was analysed for the type of organic content in smear-slides and for the type of mineral content in thin-sections. Laser granulometry was performed with a Malvern Mastersizer 2000 after treatment with hydrogen peroxide (2 ml, 35 %) to dissolve the organic content, nitric acid (1 ml, 10 %) to dissolve the calcareous content and sodium hexametaphosphate (300 mg) to prevent grain flocculation. The organic content was estimated using loss on ignition after Heiri et al. (2001). The results of these analyses facilitated sediment description,

correlation and interpretation, which are visualised in the core logs. Varve-counting was executed by two researchers, independently from another, performing three counts each on the exact same sections of high-resolution core surface images in combination with X-ray CT-scan images. The derived accumulation rates are reported in accordance to Zolitschka et al. (2015) with a 2σ error margin.

3.3 Sediment chronology

Age control in the sediment record is concentrated on a composite master-core, which is representative for the entire recovered stratigraphy of Lake Huelde. The master-core consists of core site Pos15 and the lowest part of Pos18 (Fig. 3). The two cores are conjoined at a very distinctive stratigraphic position, i.e. at the lower contact of sandy layer hN.

In order to date the master-core and ultimately to date sandy layers, we applied several dating techniques. The uppermost sandy layer was identified as the tsunami deposit of the AD 1960 Great Chilean Earthquake tsunami by locating the ^{137}Cs peak of the mid-1960s at ~5 cm above the tsunami deposit and by an accumulation rate model based on excess ^{210}Pb that dates the sediment immediately above the tsunami deposit to $\text{AD } 1961 \pm 5$ years (Kempf et al., 2015).

Feldspar grains from a sandy layer underneath the AD 1960 deposit was dated using infrared stimulated luminescence (IRSL) to $\text{AD } 1839 \pm 20$ years (Messens, 2014). We interpret the sand to be deposited by the AD 1837 tsunami, which provides age-depth information for the core's age-depth relationship.

All other age-depth information below depths of ~1 m is based on 22 radiocarbon dates (Tab. 1). The radiocarbon samples were retrieved from gyttja deposited independently from sandy layers, which will be interpreted as tsunami deposits in section 5.2. The samples were chosen at depths close to, but definitely clear from, sandy layers as to minimize interpolation errors and the likelihood of dating reworked material, respectively. To retrieve datable material, we sieved 1 cm slices (in some cases more) of lake sediment with a $250\text{ }\mu\text{m}$ mesh and picked terrestrial plant fragments from the residue, such as seeds, culms and leaves until enough organic material was collected for a radiocarbon sample (~2 mg). The radiocarbon samples were analysed at the ^{14}C Chrono Centre for Climate, the Environment, and Chronology at Queen's University, Belfast.

3.4 Age-depth modelling

We applied the age-depth information to two age-depth model algorithms to avoid algorithm-specific artefacts. One of two age-depth models presented here is calculated with an R-based algorithm called Bacon (Blaauw and Christen, 2011). Bacon uses Bayesian statistics to reconstruct the accumulation history by combining radiocarbon dates and calibrated age-information with prior information, e.g. accumulation rate and the variability thereof.

Bacon divides the core into 100 to 200 sections and through Markov Chain Monte Carlo (MCMC) iterations estimates the accumulation rate for each section. Combined with the age-depth information these accumulation rates then form the age-depth model. Intervals of extremely high accumulation rates, e.g. tsunami deposits, can be treated as instantaneously deposited layers. A time interval of non-deposition or erosion can be inserted into the model as a hiatus. The age-depth model quantifies the modelled duration of the hiatus with a probability density function (PDF). The model allows extraction of age-distributions for any section. This way the probabilistic character of radiocarbon dates and age-depth modelling is not lost in the process. The Bacon age-depth model is used for the regional correlation of tsunami deposits.

The other age-depth model was calculated using a P_Sequence in OxCal v.4.2 (Bronk Ramsey, 2008) with a k-variable of 0.3 (Bronk Ramsey and Lee, 2013). The tsunami deposits were removed from the master core log for age-depth modelling purposes. The age-depth model code includes R_Date()- and Date()-functions for all age-depth information. The age-depth model is then computed in similar fashion to the Bacon algorithm using Bayesian statistics and MCMC iterations. Ages of sandy layers were extracted within OxCal using the Date()-function.

4 Results

4.1 Lake Huelde acoustic imagery

Lake Huelde consists of two sub-basins, a small one in the south-western part, and the bigger one in the central and northern part of the lake. A small stream enters the lake from the east and Lake Huelde discharges in the southwest towards the ocean at all times. Lake Huelde is currently a freshwater lake, implying that there is currently no tidal influx of saline water from the Pacific during high tide. The deepest part of Lake Huelde is 11 m deep.

Lake Huelde sub-bottom profiles show a flat plateau at ~1.5 m at the western part of the lake at the outlet river. An instrument-specific ringing artefact disturbs the acoustic signal on the plateau, because of shallow water depth. The plateau has a wedge-shaped geometry with a lower reflector at burial depths between 1.5 and 6 m dipping towards the lake basin at ~2° (Fig. 2a). Side scan sonar data reveals that the surface of the plateau is featureless except for a channel in the south, where it cuts

across the plateau from the mouth of the outlet towards the lake basin in WNW to ESE direction (Figs. 2b and c). The plateau's slope towards the basin is steep (7.5–12°). In some areas the slope failed in intact rotated sediment blocks with confined compressional toes at the foot of the slope. The slide scars are visible on the lake floor as 30–50 m long and 1–3 m wide curved features with along-slope orientation.

Side scan sonar data show a lobe-shaped area with high reflectivity in the lake basin, adjacent and eastward of the cross cutting channel. The lobate area is 250 m long and 150 m wide and extends into the deepest parts of the lake basin. Scattered on and around this lobate area are high-reflectivity spots of irregular jagged shapes. Lobe and irregular bright spots were interpreted as traces of the AD 1960 tsunami inundation to Lake Huelde (Kempf et al., 2015). The high reflectivity of the lobe is interpreted to be due to acoustic swaths penetration of the side scan sonar signal through the acoustically nearly transparent surface sediments and reflection by the sandy AD 1960 tsunami deposit. The scattered bright spots are most likely plants uprooted on the barrier, washed together and deposited at the lake floor surface, because some of the anchors on recovery caught onshore plants during fieldwork.

The amplitude of Lake Huelde's basin floor reflection is exceptionally low on sub-bottom profiles. The topmost 0.2 to 0.4 m of basin sediment are acoustically almost transparent. This topmost layer is relatively smooth and drapes over a hummocky lower contact reflection in the west, which transitions to a flat reflection in the east. At the base of the uppermost layer the acoustic signature changes from nearly transparent at the top to almost entirely opaque below. Biogenic gas in the sediment often prevents acoustic penetration beyond the uppermost high-amplitude reflection, which was interpreted as being caused by the AD 1960 tsunami deposit (Kempf et al., 2015). However, a few acoustic windows allow imaging of numerous buried high-amplitude reflections, similar to the uppermost high-amplitude reflection, within acoustically nearly transparent sediment, similar to the uppermost 0.2 to 0.4 m of sediment in the lake basin (Fig. 2a). In total, we count 9 distinct high-amplitude reflections. Unfortunately, the acoustic penetration to greater depths is so fragmentary, that widespread correlation across sub-bottom profiles and to sediment cores is not possible.

4.2 Lake Huelde sedimentary facies

The sedimentary sequence retrieved in the cores from Lake Huelde consists of three different facies associations. Two of them consist of multiple facies (Figs. 3 and 4).

4.2.1 Gyttja

More than 85 % of Lake Huelde's sediment consists of gyttja as is typical for humic lakes on Chiloé Island (Villalobos et al., 2003). The gyttja is dark brown in

colour and composed of silt, diatoms and a wide range of particles of organic matter, e.g. seeds, pollen, multicellular algae, leaves and other plant fragments. All radiocarbon samples were sieved from sediment of this facies association. The magnetic susceptibility of the gyttja is low, with values usually between 0 and 30×10^{-5} SI with peaks as high as 50×10^{-5} SI. The inorganic particles of the gyttja are poorly to very poorly sorted with a median grain size of $15 \mu\text{m}$ ($\phi = 6.06$). In the uppermost and therefore least consolidated parts of the gyttja contain up to 80 wt% of water. Dry sediment consists of 25 to 40 wt% organic matter. There are two facies of gyttja. The more abundant facies is homogenous and for the most part featureless, except for very sporadic leaves or other plant macro-remains. The other facies consists of intervals of finely (1–3 mm) laminated gyttja (Fig. 4a). The laminae consist of couplets of dark brown layers and yellowish grey layers. The laminated intervals always have a sandy layer (described below) at their basal contact. Towards the top, the laminae gradually fade into homogenous gyttja.

4.2.2 Volcanic ash

Sporadically, the gyttja-dominated stratigraphy incorporates thin (0.1–0.5 cm) grey layers (Fig. 3). Their relative abundance in the sedimentary record of Lake Huelde is below 1 % of the entire stratigraphy. The thin layers lack the organic content of the gyttja. Silty, transparent and amorphous shards (glass) make up almost the entire mineral content. They occur either as singular layers or in groups of two or three (Fig. 4b). Their distribution within the stratigraphy is concentrated in the lower half of the sedimentary record. The thin grey layers often form a distinct stratigraphic pattern, which appears to be identical in the entire lake basin. Their basin-wide distribution makes them a useful tool for core-to-core correlation (Fig. 3). Because of the amorphous mineral content and the fine grain size, we interpret these thin grey layers as tephra, i.e. volcanic ash. They are interpreted as wind transported ashes from eruptions of the volcanoes east of the study area, e.g. Chaitén.

4.2.3 Sandy layers

Sandy layers interrupt the gyttja-dominated sediment frequently. In general, the sandy layers contain three sediment facies, which occur in specific sequences, described here in stratigraphic order from bottom to top (Fig. 4c).

- i) Mud rip-up clasts in a sandy matrix – The mud clasts have varied sizes from 0.5 cm to larger than core diameter (6 cm). The clasts are dark brown, identical to the gyttja described above, and their shape is angular. They can occur singularly or arranged in thick layers. The matrix between the mud clasts is well-sorted medium sand with median grain sizes of $\sim 205 \mu\text{m}$ ($\phi = 2.29$). The mud clasts predominantly occur in cores closest to the river outlet on the western side of Lake Huelde. Magnetic susceptibility on intervals with mud clasts is high variable, which is due to the two different

materials that can be measured (gyttja of the mud clasts vs. the sand of the matrix). The lower contact of this facies is sometimes erosional. Maximum magnetic susceptibilities are extremely high ($>1000 \times 10^{-5}$ SI). Because of their angular shape and the material, they are interpreted as mud rip-up clasts in a sandy matrix.

- ii) Massive sand – Intervals of massive, well to moderately well sorted sand is the most abundant facies within the facies association of sandy layers. Some intervals can contain finely dispersed organic material, which can give the interval a brown colour; otherwise the intervals of massive sand are grey. The sand consists of a variety of minerals. The most abundant minerals are orthoclase, plagioclase, quartz, iron oxides epidote and hornblende. In mineral content, magnetic susceptibility and grain size the massive sand is identical to the sand in the matrix between the mud rip-up clasts. Massive sand is often the lowermost facies in a sandy layer and its lower contact can be erosional.
- iii) Mud caps – This facies consists of brown mud. The brown colour of this silty mud grades from dark to light brown and is in general lighter than the brown of the gyttja, however the hue is similar. The layers are between 0.2 cm and 5 cm thick and their magnetic susceptibility is low ($<50 \times 10^{-5}$ SI). These mud layers comprise the stratigraphic top in the general sedimentary sequence of sandy layers, which is why we interpret them as mud caps.

All three facies together comprise a full sequence. Sandy layers may consist of multiple complete sequences of all three facies, of only a singular sedimentary sequence of a sandy layer or only one or more subsets thereof. There are 17 separate sandy layers in the Lake Huelde sedimentary record. We label the sandy layers with the prefix "h" for "Huelde" followed by a capital letter running in alphabetical order down the stratigraphic order.

The uppermost sandy layer (hA) was interpreted as the AD 1960 tsunami deposit by Kempf et al. (2015), where these facies were described in detail. The sandy layers vary strongly in their lateral extent, thickness, maximum and average magnetic susceptibility from core to core and from sandy layer to sandy layer (Figs. 5 and 6, Tab. 2). They are between 0.5 and 130 cm thick and their maximum magnetic susceptibility ranges from 92×10^{-5} SI to 3791×10^{-5} SI. Some sandy layers, e.g. AD 1960 or hJ, become thinner and show a decreasing magnetic susceptibility towards the northeast (Fig. 5); others, e.g. hN, show no spatial trend in deposit thickness or maximum magnetic susceptibility. Some sandy layers, e.g. hK, are overall thin and have relatively low magnetic susceptibility, yet are represented basin wide at all core sites; while others, e.g. hD, are relatively thick with a high magnetic susceptibility, yet they are spatially confined to only a few core sites in the proximal area. The overall variability of these sandy layers is striking.

5 Discussion

5.1 Core chronology

The age-depth model outputs of both algorithms (Bacon and OxCal) agree with each other to a large extent (Figs. 7 and 8). Model-specific artefacts, if they exist in the presented age-depth relationships, are therefore considered negligible.

The age-depth models of the master core put the depths of the 10.5 m long master-core into relation with ages from 5515 ± 140 cal. years BP at the bottom to -62 cal. years BP (AD 2012) at the top. As lower contacts of sandy layers can be erosional, we considered the possibility of hiatuses in the sediment stratigraphy of the master-core. However, only one erosional hiatus was detected, because all other hiatuses, if they exist, are below the temporal resolution of the age-depth models. The hiatus is located between the AD 1960 tsunami deposit and the sandy layer hB (later identified as the AD 1837 tsunami deposit). This hiatus is present at most, but not all core sites, e.g. core site Pos13 (Fig. 3).

The average sedimentation rate over the entire master core is 1.55 mm yr^{-1} with moderate variability (less than one order of magnitude), if sandy layers are neglected. The layer thickness (1–2 mm) in finely laminated intervals suggests that the fine laminae may be deposited annually, because it fits the average sedimentation rate (1.55 mm yr^{-1}). The laminae also share exceptional visual resemblance to annually deposited layers (i.e. varves) in Bradley Lake, a humic coastal lake in Cascadia (Kelsey et al., 2005). Strong seasonality in south central Chile, with wet, cold winters and dry, warm summers (Bertrand et al., 2014) has been described to cause annually laminated deposits in Lake Puyehue, ~ 200 km north of Lake Huelde (Fagel et al., 2007).

We suspect that saline bottom water, which remains in Lake Huelde for several decades after a tsunami inundation, controls the fine lamination. The saline bottom water is protected from efficient mixing, because of the very limited inflow from the river and the limited range of wind waves in the small Lake Huelde. As long as the lake remains strongly stratified, anoxic conditions allow seasonal variations to be preserved as varves. The saline bottom water is only slowly replaced by freshwater, which would explain the gradual fading of the fine laminae. Saline bottom water was observed several decades after a tsunami inundation in Lake Budi in Chile (Wallner, 2008) and Bradley Lake in Cascadia (Kelsey et al., 2005), which is consistent with the amount of visible varves in Lake Huelde.

Three intervals of finely laminated gyttja above sandy layers hJ, hK and hM (Fig. 4a) are tentatively interpreted as being annually laminated (i.e. varves) and were varve-counted. The sedimentation rate produced by the Bacon age-depth model can be compared with the varve-counted sedimentation rate at the same depth as an independent control. Pairs of modelled and varve-counted accumulation rates above sandy layers hJ (modelled: 2.47 mm yr^{-1} ; varve-counted: $3.37 \pm 0.27 \text{ mm yr}^{-1}$), hK

(modelled: 1.73 mm yr^{-1} ; varve-counted: $1.57 \pm 0.09 \text{ mm yr}^{-1}$) and hM (modelled: 1.52 mm yr^{-1} ; varve-counted: $1.93 \pm 0.25 \text{ mm yr}^{-1}$) show similar variation. The accumulation rate variations in the age-depth models are thereby independently confirmed and do not stem from naturally or artificially contaminated radiocarbon samples. At the same time, the annual character of the laminations could be confirmed, too.

5.2 Criteria for tsunami deposit interpretation

We correlate the sandy layers in sediment cores with the high-amplitude reflections on sub-bottom profiles, due to the contrast of acoustic impedance of sandy deposits to gyttja, and we correlate the gyttja with the acoustically nearly transparent intervals between the high-amplitude reflections. We hypothesize that all of the described sandy layers are tsunami deposits, because they share sedimentary characteristics with the uppermost sandy layer, which was identified as the AD 1960 tsunami deposit (Kempf et al., 2015). To support the tsunami deposit interpretation we discuss the following criteria; they are not stand-alone criteria, however, together these criteria make a good case for tsunami deposition and can be used to exclude other causative processes, if fulfilled.

i) High magnetic susceptibility – The mineral content in the sediment cores controls the magnetic susceptibility. The sedimentary surrounding of Lake Huelde consists of glaciofluvial terraces in the north, east and south (Glasser et al., 2008). The glaciofluvial terraces are sourced from metamorphic rocks of the Palaeozoic and Triassic Cordillera de Pirulil (a part of Chile's Coastal Cordillera) to the east of the study area (SERNAGEOMIN, 2003). Dunes and beaches dominate the sediment to the west of the lake. All source sediments have high magnetic susceptibilities (Kempf et al., 2015), while the lacustrine sediment, i.e. gyttja, has a low magnetic susceptibility. High magnetic susceptibility in lake sediment therefore means that there is an increased input of a terrigenous fraction from outside of the lake. This is a site-specific criterion for recognizing a deposit with sediment sources outside of Lake Huelde. This criterion cannot be translated to other regions without prior investigation of the study area.

ii) Traceability in the sedimentary record – Tsunamis are typically large-scale inundations, which interrupt the normal lake sediment accumulation. Tsunami deposits on land are often described as quasi-continuous deposits, which wedge out towards their maximum lateral extent with a high degree of variability in thickness (e.g. Goto et al., 2014; Richmond et al., 2012). In lakes, tsunamis can erode the typically muddy lacustrine sediment and can transport the fine-grained fraction suspension load beyond the extent of sandy deposition (Kelsey et al., 2005; Kempf et al., 2015). Therefore tsunami deposits should be traceable throughout large parts of

the Lake Huelde. Therefore, we consider representation in most parts of the lake basin indicative of tsunami origin.

iii) Mud rip-up clasts – Short-lived extreme flow conditions in otherwise low flow energy environments have the potential to erode fine-grained and cohesive sediment in bulk pieces. These pieces are called mud rip-up clasts and tsunamis are one of the few processes that may generate them (e.g. Bondevik et al., 1997; Peters et al., 2007), together with a range of mass transport processes (e.g. Lee et al., 2013) and storm surges (e.g. Phantu Wongraj et al., 2013). Large-scale mass transport processes can be excluded, because of the lack of long or steep slopes in the comparatively small and shallow Lake Huelde.

iv) Overlaying finely laminated gyttja – Tsunami inundations are violent interruptions to the normal state of the sedimentary lacustrine environment. In contrast to processes that are confined to the lake basin, e.g. flood turbidites or subaqueous landslides, tsunamis introduce a significant amount of saline water to the lake, which can enforce a stable stratification of the water column for several decades (e.g. Kelsey et al., 2005; Wallner, 2008). Subsequent changes in the sedimentation pattern can be ascribed to the sudden impact that a tsunami can have on the lacustrine environment. We use overlaying finely laminated gyttja as an indication of this process and as a criterion for large wave inundation of marine water, i.e. a tsunami.

v) Age-correlation – The AD 1960 tsunami deposit in Lake Huelde was identified through precise dating (Kempf et al., 2015). Megathrust earthquake-induced tsunamis usually hit coastlines of a 100 km or more (e.g. Fritz et al., 2011; Mori et al., 2011). Accordingly, if older sandy layers in Lake Huelde coincide chronologically with regionally known tsunami deposits, then a correlation across study areas seems likely. This criterion can only be applied to sandy layers of an equal or younger age than the oldest regionally known tsunami deposits. For south central Chile, tsunami deposits are known for the last ~2000 years (Cisternas et al., 2005).

We can exclude large river floods as a cause for sandy layers, because core sites Pos17 and Pos19 (closest to the river inlet) contain the least complete record of sandy layers. Furthermore, sandy layers in Lake Huelde are finest at core sites Pos17 and Pos19, which disagrees with the understanding that sandy flood turbidites typically become finer with distance from the source (cf. Wilhelm et al., 2015).

The criteria listed above are also indicative of storm surge deposits. Generally, the differentiation between storm surge and tsunami deposits is a difficult issue at most subduction zone coastlines. There is little data about storm surges or the deposits thereof in Chile. The few sites that have been studied, however, are confined to beaches under persistent stormy conditions, located ca. 1500 km further to the North (May et al., 2013). This makes strong winter storms an unlikely source for the large

wave event deposits. At our study site, we bypass this differentiation problem of hurricane-type storm surges, because tropical cyclones, which could have the potential to produce a deposit more than 1 km inland, do not occur on the western South American coast – not even under more favourable El Niño conditions (Fedorov et al., 2010). Fulfilling the above-listed criteria is therefore treated as indicative for tsunami origin only. Confidence in the tsunami interpretation depends on the degree to which the criteria are fulfilled (Tab. 2).

Eventually, we interpret all sandy layers to be tsunami deposits. We interpret 10 sandy layers (AD 1960, AD 1837, hE, hG, hH, hJ, hK, hM, hN and hQ) as tsunami deposits with a high level of confidence. All 10 sandy layers fulfil at least three of the above-defined criteria (Tab. 3). Six sandy layers are interpreted as tsunami deposits with medium level confidence (AD 1575, hD, hF, hI, hO and hP). They fulfil at least two of the applicable criteria. Only 1 of the 17 sandy layers (hL) fulfils none of the criteria fully. With the variability of tsunami deposits in mind, this interpretation is speculative. However, by analogy to the other sandy layers the tsunami interpretation is the most plausible, especially considering the absence of competing and plausible explanations.

5.3 Regional historical, paleoseismic and paleotsunami records

In AD 1960, the Great Chilean Earthquake (M_w 9.5) with its rupture zone mostly offshore (Moreno et al., 2009), triggered a tsunami with up to 20 m wave height along the coast (Sievers et al., 1963). The tsunami caused vast damage and casualties in both near-field and far-field areas (e.g. Lander and Lockridge, 1989). Tsunami deposits of the AD 1960 event are described along the central and northern part of the rupture zone, including on Chiloé Island (Fig. 1 and 9) (Atwater et al., 2013; Cisternas et al., 2005; Ely et al., 2014; Garrett et al., 2013). Lake Huelde was inundated by the AD 1960 tsunami through the outlet river channel and by barrier overspill (Kempf et al., 2015).

The historical and sedimentary records describe a tsunamigenic earthquake in AD 1837 with a speculated rupture zone in the southern half of the 1960 rupture zone (Cisternas et al., 2017, 2005; Garrett et al., 2015; Lomnitz, 2004, 1970; Moernaut et al., 2014). The subsequent tsunami damaged buildings on Chiloé Island and in far-field regions (Lomnitz, 2004, 1970), e.g. in Hawaii (Lander and Lockridge, 1989) and Japan (Cisternas et al., 2005), and deposited a sand layer on top of a earthquake-trigger landslide in Cocotué on north-western Chiloé Island (Cisternas et al., 2017). IRSR dating of the basal sand of the uppermost package of tsunami deposits at core site Pos12 produced an age of AD 1839 $\pm$ 20. This suggests that the AD 1837 tsunami reached and deposited sand in Lake Huelde (Tab. 3) and that the 1960 tsunami eroded

the post-1837 sediment at core site Pos12 (and in all other cores, except in core Pos13), where the sand was IRSL-dated (Messens, 2014).

The AD 1575 earthquake and tsunami are known from the historical record (Cisternas et al., 2005; Lomnitz, 2004, 1970). The seismic shaking was recorded in the form of seismoturbidites in at least three Chilean lakes (Moernaut et al., 2014) and in Fiordo Reloncaví (St-Onge et al., 2012). Tsunami deposits recorded inundation in coastal lowlands in Cocotué (Cisternas et al., 2017), Chucalén (Garrett et al., 2015), Maullín (Cisternas et al., 2005) and in Tirúa (Ely et al., 2014) (Fig. 1). Co-seismic subsidence in Tirúa was evidenced by changes in diatom assemblage (Ely et al., 2014). All lines of evidence show that the effect and size of the AD 1575 rupture were comparable with the AD 1960 M_w 9.5 earthquake, except for a potential lack of co-seismic subsidence at Chucalén (Garrett et al., 2015) and the current absence of evidence for a far-field tsunami in Japan (e.g. Ando, 1975; Garrett et al., 2016). One tsunami deposit in the Lake Huelde record is dated to AD 1467 to AD 1647 (median AD 1553) overlapping the AD 1575 event (Figs. 7, 8 and 9; Tabs. 2 and 3).

Sudden subsidence events, indications for seismic shaking and/or tsunami deposits in coastal lowlands suggest four megathrust earthquakes and tsunamis (event D, C, bc1 and bc2 after Cisternas et al. 2005, 2017) occurred after AD 1100 and before the beginning of historical documents in AD 1541 (Cisternas et al., 2017, 2005; Garrett et al., 2015). Correlated and varve-dated lacustrine seismoturbidites produced by strong shaking pinpoint the ages of two earthquakes to $AD\ 1319 \pm 9$ and $AD\ 1127 \pm 44$ (Moernaut et al., 2014). Both events appear to be represented in the Lake Huelde record as tsunami deposits (tsunami deposits hE and hD, Figs. 3 and 9). Two tsunami deposits older than AD 1127 are described in Maullín (events E and G), to each of which we can correlate a tsunami deposit in Lake Huelde (tsunami deposits hF and hG), with associated modelled ages of 1250 ± 50 and 1690 ± 90 cal. years BP, respectively. Another tsunami deposit from Lake Huelde (tsunami deposit hH, 1860 ± 80 years BP) matches a co-seismic subsidence event (event H) with existing but questionable evidence of tsunami deposition in Maullín (Cisternas et al., 2005; pers. comm.). Only one co-seismic subsidence event (event F) described in Maullín (no tsunami deposit reported) has no match in the Lake Huelde record (Fig. 9).

All discussed tsunami deposits have evidence of seismic shaking or co-seismic deformation on the Chilean coast. This means that none of the discussed events from ~2000 years BP onwards are considered to be induced by a tsunami source other than a Chilean megathrust earthquake or an earthquake on a related fault. Furthermore, truly giant tsunamis from across the Pacific in recent past, e.g. AD 1964 Alaska and AD 2011 Tohoku-oki, have failed to leave a sedimentary trace in Lake Huelde.

Accordingly, we consider far-field sources in the deeper record of Lake Huelde before ~2000 years BP as unlikely.

In summary, Lake Huelde has been a reliable recorder of large-scale tsunamis in the past ~2000 yrs. The Lake Huelde record contains deposits of all three historically known tsunamis in the region, i.e. the AD 1960, AD 1837 and AD 1575 tsunamis. Older tsunami deposits from Lake Huelde, with the exception of two smaller tsunami events (bc1 and bc2) in Cocotué (Cisternas et al., 2017), match all four known prehistoric tsunamis from south central Chile between ~900 cal. years BP and ~2000 cal. yrs. BP and one co-seismic subsidence event in Maullín (event E), to which no tsunami deposit was linked until now. The Lake Huelde record matches the historical and prehistoric record in all major tsunamigenic earthquakes without either over- or underrepresentation for the last ~2000 years (Fig. 9). The correlation of each of these tsunami deposits indicates that during the same time no unmatched and therefore probable storm deposit is known on the south central Chilean coast.

5.4 Extending the regional tsunami history

The general agreement of the presented record with the existing historical, paleoseismic and paleotsunami records projects a high degree of reliability in the older half of the record for which a quality control is unavailable as it goes beyond all previous paleotsunami records in the region. We introduce 9 previously unknown tsunami deposits, namely hI to hQ in Lake Huelde (Tabs. 2 and 3) to the paleotsunami catalogue in south central Chile.

According to the criteria defined in section 5.2, the confidence level of the tsunami interpretation for the lower 9 sandy layers is high for 5, medium for 3 and low for 1. On all purely sedimentological criteria (criteria i to iv) the lower 9 tsunami deposits match the upper 8 tsunami deposits, which are either historically confirmed or confirmed by correlation across multiple study sites.

Since the AD 1837 and 1960 Chilean tsunamis, it is documented that extreme tsunamis originating from the Peru-Chile subduction zone can have a strong impact on coasts as far as ~17000 km away in Japan (Cisternas et al., 2005; Lander and Lockridge, 1989). It remains unclear whether reciprocally similar far-field sources can produce large tsunamis on the Chilean coast; until now no far-field tsunami is known to have caused damage as far south as Chiloé Island.

With 17 tsunami deposits since ~5500 cal. years BP the average tsunami recurrence time is ~325 years. However, the variations in recurrence time are very large. The shortest inter-event period was between hO and hP with only ~60 years (difference of

medians); the longest inter-event period was between hP and hQ with ~760 years (difference of medians). Such strong variation in the inter-event periods makes tsunami hazard assessment a challenging task. The rupture zone of the AD 1960 Great Chilean Earthquake in south central Chile could produce a tsunamigenic earthquake today or in 700 years without shortening the shortest or lengthening the longest recurrence time, respectively, according to the Lake Huelde dataset.

5.5 Potential and limitations of coastal settings for tsunami research

Sandy tsunami deposits have been studied mainly in three different environments, i.e. beach swales, coastal marshes and coastal lakes (e.g. Garrett et al., 2015; Jankaew et al., 2008; Kelsey et al., 2005). These environments have all been demonstrated to record tsunami inundation in various forms and hold valuable information for paleotsunami research (Fig. 10).

Of the three mentioned environments, beach swales are the most proximal to the coast. The normal sediment in beach swales can be sand or sandy soil (e.g. Brill et al., 2011; Jankaew et al., 2008), which does not always offer a strong contrast to tsunami deposits (e.g. Spiske et al., 2013). The paleotsunami records in beach swales often allow both radiocarbon dating (e.g. Jankaew et al., 2008) and optically stimulated luminescence (OSL) dating techniques (e.g. Brill et al., 2012), offering two independent dating methods.

Both beach swales and coastal marshes offer a direct three-dimensional view on the depositional environment, a cost-effective fieldwork and an easy access to tsunami deposits (e.g. Sawai et al., 2009). Coastal marshes have proven to be excellent tsunami recorders in south central Chile (e.g. Dura et al., 2015; Ely et al., 2014; Garrett et al., 2015; Hong et al., 2016). Another compelling argument for using coastal marshes for paleotsunami research is that in addition to tsunami deposits these environments can also record relative sea-level (RSL) changes (Dura et al., 2016b; Garrett et al., 2015). In cases of co-seismic vertical deformation in connection with a tsunami deposit the possibility of a storm surge to be responsible for the large wave event can be considered highly unlikely and the near-field earthquake source of the tsunami can be confirmed (Cisternas et al., 2005; Dura et al., 2016b; Garrett et al., 2015).

Coastal lakes do not allow the easy access to tsunami deposits and a proxy for co-seismic vertical deformation from lake sediments has not been developed yet. However, coastal lakes, when deep enough, like Lake Huelde, often contain a long (>4 ka) and continuous sedimentary record (e.g. Bondevik et al., 1997; Grauert and Bjo, 2001; Hutchinson et al., 2000; Kelsey et al., 2005). The typical sedimentary facies in proximal coastal lakes appear to be similar to tsunami deposits in marshes or swales with sands, mud rip-up clasts, organic-rich layers and mud caps (Bondevik et

al., 1997; Kelsey et al., 2005; Kempf et al., 2015). However, the potential to preserve tsunami deposits that consists of resuspended fine-grained detritus seems higher in coastal lakes than in marshes (cf. Kempf et al., 2015; Szczuciński et al., 2007).

In Lake Huelde, the oldest sediment of the presented record is still lacustrine, which means that the expected underlying estuarine sediments have not been reached. Hence, there is a potential for an even longer tsunami record in Lake Huelde. The presented record surpasses the recovered time span of all other paleotsunami records in south central Chile by ~3500 years. The much longer record contained in this coastal lake, compared to the coastal marsh records can be explained by a lower sensitivity to RSL changes. The early and mid-Holocene (7-5 ka) RSL rise in south central Chile created the accommodation space needed for tsunami deposit preservation in coastal marshes, despite the slowly falling RSL in the past 5000 years (Dura et al., 2016a).

Sedimentary paleotsunami records from coastal marshes in south central Chile are limited to a maximum of ~2000 years BP (Maullín record) (Cisternas et al., 2005), which corresponds to 1 to 3 m of gradual RSL fall (Dura et al., 2016a). In contrast, the oldest tsunami deposit in Lake Huelde is recorded at 5.160 ± 200 years BP, which corresponds to at least (the record was only limited by core penetration depth) 3 to 6.5 m RSL fall, since the first recording and preservation of a tsunami deposit. It appears that the coastal lake environment in Lake Huelde is 2 to 3 times less sensitive to RSL change than the marsh environment in Maullín.

The lower sensitivity to RSL change is probably due to the outlet river channel connecting Lake Huelde with the Pacific Ocean. The AD 1960 tsunami was demonstrated to have overtopped the barrier, but the main pathway for sediment discharge into Lake Huelde was the river channel (Kempf et al., 2015). Smaller tsunamis will still reach the lake by bypassing the barrier through the river channel. The RSL fall since 7–5 ka (Dura et al., 2016a) is expected to have made Lake Huelde less sensitive to tsunami inundation over time. This does not appear to have affected the reliability of the tsunami record, because deposits of all of the youngest 8 historically and geologically known tsunamis were found in the Lake Huelde record without over- and underrepresentation.

In addition to the difference in sensitivity to RSL changes, coastal marshes and lakes exert different post-depositional processes to the tsunami deposit. In a lake basin the post-depositional processes are usually limited to compaction, dissolution by pore water and bioturbation. In beach swales and marshes the same processes are exerted to tsunami deposits, however, the more dynamic sedimentary environment of beach swales and marshes may alter, erode or prevent tsunami deposits, e.g. aeolian erosion, river channel migration or lack of accommodation space, respectively.

If time span and recurrence analyses are the aim of the paleotsunami study we recommend focussing on coastal lake records when and where they are available.

6 Conclusions and summary

We present a paleotsunami record from the coastal Lake Huelde on Chiloé Island, Chile, containing 17 sandy layers, which we interpret as tsunami deposits. The tsunami deposits consist of three facies, i.e. mud rip-up clasts, massive sand and mud caps. For the core chronology we draw information from radionuclide analyses, IRSL-dating and radiocarbon dating. The age-depth information is used in two Bayesian age-depths models, the result of which agree with each other to a large extent (no model specific artefacts). We demonstrate that the 8 youngest tsunami deposits match the 8 youngest historically and geologically known major tsunamis without over- or underrepresentation, which means that Lake Huelde was a reliable recorder of tsunami inundation for the last ~2000 years. With this record we were also able to extend the tsunami history on the AD 1960 Great Chilean Earthquake rupture zone by 9 tsunamis (by ~3500 years) to ~5500 cal. years BP. The average recurrence time of tsunami deposition in Lake Huelde is ~325 years. However, the strong variation in the record (shortest inter-event time is ~60 years; longest is ~760 years) will pose a challenge to tsunami hazard assessment. The advantageous conditions for tsunami deposition and preservation in coastal lakes highlight the high potential of coastal lakes to contain the longest continuous paleotsunami records.

Acknowledgements

PK acknowledges financial support by the Special Research Fund of Ghent University (BOF), JM from the Chilean Fondecyt projects no. 1150346 and 1150321 and from the Swiss National Science Foundation (SNF) grant 133481, MVD from the Research Foundation Flanders (FWO travel grant K201512N). We thank Koen De Rycker and Dr. Gauvain Wiemer for fieldwork support, Dr. Claire Schepens and Dr. Eric Achten for CT-scanner support, Dr. Maarten Blaauw for advice on the age-depth model Bacon, and Dr. Marco Cisternas for constructive criticism on an earlier version of the manuscript. Dr. Witold Szczuciński and an anonymous reviewer are thanked for their constructive criticism.

References

- Amante, C., Eakins, B.W., 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA.
doi:10.7289/V5C8276M
- Ando, M., 1975. Source mechanisms and tectonic significance of historical earthquakes along the nankai trough, Japan. *Tectonophysics* 27, 119–140.
doi:10.1016/0040-1951(75)90102-X
- Angermann, D., Klotz, J., Reigber, C., 1999. Space-geodetic estimation of the nazca-south america euler vector. *Earth and Planetary Science Letters* 171, 329–334.
doi:10.1016/S0012-821X(99)00173-9

- Antonopoulos, J., 1979. Catalogue of tsunamis in the Eastern Mediterranean from antiquity to present times. *Annales Géologiques des Pays Hélieniques* 114–130.
- Atwater, B.F., 1987. Evidence for great holocene earthquakes along the outer coast of Washington State. *Science* 236, 942–944. doi:10.1126/science.236.4804.942
- Atwater, B.F., Cisternas, M., Yulianto, E., Prendergast, A.L., Jankaew, K., Eipert, A.A., Ignatius, W., Fernando, S., Tejakusuma, I., 2013. The 1960 tsunami on beach-ridge plains near Maullín, Chile: Landward descent, renewed breaches, aggraded fans, multiple predecessors. *Andean Geology* 40, 393–418. doi:10.5027/andgeoV40n3-a01
- Bertrand, S., Huguen, K., Sepúlveda, J., Pantoja, S., 2014. Late Holocene covariability of the southern westerlies and sea surface temperature in northern Chilean Patagonia. *Quaternary Science Reviews* 105, 195–208. doi:10.1016/j.quascirev.2014.09.021
- Blaauw, M., Christen, J.A., 2011. Flexible Paleoclimate Age-Depth Models Using an Autoregressive Gamma Process. *Bayesian Analysis* 6, 457–474. doi:10.1214/11-BA618
- Bondevik, S., Inge Svendsen, J., Mangerud, J., 1997. Tsunami sedimentary facies deposited by the Storegga tsunami in shallow marine basins and coastal lakes, western Norway. *Sedimentology* 44, 1115–1131. doi:10.1046/j.1365-3091.1997.d01-63.x
- Brill, D., Brückner, H., Jankaew, K., Kelletat, D., Scheffers, a., Scheffers, S., 2011. Potential predecessors of the 2004 Indian Ocean Tsunami — Sedimentary evidence of extreme wave events at Ban Bang Sak, SW Thailand. *Sedimentary Geology* 239, 146–161. doi:10.1016/j.sedgeo.2011.06.008
- Brill, D., Klasen, N., Jankaew, K., Brückner, H., Kelletat, D., Scheffers, a., Scheffers, S., 2012. Local inundation distances and regional tsunami recurrence in the Indian Ocean inferred from luminescence dating of sandy deposits in Thailand. *Natural Hazards and Earth System Science* 12, 2177–2192. doi:10.5194/nhess-12-2177-2012
- Bronk Ramsey, C., 2008. Deposition models for chronological records. *Quaternary Science Reviews* 27, 42–60. doi:10.1016/j.quascirev.2007.01.019
- Bronk Ramsey, C., Lee, S., 2013. Recent and Planned Developments of the Program OxCal. *Radiocarbon* 55, 720–730.
- Cisternas, M., Atwater, B.F., Torrejón, F., Sawai, Y., Machuca, G., Lagos, M., Eipert, A., Youlton, C., Salgado, I., Kamataki, T., Shishikura, M., Rajendran, C.P., Malik, J.K., Rizal, Y., Husni, M., 2005. Predecessors of the giant 1960 Chile earthquake. *Nature* 437, 404–407. doi:10.1038/nature03943
- Cisternas, M., Garrett, E., Wesson, R., Dura, T., Ely, L.L., 2017. Unusual geologic evidence of coeval seismic shaking and tsunamis shows variability in earthquake size and recurrence in the area of the giant 1960 Chile earthquake. *Marine Geology* 385, 101–113. doi:10.1016/j.margeo.2016.12.007
- Dominey-Howes, D., Cummins, P., Burbidge, D., 2007. Historic records of teletsunami in the Indian Ocean and insights from numerical modelling. *Natural Hazards* 42, 1–17. doi:10.1007/s11069-006-9042-9

- Dura, T., Cisternas, M., Horton, B.P., Ely, L.L., Nelson, A.R., Wesson, R.L., Pilarczyk, J.E., 2015. Coastal evidence for Holocene subduction-zone earthquakes and tsunamis in central Chile. *Quaternary Science Reviews* 113, 93–111. doi:10.1016/j.quascirev.2014.10.015
- Dura, T., Engelhart, S.E., Vacchi, M., Horton, B.P., Kopp, R.E., Peltier, W.R., Bradley, S., 2016a. The Role of Holocene Relative Sea-Level Change in Preserving Records of Subduction Zone Earthquakes. *Current Climate Change Reports* 2, 86–100. doi:10.1007/s40641-016-0041-y
- Dura, T., Hemphill-Haley, E., Sawai, Y., Horton, B.P., 2016b. The application of diatoms to reconstruct the history of subduction zone earthquakes and tsunamis. *Earth-Science Reviews* 152, 181–197. doi:10.1016/j.earscirev.2015.11.017
- Ely, L.L., Cisternas, M., Wesson, R.L., Dura, T., 2014. Five centuries of tsunamis and land-level changes in the overlapping rupture area of the 1960 and 2010 Chilean earthquakes. *Geology* 42, 995–998. doi:10.1130/G35830.1
- Fagel, N., Boës, X., Loutre, M.F., 2007. Climate oscillations evidenced by spectral analysis of Southern Chilean lacustrine sediments: the assessment of ENSO over the last 600 years. *Journal of Paleolimnology* 39, 253–266. doi:10.1007/s10933-007-9116-z
- Fedorov, A. V., Brierley, C.M., Emanuel, K., 2010. Tropical cyclones and permanent El Niño in the early Pliocene epoch. *Nature* 463, 1066–1070. doi:10.1038/nature08831
- Fritz, H.M., Petroff, C.M., Catalán, P. a., Cienfuegos, R., Winckler, P., Kalligeris, N., Weiss, R., Barrientos, S.E., Meneses, G., Valderas-Bermejo, C., Ebeling, C., Papadopoulos, A., Contreras, M., Almar, R., Dominguez, J.C., Synolakis, C.E., 2011. Field Survey of the 27 February 2010 Chile Tsunami. *Pure and Applied Geophysics* 168, 1989–2010. doi:10.1007/s00024-011-0283-5
- Fritz, H.M., Phillips, D.A., Okayasu, A., Shimozone, T., Liu, H., Mohammed, F., Skanavis, V., Synolakis, C.E., Takahashi, T., 2012. The 2011 Japan tsunami current velocity measurements from survivor videos at Kesennuma Bay using LiDAR. *Geophysical Research Letters* 39, 6. doi:10.1029/2011GL050686
- Garrett, E., Fujiwara, O., Garrett, P., Heyvaert, V.M.A., Shishikura, M., Yokoyama, Y., Hubert-Ferrari, A., Brückner, H., Nakamura, A., De Batist, M., 2016. A systematic review of geological evidence for Holocene earthquakes and tsunamis along the Nankai-Suruga Trough, Japan. *Earth-Science Reviews* 159, 337–357. doi:10.1016/j.earscirev.2016.06.011
- Garrett, E., Shennan, I., Watcham, E.E.P., Woodroffe, S.S.A., 2013. Reconstructing paleoseismic deformation, 1: modern analogues from the 1960 and 2010 Chilean great earthquakes. *Quaternary Science Reviews* 75, 11–21. doi:10.1016/j.quascirev.2013.04.007
- Garrett, E., Shennan, I., Woodroffe, S.A.A., Cisternas, M., Hocking, E.P.P., Gulliver, P., 2015. Reconstructing paleoseismic deformation, 2: 1000 years of great earthquakes at Chucalén, south central Chile. *Quaternary Science Reviews* 113, 112–122. doi:10.1016/j.quascirev.2014.10.010
- Glasser, N.F., Jansson, K.N., Harrison, S., Kleman, J., 2008. The glacial geomorphology and Pleistocene history of South America between 38°S and

- 56°S. *Quaternary Science Reviews* 27, 365–390.
doi:10.1016/j.quascirev.2007.11.011
- Goto, K., Hashimoto, K., Sugawara, D., Yanagisawa, H., Abe, T., 2014. Spatial thickness variability of the 2011 Tohoku-oki tsunami deposits along the coastline of Sendai Bay. *Marine Geology* 358, 38–48. doi:10.1016/j.margeo.2013.12.015
- Grauert, M., Bjo, S., 2001. Storegga tsunami deposits in a coastal lake on Suduroy, the Faroe Islands. *Boreas*.
- Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments : reproducibility and comparability of results. *Journal of Paleolimnology* 25, 101–110. doi:10.1023/A:1008119611481
- Hong, I., Dura, T., Ely, L.L., Horton, B.P., Nelson, A.R., Cisternas, M., Nikitina, D., Wesson, R.L., 2016. A 600-year-long stratigraphic record of tsunamis in south-central Chile. *The Holocene*. doi:10.1177/0959683616646191
- Hutchinson, I., Guilbault, J.-P., Clague, J.J., Bobrowsky, P.T., 2000. Tsunamis and tectonic deformation at the northern Cascadia margin: a 3000-year record from Deserated Lake, Vancouver Island, British Columbia, Canada. *The Holocene* 10, 429–439. doi:10.1191/095968300666654539
- Jankaew, K., Atwater, B.F., Sawai, Y., Choowong, M., Charoentitirat, T., Martin, M.E., Prendergast, A., 2008. Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand. *Nature* 455, 1228–1231. doi:10.1038/nature07373
- Kagan, Y.Y., Jackson, D.D., 2013. Tohoku Earthquake: A Surprise? *Bulletin of the Seismological Society of America* 103, 1181–1194. doi:10.1785/0120120110
- Kelsey, H.M., Nelson, A.R., Hemphill-Haley, E., Witter, R.C., 2005. Tsunami history of an Oregon coastal lake reveals a 4600 yr record of great earthquakes on the Cascadia subduction zone. *Geological Society of America Bulletin* 117, 1009–1032. doi:10.1130/B25452.1
- Kempf, P., Moernaut, J., Van Daele, M., Vermassen, F., Vandoorne, W., Pino, M., Urrutía, R., Garrett, E., De Batist, M., 2015. The sedimentary record of the tsunami caused by the 1960 Great Chilean Earthquake in two coastal lakes on Chiloé Island, Chile. *Sedimentary Geology* 328, 73–86.
doi:10.1016/j.sedgeo.2015.08.004
- Lander, J.F., Lockridge, P., 1989. United States Tsunamis 1690 - 1988. Boulder, Colorado. National Geophysical Data Center publication, v. 41-42.
- Lee, S.H., Jung, W.-Y., Bahk, J.J., Gardner, J.M., Kim, J.K., Lee, S.H., 2013. Depositional features of co-genetic turbidite–debrite beds and possible mechanisms for their formation in distal lobated bodies beyond the base-of-slope, Ulleung Basin, East Sea (Japan Sea). *Marine Geology* 346, 124–140.
doi:10.1016/j.margeo.2013.09.001
- Lomnitz, C., 1970. Major Earthquakes and Tsunamis in Chile during the period 1535 to 1955. *Geologische Rundschau* 59, 938–960.
- Lomnitz, C., 2004. Major Earthquakes of Chile: A Historical Survey, 1535-1960. *Seismological Research Letters* 75, 368–378. doi:10.1785/gssrl.75.3.368
- May, S.M., Pint, A., Rixhon, G., Kelletat, D., Wennrich, V., Brueckner, H., 2013. Holocene coastal stratigraphy, coastal changes and potential palaeoseismological

implications inferred from geo-archives in Central Chile (29-32 degrees S). *Zeitschrift für Geomorphologie* 57, 201–228. doi:10.1127/0372-8854/2013/S-00154

- Messens, F., 2014. Luminescence dating of tsunami sand in south central Chile : a feasibility study. Ghent University.
- Moernaut, J., Van Daele, M., Heirman, K., Fontijn, K., Strasser, M., Pino, M., Urrutia, R., De Batist, M., 2014. Lacustrine turbidites as a tool for quantitative earthquake reconstruction: New evidence for a variable rupture mode in south central Chile. *Journal of Geophysical Research: Solid Earth* 119, 1607–1633. doi:10.1002/2013JB010738
- Moreno, M.S., Bolte, J., Klotz, J., Melnick, D., 2009. Impact of megathrust geometry on inversion of coseismic slip from geodetic data: Application to the 1960 Chile earthquake. *Geophysical Research Letters* 36, L16310. doi:10.1029/2009GL039276
- Mori, N., Takahashi, T., Yasuda, T., Yanagisawa, H., 2011. Survey of 2011 Tohoku earthquake tsunami inundation and run-up. *Geophysical Research Letters* 38. doi:10.1029/2011GL049210
- Nelson, A.R., Briggs, R.W., Dura, T., Engelhart, S.E., Gelfenbaum, G., Bradley, L.-A., Forman, S.L., Vane, C.H., Kelley, K.A., 2015. Tsunami recurrence in the eastern Alaska-Aleutian arc: A Holocene stratigraphic record from Chirikof Island, Alaska. *Geosphere* 11, 1172–1203. doi:10.1130/GES01108.1
- Nelson, A.R., Shennan, I., Long, A.J., 1996. Identifying coseismic subsidence in tidal-wetland stratigraphic sequences at the Cascadia subduction zone of western North America. *Journal of Geophysical Research: Solid Earth* 101, 6115–6135. doi:10.1029/95JB01051
- Peters, R., Jaffe, B., Gelfenbaum, G., 2007. Distribution and sedimentary characteristics of tsunami deposits along the Cascadia margin of western North America. *Sedimentary Geology* 200, 372–386. doi:10.1016/j.sedgeo.2007.01.015
- Phantu Wongraj, S., Choowong, M., Nanayama, F., Hisada, K.-I., Charusiri, P., Chutakositkanon, V., Pailoplee, S., Chabangbon, A., 2013. Coastal geomorphic conditions and styles of storm surge washover deposits from Southern Thailand. *Geomorphology* 192, 43–58. doi:10.1016/j.geomorph.2013.03.016
- Richmond, B., Szczuciński, W., Chagué-Goff, C., Goto, K., Sugawara, D., Witter, R., Tappin, D.R., Jaffe, B., Fujino, S., Nishimura, Y., Goff, J., 2012. Erosion, deposition and landscape change on the Sendai coastal plain, Japan, resulting from the March 11, 2011 Tohoku-oki tsunami. *Sedimentary Geology* 282, 27–39. doi:10.1016/j.sedgeo.2012.08.005
- Sawai, Y., Kamataki, T., Shishikura, M., Nasu, H., Okamura, Y., Satake, K., Thomson, K.H., Matsumoto, D., Fujii, Y., Komatsubara, J., Aung, T.T., 2009. Aperiodic recurrence of geologically recorded tsunamis during the past 5500 years in eastern Hokkaido, Japan. *Journal of Geophysical Research: Solid Earth* 114. doi:10.1029/2007JB005503
- Scheffers, A., Kelletat, D., 2003. Sedimentologic and geomorphologic tsunami imprints worldwide—a review. *Earth-Science Reviews* 63, 83–92. doi:10.1016/S0012-8252(03)00018-7

- SERNAGEOMIN, 2003. Mapa Geologico de Chile: Version Digital. Gobierno de Chile, Santiago de Chile.
- Sievers, H., Villegas, G.C., Barros, G., 1963. The seismic sea wave of 22 May 1960 along the Chilean coast. *Bulletin of the Seismological Society of America* 53, 1125–1190.
- Spiske, M., Piepenbreier, J., Benavente, C., Bahlburg, H., 2013. Preservation potential of tsunami deposits on arid siliciclastic coasts. *Earth-Science Reviews* 126, 58–73. doi:10.1016/j.earscirev.2013.07.009
- St-Onge, G., Chapron, E., Mulsow, S., Salas, M., Viel, M., Debret, M., Foucher, A., Mulder, T., Winiarski, T., Desmet, M., Costa, P.J.M., Ghaleb, B., Jaouen, A., Locat, J., 2012. Comparison of earthquake-triggered turbidites from the Saguenay (Eastern Canada) and Reloncavi (Chilean margin) Fjords: Implications for paleoseismicity and sedimentology. *Sedimentary Geology* 243–244, 89–107. doi:10.1016/j.sedgeo.2011.11.003
- Sugawara, D., Minoura, K., Imamura, F., 2008. Chapter 3 - Tsunamis and Tsunami Sedimentology, in: Minoura, T., Shiki, Y., Tsuji, T., Yamazaki, K. (Eds.), *Tsunamiites*. Elsevier, Amsterdam, pp. 9–49. doi:10.1016/B978-0-444-51552-0.00003-5
- Szczuciński, W., 2012. The post-depositional changes of the onshore 2004 tsunami deposits on the Andaman Sea coast of Thailand. *Natural Hazards* 60, 115–133. doi:10.1007/s11069-011-9956-8
- Szczuciński, W., Niedzielski, P., Kozak, L., Frankowski, M., Ziola, A., Lorenc, S., 2007. Effects of rainy season on mobilization of contaminants from tsunami deposits left in a coastal zone of Thailand by the 26 December 2004 tsunami. *Environmental Geology* 53, 253–264. doi:10.1007/s00254-007-0639-4
- Villalobos, L., Parra, O., Grandjean, M., Jaque, E., Woelfl, S., Campos, H., 2003. A study of the river basins and limnology of five humic lakes on Chiloé Island. *Revista chilena de historia natural* 76. doi:10.4067/S0716-078X2003000400003
- Wallner, J., 2008. Holozäne Landschaftsentwicklung am Lago Budi, Chile (38,9°S) - Paläolimnologisch/paläoseismische Untersuchungen an Lagunensedimenten. University of Jena.
- Wilhelm, B., Sabatier, P., Arnaud, F., 2015. Is a regional flood signal reproducible from lake sediments? *Sedimentology* 62, 1103–1117. doi:10.1111/sed.12180
- Zolitschka, B., Francus, P., Ojala, A.E.K., Schimmelmann, A., 2015. Varves in lake sediments – a review. *Quaternary Science Reviews* 117, 1–41. doi:10.1016/j.quascirev.2015.03.019

Figure captions

Figure 1: a) Overview map of the study area with rupture lengths of past megathrust earthquakes. b) The AD 1960 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).

Figure 2: This figure is modified after Kempf et al. (2015). a) sub-bottom profile across the basin in Lake Huelde. High-amplitude reflections are traced with coloured solid lines. Core penetration depths are to scale at the projected perpendicular position to the sub-bottom profile. b) side scan sonar reflectivity map of Lake Huelde with a zoom-in on the tidal delta plateau and the slide scars on its northern slope. c) interpretation map of the side scan sonar data in Lake Huelde with core sites (black dots).

Figure 3: Core correlation with indication for master core sections (blue rectangles on cores Pos15 and Pos18), age information, and correlated tsunami deposits. The core-to-core correlation is based on thin, grey tephra layers, CT-scans and magnetic susceptibility logs. ^{14}C -ages that were rejected by the age depth model are not annotated, but they are listed in table 1 and plotted in figure 4.

Figure 4: Split core images and CT-scan of Lake Huelde sediment; a) homogeneous gyttja below a sandy layer and finely laminated (varved) gyttja above a sandy layer; b) thin singular (left) and multiple (right) tephra layers in homogeneous gyttja; c) examples of sandy layer facies, i.e. mud cap, massive sand and mud rip-up clasts.

Figure 5: Lake Huelde tsunami deposit maps with maximum magnetic susceptibility and deposit thickness represented in size and colour of the circle, respectively.

Figure 6: Lake Huelde tsunami deposit maps with average magnetic susceptibility and deposit content represented in size and colour of the circle, respectively.

Figure 7: Bacon-based age-depth model of Lake Huelde's master core. The core sites, images and log on the left together with the age information (mostly radiocarbon dates) give input to the age-depth model algorithm. Tsunami deposits (horizontal grey bars) are considered instantaneous deposits.

Figure 8: OxCal's P_Sequence-based age-depth model of Lake Huelde's master core. The core sites, images and log on the left, together with the age information (mostly radiocarbon dates; R_Dates) give input to the P_Sequence algorithm. The depth is corrected by removing the instantaneous tsunami deposits from the core log. The tsunami deposit ages are extracted, where the deposits were removed from the model.

Figure 9: Comparison between dates for tsunami deposits from Lake Huelde (grey and coloured probability density functions) and known historical and prehistoric records of shaking (stars), co-seismic subsidence (downward arrows) and tsunami deposition (waves).

Figure 10: Typical sedimentological logs of tsunami deposits in a beach swale, a proximal marsh, a distal marsh, a proximal coastal lake and a distal coastal lake environment.

Table 1: Radiocarbon data for fossil plant fragments from the master core in Lake Huelde.

Table 2: Tsunami deposit data and age information. Reported ages are extracted from the Bacon age-depth model (Fig. 7).

Table 3: Summary of confidence levels for the interpretation of sandy layers as tsunami deposits in Lake Huelde with maximum magnetic susceptibility, traceability of the sandy layers throughout the sedimentary record, content of mud rip-up clasts and age-correlation to known tsunamis. Characteristics written in green contribute to confidence; red denotes doubt and black stands for neutral or inconclusive characteristics.

- normal grading
- leaves and plant fragments
- twiglets and flattened plants
- shells and shell fragments
- bioturbation
- rootlets
- soil
- mud
- homogenous/laminated gyttja
- massive sand
- cross bedded/laminated sand
- mud rip-up clasts, sandy matrix

proximal marsh

beach swale

distal marsh

proximal lake

distal lake

Atwater et al., 2013
Sawai et al., 2009
Nelson et al., 1996

Jankaew et al., 2008
Brill et al., 2011
Spiske et al., 2013

Richmond et al., 2012

Bondevik et al., 1997
Kelsey et al., 2005
Kemp et al., 2015

Kelsey et al., 2005
Kemp et al., 2015

detrital layer ID	max. magnetic susceptibility	traceability in the sedimentary record	mud rip-up clasts	laminated gyttja in post-event sediment
	10 ⁻⁵ SI	in cores / total cores		
AD 1960	1794	12/12	yes	yes
AD 1837	1585	5/8?	yes	inconclusive
AD 1575	763	1/8 (very low)	yes	inconclusive
hD	865	3/8	yes	no
hE	816	5/8	yes	inconclusive
hF	92 (very low)	2/8	not observed	yes
hG	1367	6/8	yes	yes
hH	773	7/8	not observed	yes
hI	310	4/7	not observed	yes
hJ	1030	6/6	yes	yes
hK	162	5/5	yes	yes
hL	172	2/5	not observed	no
hM	2480	5/5	yes	yes
hN	3791	5/5	yes	inconclusive
hO	200	3/3	not observed	yes
hP	132	2/2	yes	inconclusive
hQ	877	1/1	yes	yes

age-correlated to other tsunami deposits	confidence level
AD 1960	high
AD 1837	high
AD 1575	medium
event C (Cisternas et al., 2005; Garrett et al., 2015)	medium
event D (Cisternas et al., 2005; Garrett et al., 2015)	high
event E (Cisternas et al., 2005)	medium
event G (Cisternas et al., 2005)	high
event H (Cisternas et al., 2005)	high
preceeds all other regional records	medium
preceeds all other regional records	high
preceeds all other regional records	high
preceeds all other regional records	low
preceeds all other regional records	high
preceeds all other regional records	high
preceeds all other regional records	medium
preceeds all other regional records	medium
preceeds all other regional records	high

tsunami deposit ID	in number of cores	2 σ range of modelled age (cal. yr BP)	median (cal. yr BP)	reported as (AD/cal. yrs BP)	age information source
AD 1960	13/13	-12 - -6	-10	AD 1960	Cisternas et al., 2005; Lomnitz, 1970, 2004
AD 1837	5/8?	101 - 121	111	AD 1837	Cisternas et al., 2005; Lomnitz, 1970, 2004
AD 1575	1/8	303 - 483	397	AD 1575	Cisternas et al., 2005; Lomnitz, 1970, 2004
hD	3/8	553 - 670	593	AD 1355 $\pm$ 60/AD 1319 $\pm$ 9	this study/Moernaut et al., 2014
hE	5/8	655 - 764	704	AD 1245 $\pm$ 55/AD 1127 $\pm$ 44	this study/Moernaut et al., 2014
hF	2/8	1185 - 1291	1253	1250 $\pm$ 50 cal. yrs BP	this study
hG	6/8	1604 - 1786	1693	1690 $\pm$ 90 cal. yrs BP	this study
hH	7/8	1761 - 1926	1856	1860 $\pm$ 80 cal. yrs BP	this study
hI	4/7	1903 - 2006	1962	1960 $\pm$ 50 cal. yrs BP	this study
hJ	6/6	2128 - 2302	2200	2200 $\pm$ 90 cal. yrs BP	this study
hK	5/5	2563 - 2821	2672	2670 $\pm$ 130 cal. yrs BP	this study
hL	2/5	3182 - 3407	3299	3300 $\pm$ 110 cal. yrs BP	this study
hM	5/5	3590 - 3897	3742	3740 $\pm$ 150 cal. yrs BP	this study
hN	5/5	3729 - 4011	3889	3890 $\pm$ 140 cal. yrs BP	this study
hO	3/3	4156 - 4535	4342	4340 $\pm$ 190 cal. yrs BP	this study
hP	2/2	4209 - 4603	4403	4400 $\pm$ 200 cal. yrs BP	this study
hQ	1/1	4962 - 5360	5162	5160 $\pm$ 200 cal. yrs BP	this study

sample ID	lab ID	depth in master core (cm)	material	14C age $\pm 1\sigma$ (14C years BP)	$\delta^{13}C$ (‰)	calibrated 2 σ ranges (cal. years BP)	relative probability (%)	median age with 2 σ range (cal. years BP)
HU03-95	UBA-23494	95	plant fragments	317 $\pm$ 31	-29.0	300 - 470	95.4	390 $\pm$ 90
HUEL03A-88.5	UBA-23326	123.5	plant fragments	369 $\pm$ 36	-28.7	315 - 415 420 - 505	44.3 51.1	430 $\pm$ 120
HUEL03A-112	UBA-21474	143	wood	1214 $\pm$ 34	-27.5	980 - 1178	95.4	not reported
HUEL03A-126.5	UBA-23495	161.5	plant fragments	760 $\pm$ 31	-27.9	665 - 735	95.4	690 $\pm$ 40
HUEL03B-30.5	UBA-23327	208.5	plant fragments	848 $\pm$ 31	-25.6	685 - 800 870 - 900	90.5 4.9	755 $\pm$ 90
HUEL03B-71.5	UBA-23802	249.5	plant fragments	1694 $\pm$ 30	-27.7	1433 - 1441 1457 - 1462 1468 - 1613 1663 - 1695	0.9 0.5 90.0 4.1	not reported
HUEL04A-51.5	UBA-23328	301	plant fragments	1289 $\pm$ 29	-29.8	1180 - 1290	95.4	1235 $\pm$ 70
HUEL04A-59.5	UBA-23803	311.5	plant fragments	1423 $\pm$ 32	-26.7	1290 - 1375	95.4	1325 $\pm$ 40
HUEL04A-107	UBA-23804	359	plant fragments	1863 $\pm$ 29	-27.0	1720 - 1875	95.4	1800 $\pm$ 90
HUEL04B-14.5	UBA-23329	398.5	single leaf	2032 $\pm$ 32	-21.8	1895 - 2065 2080 - 2110	90.8 4.6	1985 $\pm$ 100
HUEL04B-55.5	UBA-23500	429.5	plant fragments	2056 $\pm$ 30	-27.5	1945 - 2120	95.4	2025 $\pm$ 90
HUEL05A-10.5	UBA-23330	435	plant fragments	2015 $\pm$ 27	-32.4	1890 - 2010 2015 - 2040	91.1 4.3	1965 $\pm$ 70
HUEL05A-56.5	UBA-23805	479	plant fragments	2201 $\pm$ 31	-26.5	2130 - 2320	95.4	2235 $\pm$ 110
HUEL04B-113.5	UBA-21475	495	plant fragments	2292 $\pm$ 43	-20.9	2150 - 2275 2290 - 2360	41.4 54.0	2315 $\pm$ 130
HUEL27A-3.5	UBA-23331	562.5	plant fragments	2266 $\pm$ 34	-24.3	2155 - 2265 2295 - 2350	53.3 42.1	2245 $\pm$ 120
HUEL27A-23.5	UBA-23502	583	plant fragments	6628 $\pm$ 42	-29.3	7429 - 7566	95.4	not reported
HUEL27A-61.5	UBA-23332	621	wood	3029 $\pm$ 39	-25.5	3004 - 3259 3291 - 3334	88.2 7.2	not reported
HUEL27A-72	UBA-23843	628	plant fragments	2533 $\pm$ 35	-27.4	2490 - 2645 2655 - 2670 2675 - 2750	58.9 1.0 35.6	2620 $\pm$ 160
HUEL27A-141.5	UBA-23333	700.5	plant fragments	3155 $\pm$ 31	-29.9	3265 - 3290 3330 - 3450	5.4 90.0	3380 $\pm$ 80
HUEL27B-50.5	UBA-23504	755.5	plant fragments	3325 $\pm$ 34	-33.1	3460 - 3640	95.4	3555 $\pm$ 100
HUEL27B-107.5	UBA-23334	812.5	plant fragments	3718 $\pm$ 38	-26.2	3925 - 3945 3965 - 4160 4205 - 4225	1.6 92.3 1.5	4055 $\pm$ 120
HUEL27b	UBA-21477	829	single culm	3692 $\pm$ 35	-27.5	3920 - 4105 4110 - 4150	87.8 7.6	4035 $\pm$ 110
HUEL22b	UBA-21473	1056.5	single culm	4757 $\pm$ 36	-31.2	5330 - 5380 5455 - 5590	12.8 82.6	5515 $\pm$ 140