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# Larger earthquakes recur more periodically: New insights in the megathrust earthquake cycle from lacustrine turbidite records in south-central Chile

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## ABSTRACT

Historical and paleoseismic records in south-central Chile indicate that giant earthquakes on the subduction megathrust – such as in AD1960 ($M_w$ 9.5) – reoccur on average every ∼300 yr. Based on geodetic calculations of the interseismic moment accumulation since AD1960, it was postulated that the area already has the potential for a $M_w$ 8 earthquake. However, to estimate the probability of such a great earthquake to take place in the short term, one needs to frame this hypothesis within the long-term recurrence pattern of megathrust earthquakes in south-central Chile. Here we present two long lacustrine records, comprising up to 35 earthquake-triggered turbidites over the last 4800 yr. Calibration of turbidite extent with historical earthquake intensity reveals a different macroseismic intensity threshold (≥VII1/2 vs. ≥VI1/2) for the generation of turbidites at the coring sites. The strongest earthquakes (≥VII1/2) have longer recurrence intervals (292 ±93 yrs) than earthquakes with intensity of ≥VI1/2 (139 ± 69 yr). Moreover, distribution fitting and the coefficient of variation (CoV) of inter-event times indicate that the stronger earthquakes recur in a more periodic way (CoV: 0.32 *vs.* 0.5). Regional correlation of our multi-threshold shaking records with coastal paleoseismic data of complementary nature (tsunami, coseismic subsidence) suggests that the intensity ≥VII1/2 events repeatedly ruptured the same part of the megathrust over a distance of at least ∼300 km and can be assigned to $M_w \geq 8.6$. We hypothesize that a zone of high plate locking – identified by geodetic studies and large slip in AD 1960 – acts as a dominant regional asperity, on which elastic strain builds up over several centuries and mostly gets released in quasi-periodic great and giant earthquakes. Our paleo-records indicate that Poissonian recurrence models are inadequate to describe large megathrust earthquake recurrence in south-central Chile. Moreover, they show an enhanced probability for a $M_w$ 7.7–8.5 earthquake during the next 110 years whereas the probability for a $M_w \geq 8.6$ (AD1960-like) earthquake remains low in this period.

## 1. Introduction

Understanding the spatial and temporal recurrence pattern of large earthquakes is a crucial requisite for reliable seismic hazard assessments (Satake and Atwater, 2007). In addition to constraining the average recurrence rates for different magnitude classes, one needs to determine the best model for describing the temporal aspect of the seismic cycle. Earthquake probabilities for a certain time window can be calculated by fitting past recurrence times with a probabilistic density function. Due to the short temporal span of seismological and historical data, and the typical uncertainties and assumptions related to paleoseismic research, many challenges exist for integrating earthquake time series into recurrence models (Wu et al., 1995). Quasi-periodic recurrence has been revealed for some fault-specific cases, e.g. for the largest earthquakes on some isolated segments of major transform faults (Scharer et al., 2010; Berryman et al., 2012). More complex trans-

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form fault systems may exhibit a clustered recurrence, in which several short intervals alternate with much longer ones (Kenner and Simons, 2005 and references therein). For some subduction megathrusts, analogue models and paleoseismic studies suggest quasi-periodicity (Sykes and Menke, 2006; Corbi et al., 2013), which can be modulated into "supercycles" in which a complete segment rupture ends a series of earthquakes of varying magnitude (Goldfinger et al., 2013; Herrendörfer et al., 2015). Alternatively, time-independent (Poissonian) recurrence models are found adequate to describe the recurrence of small earthquakes or for analysis of regional seismic hazards (Wu et al., 1995; Gomez et al., 2015). Poissonian recurrence models are commonly adopted for fault-specific cases where paleoseismic data is lacking.

Determination of the best recurrence model strongly depends on the "quality" of paleoseismic records: i.e. the amount of recorded events, the dating accuracy, and information on paleo-earthquake size. In lacustrine paleoseismology, several attempts have been made to constrain the local seismic intensity or peak ground acceleration of paleo-earthquakes that are recorded in sedimentary sequences as soft-sediment deformations, landslides, turbidites and post-seismic catchment responses (Strasser et al., 2011; Howarth et al., 2014; Avsar et al., 2016; Wilhelm et al., 2016). In south-central Chile, previous studies revealed strong relationships between seismic intensity during historical earthquakes, and type, presence, thickness and extent of earthquake-triggered lacustrine turbidites (Moernaut et al., 2014; Van Daele et al., 2015). This calibration of the sedimentary archive to historical events allowed defining a site-specific earthquake recording threshold (EQRT), i.e. the minimal seismic intensity required to produce a macroscopically visible turbidite at a given coring site. The studied sediment cores however only covered about 500–900 yr and 5–7 events, and are thus not suited for deducing the temporal recurrence patterns of strong megathrust earthquakes.

Here, we present two long lacustrine turbidite records obtained in locations with different EQRTs and which contain up to 35 earthquake-triggered turbidites over the last 4800 yr. This allows us – for the first time – to determine and compare the recurrence patterns of earthquake shaking of different intensity. Correlation with other records allows complementing the regional paleoseismic catalogue and putting forward possible seismo-tectonic mechanisms that explain the obtained recurrence patterns.

## 2. Setting and field data acquisition

Our study area is the Valdivia Segment of the subduction zone in south-central Chile (Fig. 1). Historical documents attest that this segment has been struck by four significant megathrust earthquakes (in AD1575, AD1737, AD1837 and AD1960) during the last ∼500 yr (Lomnitz, 1970; Cisternas et al., 2005). Combined with lacustrine (Moernaut et al., 2014) and coastal paleoseismic records (Cisternas et al., 2017), it was suggested that the megathrust earthquake cycle is characterized by a variable rupture mode in terms of rupture location, rupture extent and coseismic slip. Long coastal records revealed that the largest "1960-like" megathrust earthquakes and tsunamis occur on average every ∼300 yr, albeit with considerable temporal variability (Cisternas et al., 2005; Kempf et al., 2017). The AD1960 earthquake ($M_w$ 9.5) is notorious for having the highest instrumentally-recorded magnitude worldwide. It ruptured the subduction megathrust over about ∼1000 km with an average slip of ∼17 m, which peaked to ∼44 m in an asperity at 40–41°S (Fig. 1; Moreno et al., 2009). Modeling of geodetic (GPS) data revealed a heterogeneous pattern of plate interface locking during the current interseismic period and it was postulated that several highly-locked patches may already be capable of producing a $M_w$ 8 earthquake (Moreno et al., 2011). However, to estimate the probability of such a great earthquake in the near future, this hypothesis needs to be framed within the long-term recurrence pattern of megathrust earthquakes in south-central Chile.

We studied the sedimentary infill of Lake Calafquén and Lake Riñihue, two large and deep glacigenic lakes at the western foot of the volcanically active Andean Cordillera at 39.5–40°S latitude (Fig. 1, Fig. 2, SI-Fig. 1). Previous studies on short sediment cores (0.5–1.5 m long) showed that the sedimentary infill consists of annually-laminated hemipelagic sediments, interrupted by tephra layers, lahar deposits, mass-transport deposits (MTD) and turbidites (Moernaut et al., 2014; Van Daele et al., 2014). Turbidites in isolated sub-basins were accurately dated and analysis of their composition revealed that most of these were produced by surficial remobilization of hemipelagic slope sediments during strong historical earthquakes (Moernaut et al., 2017). The EQRT in these sub-basins was determined to range between VI1/2 and VII1/2, with the lowest threshold values at the immediate foot of sedimentary slopes (Fig. 2; Moernaut et al., 2014). For the present study, we obtained long sediment cores CAL1 (8.60 m) and RIN2 (7.25 m) with a hammer-driven piston coring system at short coring sites with an EQRT of VII1/2 and VI1/2, respectively. This difference in EQRT is expressed by the absence of the AD1837, AD1737 and AD∼1466 earthquakes in the short core of CAL1 (CASC01), whereas both sites contain turbidites related to the AD1960, AD1575 and AD∼1319 earthquakes (Fig. 3; Moernaut et al., 2014). The seismic–stratigraphic characteristics at the coring sites were analyzed on high-resolution (3.5 kHz pinger) subbottom profiles, making sure we selected the best coring location in terms of record continuity, i.e. avoiding – if possible – any mass-transport deposits and hiatuses at the core site (SI-Fig.2).

## 3. Data analysis

Sedimentological analysis consisted of a detailed macro- and microscopic description, high-resolution magnetic susceptibility and $\gamma$-density measurements using a GEOTEK core logger (details in Moernaut et al., 2014). Turbidites were identified based on their homogeneous or fining-upwards characteristics, which clearly contrast to the millimeter-scale laminations of the hemipelagic "background" sediments. Smear slide analysis and magnetic susceptibility confirmed that the identified turbidites are composed of diatomaceous mud produced by remobilization of hemipelagic slope sediments, and can be classified as LT1s ("lacustrine turbidites type 1") after Van Daele et al. (2015). The sediments were dated using a combined approach of i) varve counting (on the short cores) and identification of historical events (see Moernaut et al., 2014), ii) AMS $^{14}$C dating (SI-Table 1) and iii) geochemical identification of well-studied regional tephra marker beds (SI-Table 1, Fontijn et al., 2016). The $^{14}$C dating was performed on bulk sediments and – where available – on macro-remains of terrestrial material. $^{14}$C ages were calibrated using the SHCal13 calibration curve (Hogg et al., 2013). The $^{14}$C ages of the bulk sediment samples were corrected for a soil-related "old-carbon" effect by subtracting the offset between the AD1575 historic event and the weighted average of the calibrated $^{14}$C age for bulk sediment at the corresponding depth (SI-Table 1; see Moernaut et al., 2017). Regional marker tephras were identified in the studied cores and on terrestrial outcrop samples by Fontijn et al. (2016), who used terrestrial samples for additional $^{14}$C dating and combined these to model the ages of tephras (mean age $\pm 2\sigma$) in a regional stratigraphic framework.

All dates were used to produce a continuous age-depth model for each core using the Bayesian software BACON (Fig. 4, Blaauw and Christen, 2011). All event layers (turbidites, tephras, lahars) were excluded from the stratigraphic records. Turbidite ages were extracted from these models (SI-Table 2 and SI-Table 3) and inter-event times between (weighted mean) ages were analyzed by