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Insights from geochemistry and diatoms to characterise a tsunami's deposit and maximum inundation limit

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ABSTRACT

Geochemical proxies and diatom assemblages were used in combination with grain size characteristics not only to describe the deposit left behind by the 27 February 2010, Maule tsunami at Las Cañas, Maule Region, Chile, but also to trace the maximum inundation limit of the event. The sandy deposit was laid down between 160 and 260 m inland behind an eroded sand dune and a lagoon but reached only 60% of the total tsunami inundation distance of 380 m, which was marked by organic debris, pumice clasts and wooden logs. It consisted of coarse to medium sand that thinned and fined inland. At the most seaward point, the 22 cm thick deposit exhibited a fining upward unit overlain by a couplet of coarsening–fining upward units, suggesting deposition by at least two waves, while farther inland the fining upward deposit was probably left behind by only one wave. Chemical proxies (Ca/Ti vs Sr/Ba) allow us to distinguish the deposit from the surrounding soil and indicate that it was sourced from the beach and/or dune area, with diatom assemblages confirming the marine origin of the deposit. Saltwater indicators (e.g. Cl, S) provide evidence for the maximum inundation limit beyond the extent of the sandy deposit, despite dilution and dissolution by 500 mm of rainfall in the six months since the tsunami. Marine and marine/brackish diatom assemblages decreased landward but were found up to the inundation limit and immediately beyond, suggesting the effect of diatom-bearing sea spray at the wave front or redistribution of the detrital assemblage associated with tsunami inundation due to wind. While the latter might result in a slight over-estimation of the inundation distance, they can be used in combination with chemical proxies to trace the maximum inundation distance of recent and past tsunamis, thus allowing for a better estimation of the magnitude of past events. Post-depositional processes were found to have affected the thinner sandy deposits (<5 cm), suggesting that these are unlikely to be preserved in the geological record. This highlights the need to be able to trace the tsunami inundation limit with geochemical and/or diatom proxies without having to rely on sedimentological evidence, as it is now widely recognised that conventional approaches used by tsunami researchers have led to an under-estimation of previous events.

1. Introduction

The offshore Nazca–South American plate boundary, one of the most seismically-active areas worldwide (Kulikov et al., 2005) causes Chile to experience on average a magnitude 8 earthquake, either as a subduction event or an intraplate rupture, every 10 years or so (Madariaga et al., 2010). Cisternas et al. (2005) also reported on a long record of earthquakes and tsunamis that preceded the Mw 9.5 Valdivia earthquake and tsunami.

In the Concepción–Constitución seismic gap, south-central Chile, the last subduction zone event (estimated M $\approx$ 8.5) occurred in 1835 (Lomnitz, 1970; Campos et al., 2002; Lomnitz, 2004), until the 27 February 2010 Mw 8.8 Maule earthquake (Fig. 1) (Moreno et al., 2010). At the time it was the fifth largest earthquake since instrumental recordings began, rupturing an area extending about 550 km with an average slip of around 5 m (Lay et al., 2010). More recently, on 1 April 2014, a Mw 8.2 earthquake occurred in the Iquique or northern Chile seismic gap (Fig. 1).

The 2010 Maule earthquake and subsequent tsunami caused economic losses of about US$30 billion or 17% of Chile's GDP, with 521 fatalities and 56 people still missing (American Red Cross Multi-Disciplinary Team, 2011; NGDC, 2014). The tsunami accounted for 156 deaths, mainly around the Maule and Bío-Bío regions, but also offshore on Robinson Crusoe and Mocha Islands (Fritz et al., 2011; NGDC, 2014) (Fig. 1).

One to four main waves were noted by eyewitnesses with the first arriving within 30 min of the earthquake (EERI, 2010). Run-up and inundation were highly variable along the 800 km long stretch of affected

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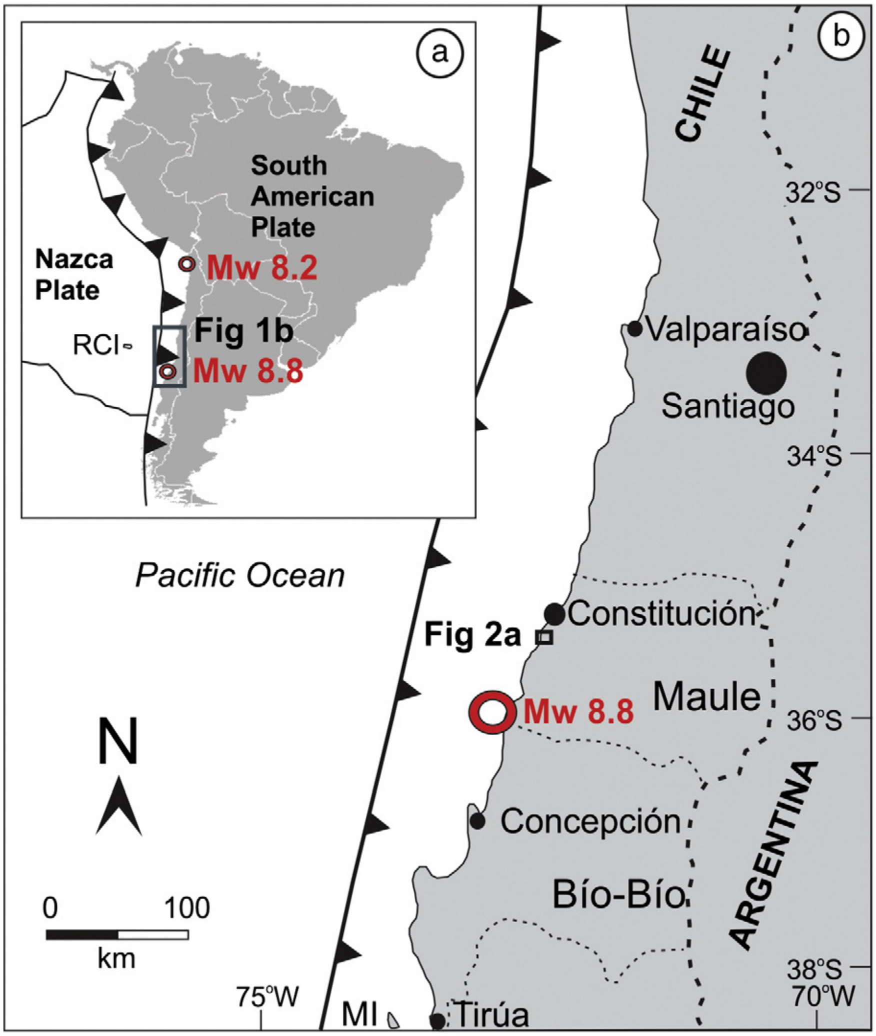

Fig. 1. a. Location map with Nazca subduction zone and Robinson Crusoe Island (RCI). The locations of the epicentres of the 2010 Mw 8.8 Maule and the 2014 Mw 8.2 Iquique earthquakes are also shown. b. Map showing the location of the Mw 8.8 epicentre, Constitución and Concepción in the Maule and Bío-Bío regions, respectively, Mocha Island (MI), and the study area.

coast with a maximum local run-up height of 29 m recorded at Constitución (Fritz et al., 2011) and a maximum inundation of 2.6 km at Talcahuano, a few km NW of Concepción (Morton et al., 2011). Fritz et al. (2011) noted that north of Constitución the run-up height distribution generally decreased from about 10 m to less than 5 m around Valparaíso 250 km away. Along a stretch of about 350 km south of Constitución as far as Tirúa (Fig. 1), run-up heights were within a broad range of 5–15 m and then dropped markedly to Mehuín, 120 km farther south (Fritz et al., 2011).

It is becoming increasingly apparent to the tsunami community that models based upon historical records alone are insufficient to fully understand the long-term nature of the hazard (Goff, 2011). Many researchers are turning to the prehistoric record for answers and while this is to be applauded, much of the work relies heavily on studies of the sedimentary evidence alone, or with the addition of some microfossil analyses (e.g. Jankaew et al., 2008). While in individual cases it may prove sufficient to identify palaeotsunamis this is rarely the case and a more diverse and comprehensive suite of proxies needs to be used (Chagué-Goff et al., 2011; Goff et al., 2012). Not surprisingly, the nature and extent of proxies used, and their perceived value invariably indicate a strong bias towards the expertise of those involved in the research.

Many of the proxies used to help identify palaeotsunami deposits have been developed and improved through studies of recent events (e.g. Chagué-Goff et al., 2011). While some criteria are used to infer the marine origin of the sediment (e.g. microfossils, macrofossils, marine geochemical indicators), others characterise the sediment, thus providing information about its source (e.g. grain size, mineralogy, geochemistry). It is also important to recognise that the study of recent events informs us about the deterioration or breakdown of the proxy evidence for a tsunami over time, its taphonomy (Chagué-Goff et al., 2012a; Goff et al., 2012; Szczuciński, 2012). Of particular note is the point that evidence for tsunami inundation is not just about the sediment, there is invariably an affected human community, a strandline of debris, and salt burnt vegetation (e.g. Chagué-Goff et al., 2011; Richmond et al., 2011). While all of these points have relevance for the study of palaeotsunamis, it is the last two that are of most immediate significance for understanding the magnitude of the events (and indirectly the source).

The maximum extent of tsunami inundation is generally defined by either a strandline of debris or the contact between salt burnt and unaffected vegetation, but these can often be some distance inland from the maximum landward extent of the visible deposit (e.g. Java 2006: Moore et al., 2011; Samoa 2009: Chagué-Goff et al., 2011; Chile 2010: Morton et al., 2010, 2011; Yoshii et al., 2013; Japan 2011: Goto et al., 2011; Abe et al., 2012; Chagué-Goff et al., 2012a,c).

Following the 2010 Maule tsunami, Morton et al. (2010, 2011) reported disjuncts between the maximum extent of the sandy deposit and the inundation limit exceeding 150 m (e.g. 700 m and 850 m, respectively at La Trinchera (35 km N of Constitución); 800 m and 1100 m at Purema, 1600 m and 2400 m at Coliumo (these sites range