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Tectonic and morphosedimentary features of the 2010 Chile earthquake and tsunami in the Arauco Gulf and Mataquito River (Central Chile)

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ABSTRACT

Effects of the 2010 Chilean earthquake and tsunami were evaluated at coastal sites between two zones of different coseismic deformations. Land deformation, run-up, inundation extent and deposit extent and thickness were measured in the field, providing insights into the processes and morphological changes associated with tsunami inundation and backwash. Three to five waves, of up to 10 m height, deposited several related layers along the coast, the thickness of these sandy deposits does not exceed 80 cm, and is generally less than 30 cm. Coseismic deformation measured by means of bio- and geomorphic markers agrees well both with model deformation and measured GPS. There is no relationship between the run-up height and the trend of coseismic deformation (uplift or subsidence), mainly because the effects of the tsunami were influenced locally by offshore bathymetry and coastal morphology.

1. Introduction

On February 27th 2010 a Maule Region earthquake (at 06:34:14 UTC, with epicentre 35.909°S, 72.733°W, 35 km depth, USGS, 2016) with Mw 8.8 affecting central Chile, set off a tsunami that caused major damage to over 500 km of mainland coastline, as well as to several islands. Previously this area was identified as a seismic gap, with the potential to produce an earthquake of Mw 8.0–8.5 (Ruegg et al., 2009). The earthquake and tsunami killed more than 577 inhabitants in the coastal regions of central Chile.

The earthquake was generated at the gently sloping fault that conveys the Nazca plate eastward and downward beneath the South American plate. The fault rupture, largely offshore, exceeded 100 km in width and extended nearly 500 km parallel to the coast. It began deep beneath the coast and spread westward, northward and southward. As it spread, the fault slip generated earthquake shaking and also deformed the ocean floor, setting off the tsunami along the fault-rupture area. Although the maximum water level observed in several places ranged from 10 to 12 m, and although 3 to 5 waves reached the coast during the next 4 h, the sedimentary record and geomorphological changes recorded were less severe than other recent tsunami-generated by mega-earthquakes, like the 2004 Indian Ocean tsunami (Paris et al., 2007; Ontowirjo et al., 2013) or 2011 Tohoku-Oki tsunami (Mori et al., 2011; Goto et al., 2012a, 2012b; Nakamura et al., 2012; Richmond et al., 2012; Tappin et al., 2012).

Different coseismic deformations (uplift or subsidence) were observed in different sectors of the coast and therefore an attempt was made to identify whether this land deformation controls the sedimentological pattern in each area. Coseismic coastal land-level changes have been estimated by intertidal organisms in different tectonic settings (subduction zones, strike-slip fault systems, and continental thrust belts) by means of barnacles, corals, coralline algae, serpulids and molluscs (i.e. Plafker and Ward, 1992; Ortlieb et al., 1996; Ramírez-Herrera and Orozco, 2002; Ferranti et al., 2007; Shishikura et al., 2009; Castilla et al., 2010; Farías et al., 2010; Vargas et al., 2011; Melnick et al., 2012) but as has been pointed by Melnick et al. (2012): “few studies have focused on the distribution of such markers along an uplifted coastline, discussing the influence of local site effects on the accuracy of uplift measurements and the specific methodological aspects that may improve the reliability”.

After the 2010 Chile tsunami, several ITST groups (International Tsunami Survey Team, UNESCO) surveyed the effect of the tsunami, some focusing on the sedimentary record. In all cases tsunami run-up elevations and morphological changes were highly variable over short alongshore distances as a result local amplification effects due to alongshore variations in the tsunami wave heights, offshore bathymetry, shoreline orientations, and onshore topography (Fritz et al., 2011; Morton et al., 2011).

2. Methodology

From 17th to 30th March 2010 a survey of the tsunami sedimentary record was carried out in the context of the ITST (International Tsunami

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Survey Team, UNESCO). In order to study the tsunami impact, an area was selected where population was severely affected by the tsunami and where natural conditions were preserved. Two different coseismic deformation areas were selected from surface deformation models published by the California Institute of Technology just after the earthquake (Sladen, 2010). This model predicted uplift deformation in the Arauco Peninsula and stability in the Mataquito River area. With this premise, the two areas selected to survey were: a) Arauco Gulf and surrounding coast, inundated by the tsunami and also affected by coseismic uplift of up to 2.5 m, with emersion of the marine platform and tidal areas; and b) Mataquito River area, where coseismic subsidence was observed (Fig. 1). Later studies confirmed that because coseismic uplift tends to increase towards the trench, maximum amounts were modelled and observed in the southern rupture segment. The coastal subsidence was modelled and observed in the northern segment (Farías et al., 2010; Vigny et al., 2011).

Field survey methods were those applied in other post-tsunami surveys (Gelfenbaum and Jaffe, 2003; Goff et al., 2006; Jaffe et al., 2006). The terminology defined by the Tsunami Glossary published by the Intergovernmental Oceanographic Commission (2013) was used, as well as the Tsunami Survey Filed Guide published by same institution (Dominey-Howes et al., 2012). The terms that define the size of tsunami on the coast are: (a) run-up is the maximum ground elevation wetted by the tsunami on a sloping shoreline; (b) maximum inundation distance is the horizontal distance flooded by the wave (In the simplest case, the run-up value, a, is recorded at b); (c) flow depth is the depth of the tsunami flood over the local terrain height; and (d) tsunami height is the total elevation of the water free surface above a reference datum. Wave height and flow depth were measured using GPS, altimeter and tape, mainly using references such as marine remains and damage, e.g. to trees, houses, and fences, water level marks on walls and houses, and eye-witness testimony.

Run-up was measured by GPS following the maximum inundation line, identified from marine remains, garbage accumulated from the sea, accumulated vegetal remains and eye-witness testimony. The presence of marine fish and crabs in the hinterland was also recorded as markers of the inundation area. In some places a very thin layer of mud far above the last few vegetal and garbage remains marked the maximum inundation area limit. In some sites, displaced houses or boats in the hinterland were taken as markers of run-up. As with other researchers (Morton et al., 2011) the thickness of tsunami deposits was determined by digging short, shallow trenches along shore-normal and shore-parallel transects. Trenches were excavated to depths below pre-existing soil, the unaltered or eroded pre-tsunami surface. In some sites the lower limit was marked by artificial basement (concrete or asphalt).

Coseismic deformation was estimated using the Ortlieb et al. (1996) methodology, related to the presence of coralline algae. Coralline algae (lithothamnioids) located in the upper part of the infralittoral zone along rocky shorelines proved to be a useful indicator of rapid coastal uplift. As these encrusting algae cannot survive to desiccation they provide estimates of coseismic uplift. Once the algae die, their colour fades due to solar radiation (bleaching); a white band is observed, contrasting with the living algae immediately below. Measurement of the difference in elevation between this white fringe and the living algae provides a reliable indication of sudden uplift, as also observed in this area by Vargas et al. (2011). Coseismic deformation was also measured by altitude difference between tidal notches corresponding to the pre-seismic and post-seismic tidal levels. Subsidence was measured by reference to items such as harbours, telephone poles or

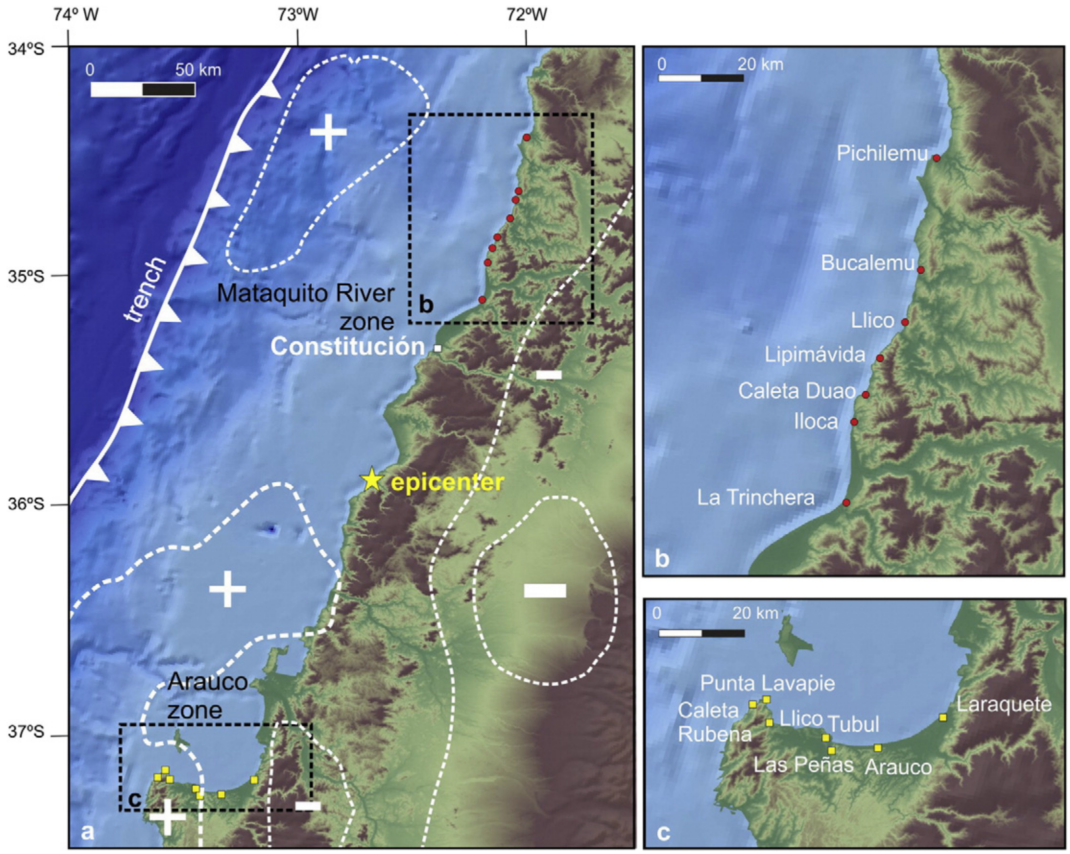

Fig. 1. Location map of the two areas studied. Land deformation (uplift, +; subsidence, −) from surface deformation models published just after the earthquake by Sladen (2010).