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Pliocene mass failure deposits mistaken as submarine tsunami backwash sediments — An example from Hornitos, northern Chile

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ABSTRACT

In this study we question the former interpretation of a shallow marine backwash tsunami origin of a conspicuous Pliocene coarse clastic unit at Hornitos, northern Chile, and instead argue for a debris flow origin for this unit. We exclude a relation to a tsunami in general and to the Eltanin impact in particular. The observed deposit at Hornitos was not generated either directly (impact-triggered tsunami) or indirectly (submarine mass flow caused by seismic shaking) by an impact. Re-calculation of the alleged impact tsunami including consideration of the Van Dorn effect shows that an impact in the Southern Ocean did not cause a significant tsunami at Hornitos. Impact-related seismic shaking was not able to trigger slides several thousands of kilometers away because the Eltanin event was a deep sea-impact that did not create a crater. Additionally, the biostratigraphic age of 5.1–2.8 Ma of the associated La Portada Formation is not concurrent with the newly established age of 2.511 ± 0.07 Ma for the Eltanin impact.

Instead, we argue for an origin of the conspicuous unit at Hornitos as a debris flow deposit caused by an earthquake in the Andean subduction zone in northern Chile. Our re-interpretation considers the local synsedimentary tectonic background, a comparison to recent submarine tsunami sediments, and recent examples of mass wasting deposits along the Chilean margin. The increased uplift during the Pliocene caused oversteepening of the coastal scarp and entailed a contemporaneous higher frequency of seismic events that triggered slope failures and cliff collapses. The coarse clastic unit at Hornitos represents an extraordinary, potentially tsunami-generating mass wasting event that is intercalated with mass wasting deposits on a smaller scale.

1. Introduction

Characteristic features of onshore tsunami deposits have been extensively studied over recent decades, especially during post-event surveys (e.g., Liu et al., 2005; Richmond et al., 2006; Bahlburg and Weiss, 2007; Bahlburg and Spiske, 2012; Goto et al., 2012; Richmond et al., 2012). While the characteristics of onshore deposits are well documented, the associated marine tsunami effects, such as sediment dispersion, erosion or deposition during run-up, and sediment bypassing, erosion or deposition caused by the backwash are scarcely known. So far, only a few studies document the impacts of recent tsunamis in marine environments. Marine disturbances and related erosion and sedimentation caused by the 2003 Tokachi-Oki tsunami were documented by Noda et al. (2007), those connected to the 2004 Indian Ocean tsunami by Di Geronimo et al. (2009), Feldens et al. (2009, 2012) and Paris et al. (2010), and the 2011 Tohoku tsunami by Kawagucci et al. (2012) and Arai et al. (2013).

A good understanding of the factors controlling the generation of both onshore and marine tsunami deposits is paramount for two reasons. Firstly, tsunami deposits often record the processes that form them (Huntington et al., 2007; Switzer et al., 2012). Second, marine sediments tend to be preferentially preserved in the pre-Quaternary geological record in comparison to coastal tsunami deposits that have a relatively low preservation potential (Spiske et al., 2013). This implies that studies of recent onshore tsunami deposits cannot necessarily be used as templates for the recognition of ancient tsunami sediments. There are several examples of unusual Precambrian to Pliocene submarine beds that have been attributed to the effects of a tsunami rather than to storms or mass wasting processes (e.g., Bailey and Weir, 1932; Ballance et al., 1981; Michalík, 1997; Hassler et al., 2000; Rossetti et al., 2000; Pratt, 2001, 2002; Scasso et al., 2005; Schnyder et al., 2005; Brookfield et al., 2006; Goto et al., 2008; Sarkar et al., 2011; Tachibana, 2013).

Recent review articles (e.g., Dawson and Stewart, 2008; Shiki et al., 2008; Sugawara et al., 2008; Bourgeois, 2009; Shanmugam, 2012) describe the characteristics of marine tsunami sediments. Erosional scours belong to these characteristics along with rip-up clasts, soft-sediment deformation, sand injections, parallel lamination, successions of sub-

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units each depicting normal grading and reflecting individual waves of the wave train, and indicators of opposite flow direction by run-up and backwash oscillations (e.g., ripples, antidunes, imbrication). Further features may be a mixture of faunal remains from different habitats, plant material indicating the terrestrial and therefore backwash origin of at least parts of the succession, and a chaotic mixture of boulders and clasts within a fine-grained matrix. Deposits generated by earthquake-triggered tsunamis may be underlain by sediments that display liquefaction, water escape structures, as well as fissures and clastic dykes caused by the seismic events. Impact-tsunami deposits may contain spherules or shocked quartz. However, the distinction of marine tsunami deposits and common turbidites may not always be possible, especially for fine-grained and distal (deep water) sediments. Furthermore, in shallow marine environments, tsunami sediments need to be discriminated from storm and flood deposits. Bourgeois (2009) notes that some of the literature describing ancient tsunami deposits is quite speculative and their interpretations may be wrong. The speculative origin of some of these sequences is underlined by several publications that re-interpret deposits which have previously been attributed to tsunami as the result of submarine debris flows or storm surges (e.g., Murty, 1982; Pickering, 1984; Bahlburg et al., 2010).

In Chile, a number of conspicuous sediment sequences found in formations of Miocene to Pliocene age have been interpreted as submarine tsunami backwash deposits (e.g., Le Roux et al., 2004; Cantalamessa and Di Celma, 2005; Le Roux and Vargas, 2005; Le Roux et al., 2008). One example is the Huentequapi sandstone as part of the Pliocene Ranquil Formation which is, like parts of the La Portada Formation, supposed to be related to the Eltanin impact (Le Roux et al., 2008; Goff et al., 2012). In contrast, broadly coeval deposits of very similar appearance at other locations and in similar tectonic environments were interpreted as submarine mass wasting deposits related to sea level changes and regional tectonics (e.g., Le Roux and Elgueta, 2000; Le Roux and Vargas, 2005; Le Roux et al., 2006). However, unequivocal evidence was not presented for any of the examples. In the case of the proposed Miocene submarine tsunami backwash deposits described by Cantalamessa and Di Celma (2005) at the Mejillones Peninsula, Bahlburg et al. (2010) argue that these deposits were the result of debris flows at the flanks of a tectonic graben system and are not at all related to any tsunami.

In this study, we discuss the origin of a chaotic, clastic deposit several meters thick that is preserved within the shallow marine sediments of the Pliocene La Portada Formation at Hornitos, northern Chile. Hartley et al. (2001) interpreted this coarse clastic bed as a deposit formed during backwash of a tsunami. Later on, the deposit was assigned to the Eltanin impact tsunami (Felton and Crook, 2003; Goff et al., 2012) that was triggered by a bolide impact in the southeast Pacific (Gersonde et al., 1997). We re-evaluate the involved depositional processes in the light of both tsunami and mass wasting events.

2. Background

2.1. Geological setting

The Coastal Cordillera of northern Chile in the region of Antofagasta (23°–24°S) forms a coast-parallel mountain range representing the westernmost continental regions of the central Andean fore-arc. It is positioned above the oceanic Nazca plate, which is being subducted eastward at an angle of c. 20° (Pardo-Casas and Molnar, 1987; Suárez and Comte, 1993). East of a 1–4 km wide coastal plain, the Coastal Cordillera rises steeply to altitudes of up to 2 km along the Great Coastal Escarpment (Paskoff, 1989; Ortlieb et al., 1996). In this region, the Coastal Cordillera mainly consists of Jurassic intrusives and volcanics that are covered by Cenozoic sediments (Ferraris and Di Biase, 1978; Pichowiak et al., 1990; Kramer et al., 2005). According to Hartley and Jolley (1995), a shallow-marine basin developed just west of the Great Escarpment during mid-Miocene to Pliocene times. At the basin margins alluvial, eolian and beach sediments developed. The clastic material that fed of the alluvial fans derived from the coastal escarpment that represented a paleo-cliff during the uplift of the Coastal Cordillera (Hartley and Jolley, 1995; Mather et al., 2014). These fan deposits are intercalated with shallow marine near-shore deposits of Pliocene to Pleistocene age (Ortlieb et al., 1996; Marquardt et al., 2004). Since then, the position of the alluvial fans and the shoreline did not change (Hartley and Jolley, 1995).

An exceptional morphological and structural feature along the coast of northern Chile is the Mejillones Peninsula just north of Antofagasta (Fig. 1). The peninsula protrudes from the main coastline by about 25 km. It is 55 km long and reaches altitudes of about 1000 m in

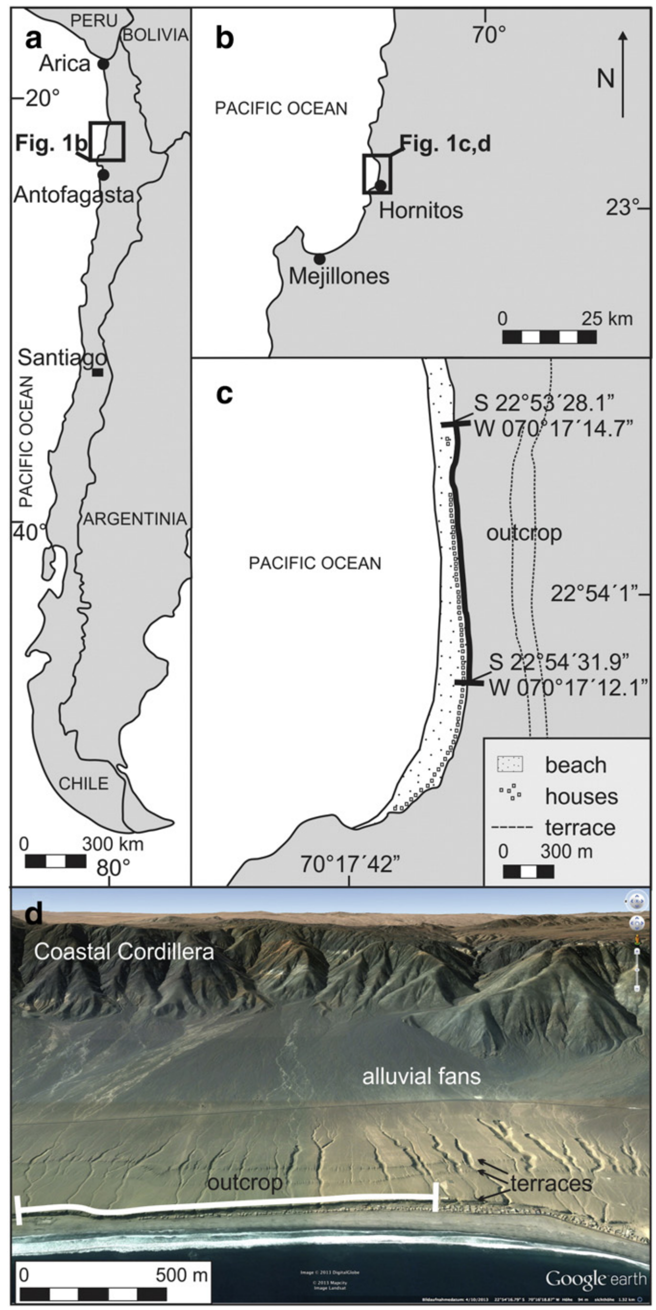

Fig. 1. Map of Chile a) depicting the location of the Mejillones Peninsula, and b) the location of Hornitos. c) Detailed overview of Caleta Hornitos and the coastal scarp where the assumed Pliocene tsunami backwash deposits (Hartley et al., 2001) crop out. d) Oblique aerial view (Google Earth, 2010) of the study site displaying the nearby Coastal Cordillera as source area for the magmatic rock slabs, the alluvial fans that transport coarse clastic material toward the sea, and the Pleistocene coastal terraces.