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GEOLOGICAL NOTE

A critical examination of evidence used to re-interpret the Hornitos mega-breccia as a mass-flow deposit caused by cliff failure

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ABSTRACT. The mega-breccia at Hornitos, northern Chile, was recently re-interpreted as a mass flow deposit caused by cliff failure, without any link to a tsunami backwash or the Eltanin meteorite impact at 2.5 Ma. While agreeing with the latter in the light of new microbiological data, it is here argued that mass flow can also be caused by tsunami backwash events and would be difficult to distinguish from those caused by gravity alone, especially as the Hornitos outcrop is of limited extent. However, a mechanism for downward dyke injection can be postulated for tsunami-related mass flows, but would not be applicable to normal debris flows generated by cliff collapse. The new age range of the Portada Formation coincides with similar deposits at Carrizalillo, Ranquil, Caldera and possibly Caleta Verde, suggesting that one or more mega-tsunamis might have struck the Chilean coastline during the Messinian.

Keywords: Eltanin, Tsunami, Mass flow, Sedimentary dykes, Rip-up mega-clasts, Foraminifer index fossils.

RESUMEN. Un análisis crítico de las evidencias presentadas para reinterpretar la mega-brecha de Hornitos como un depósito de flujo de masa generado por el colapso de un acantilado. La mega-brecha en Hornitos, norte de Chile, se ha reinterpretado recientemente como un flujo de masa generado por el colapso de un acantilado, sin vínculo ninguno con el retroceso de un tsunami o el impacto del meteorito Eltanin a los 2,5 Ma. Aunque se acepta el último en base de datos microbiológicos más recientes, en este artículo se argumenta que los flujos de masa también son generados por los retrocesos de tsunamis y son difíciles de distinguir de flujos generados solamente por gravedad, sobre todo considerando que el afloramiento en Hornitos es de extensión limitada. Sin embargo, se puede postular un mecanismo por la inyección de diques hacia abajo en el caso de flujos relacionados con los tsunamis, que no será válido para flujos de masa generados por el colapso de acantilados. El nuevo rango de edad para la Formación Portada coincide con los rangos de depósitos similares en Carrizalillo, Ranquil, Caldera y posiblemente Caleta Verde, lo que sugiere que uno o más megatsunamis azotaron las costas chilenas durante el Mesiniano.

Palabras clave: Eltanin, Tsunami, Flujo de masa, Diques sedimentarios, Megaclastos arrancados, Fósiles índice de foraminíferos.

1. Introduction

Chile, one of the seismically most affected countries in the world, has often been cited as a natural laboratory for the study of earthquakes and their associated tsunamis. Unfortunately, given the unpredictability of these occurrences, in most cases it is only possible to examine the post-event results, but these can nevertheless give valuable insights into the forces and processes involved.

One of the phenomena associated with tsunamis is a powerful backwash after the arrival of the first or highest wave, which can sweep even large objects back to sea. In Chile, a number of prominent Paleogene debris-flow deposits have been ascribed to tsunami backflows (*e.g*., Le Roux and Vargas, 2005), but this interpretation was recently questioned by Spiske *et al*. (2014). In particular, the Hornitos mega-breccia north of Antofagasta was considered by these authors to be a normal debris flow generated by cliff collapse, in contrast to Hartley *et al*. (2001) who attributed it to a tsunami backwash.

Because of the importance of true tsunami back wash deposits as a window on past events of this nature, it is imperative that they be recognized for what they are. Simply discarding deposits that may indeed reflect tsunami backwash events would deprive science of very valuable information on the nature and frequency of such occurrences. For this reason, the arguments of Spiske *et al*. (2014) are critically examined here to determine whether they constitute indisputable evidence against a tsunami origin for this and other similar deposits along the Chilean coastline.

2. Arguments for and against a tsunami origin

Spiske *et al*. (2014) strongly question the interpretation of Hartley *et al*. (2001) that the conspicuous mega-breccia at Hornitos (Fig. 1) is of tsunami backwash origin. Their title states quite emphatically: "Pliocene mass failure deposits mistaken as submarine tsunami backwash sediments…" However, a careful consideration of their arguments reveals a clear bias not founded on any indubitable facts.

First of all, there is no evidence that tsunami backflows do not produce debris flows capable of transporting huge clasts into the offshore environment. In fact, Spiske *et al*. (2014) even cite Paris *et al*. (2010), who documented that the Indian Ocean tsunami of 2004 transported boulders of 15 m diameter about 2 km offshore. Their assertion that larger rock slabs, such as one several tens of meters in length observed at Hornitos, were not moved by this event, ignores the fact that the latter mega-clast was ripped up locally from the substrate. Such slabs are easily incorporated into high-density mass flows, a process aided by the injection of clastic dykes along bedding planes (Le Roux *et al*., 2004). At Ranquil south of Concepción (Fig. 1), Le Roux *et al*. (2008) described 5 m diameter rip-up clasts injected by sand dykes in the Huenteguapi Sandstone, a mass flow deposit clearly related to a tsunami backwash. The latter interpretation was based on the fact that the mega-clast unit occurs along at least 40 km of coastline perpendicular to the flow, and that the matrix consists mainly of reworked dune sand as indicated by grain surface textures. As pointed out by these authors, dunes cannot collapse on a scale large enough to deposit a 30 m thick mass flow breccia near the edge of the continental shelf. A typical feature of this deposit is the presence of clastic dykes injected into the substrate over distances of tens of meters (Fig. 2). Since then, large-scale clastic dykes have also been documented on Mocha Island (Zambrano *et al*., 2009), 34 km from the mainland and almost 100 km south of Ranquil (Fig. 1). Such a large aerial extent would be impossible to explain by normal mass flow involving coastal dune or even coastal cliff collapse, whereas a large tsunami would be perfectly capable of eroding an entire coastline.

Distinguishing between mass flow deposits generated by normal gravity processes and those caused by tsunami backwash would be very difficult, especially in the absence of extensive outcrops. As at Ranquil, one of the criteria that could be used to determine a tsunami origin would be a large expanse of the resultant deposits, because cliff collapse can be expected to be more localized. At Hornitos, the only outcrop is a 2 km long, shore-parallel profile. However, there is no evidence that this mega-breccia did not continue laterally along the coast, because it is eroded by a Pleistocene marine terrace as clearly shown on figure 6a of Spiske *et al*. (2014). This terrace, with an age of about 125 Ka, is located between 14-25 m above sea-level (Ortlieb *et al*., 1996; Pfeiffer *et al*., 2011) and occurs widely along the central-northern Chilean coast, eroding deposits that range in age from 1.2 Ma at Tongoy (Le Roux *et al*., 2006) to at least 6.45 Ma at Caldera (Pyenson *et al*., 2014). If the Hornitos mega-breccia did extend further to

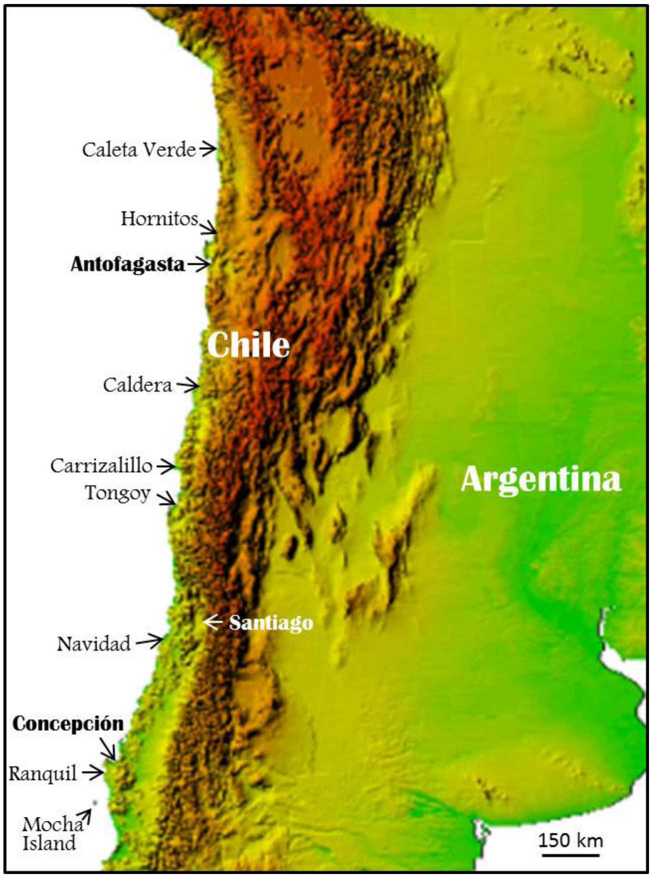

FIG. 1. Localities mentioned in text.

the south or north, therefore, it would be cut by this marine abrasion surface or the present topography in many places. As concerns the seaward extent of this deposit even less is known, because we only have the shore-parallel profile. It is therefore impossible to study downslope facies changes, making the statement by Spiske *et al*. (2014, p. 79) that "Unit VI was deposited en masse without any obvious…horizontal (*e.g*., sediment bypassing) trends", completely unfounded. Their observation that the 2004 Indian Ocean tsunami was different, as it moved only finer-grained sandy to muddy material beyond the shallow marine environment, which "is in sharp contrast to a debris flow that will move material of different grain size en masse and deposit coarse clastic components within a fine-grained matrix, as present in Hornitos", is therefore based on pure assumption. In any case, it is well known that even normal subaquatic mass flows tend to collapse, causing the elutriation of finer-grained matrix components that are deposited further downslope (Postma, 1984). Therefore, downslope facies changes, even if they could be studied at Hornitos, would neither prove nor disprove whether this mass flow deposit was tsunami-generated.

Considering then, that mass flows can be either gravity- or tsunami-generated, the argument of Spiske *et al*. (2014) that similar mega-breccias described elsewhere along the Chilean coast were not originally regarded as tsunami backflow deposits by the respective authors, is unconvincing. Le Roux *et al*. (2004), for example, interpreted mega-breccias within a submarine canyon at Carrizalillo (Fig. 1) as mass flow conglomerates, but never stated that they were caused by sea-level changes and regional tectonics, as wrongly asserted by Spiske *et al*. (2014). Subsequently, Le Roux and Vargas (2005) did relate these deposits to a tsunami backwash, although clearly not linked to the Eltanin impact as they are older than

FIG. 2. Downwardly injected sandstone dykes and sills at Ranquil (see Fig. 1 for location).

the latter. However, there is a possibility that the deposits at Carrizalillo, which have an age range of 8-5.6 Ma (Le Roux *et al*., 2005), could be temporally associated with the Hornitos occurrence as well as others, and could thus reflect an older, mega-tsunami that affected large swaths of the Chilean coastline.

First, the age of the Portada Formation at Hornitos should be reconsidered in the light of a recent study by Gutiérrez *et al*. (2013) on the Navidad Formation southwest of Santiago (Fig. 1). These authors, based on numerous Sr-istope as well as $^{40}Ar/^{39}Ar$ dates, showed that 5 foraminifer index species, including *Neogloboquadrina acostaensis* (or another, virtually indistinguishable ancestral species: see debate on this paper by Finger *et al*., 2013; Le Roux *et al*., 2013; Encinas *et al*., 2014; Le Roux *et al*., 2014) already appeared during the Early Miocene (>13.8 Ma) in the southeast Pacific Ocean, instead of during the early Pliocene (<5.3 Ma) as previously thought. In the Portada Formation this species (or its ancestor) occurs together with *Globigerinoides conglobatus*, which has an FAD of 6.27±0.04 Ma in ODP Leg 165, Site 999 (Chaisson and d'Hondt, 2000). This yields a new upper age limit of 6.31 Ma for this part of the Portada Formation, but its basal parts could be older.

South of Caldera, a mega-breccia composed of poorly sorted rip-up clasts fills a submarine canyon. It has a stratigraphic age between 6.0 and about 8.9 Ma, based on a K-Ar date of 7.6±1.3 on a tuff bed (Marquardt *et al.,* 2000) and a $^{87}Sr/^{86}Sr$ date of 6.8±0.8 Ma (Henríquez, 2006) in the overlying unit. Furthermore, the age proposed by Le Roux *et al*. (2008) for the Huenteguapi Sandstone also has to be revised, as *Globorotalia spheriomiozea* and *Globorotalia puncticulata* are among the 5 index species now considered to extend into the Early Miocene (Gutiérrez *et al*., 2013). These occur in beds below the Huenteguapi mega-breccia, which is overlain by a Zanclean to Gelasian-aged calcareous sandstone (<5.3 Ma; Finger *et al*., 2007). In addition, the mega-breccia described by Mather *et al*. (2014) at Caleta Verde, 270 km north of Hornitos, could also be tsunami-related or even be linked to the same event. Mather *et al*. (2014) tentatively assign a Pliocene age to this deposit, but it also underlies a Pleistocene marine terrace as at Hornitos. A mega-tsunami affecting at least 1,870 km of coastline could thus have occurred during the Messinian, and even though these deposits may not necessarily have been caused by the same event, many of them show features considered by various authors (*e.g.*, Dawson and Stewart, 2008; Bourgeois, 2009; Shanmugam, 2012) to be typical of tsunamis. These include erosional scours, rip-up mega-clasts, sand injections, a mixture of fauna from different habitats, liquefaction in underlying sediments, and water escape structures.

The injection of sand from the base of debris flows into the substrate is problematic, as it would require a strong downward pressure gradient. However, the velocity profile of debris flows typically shows an upward increase in flow speed (Middleton and Southard, 1984), which would imply a decrease in pressure in the same direction according to the Bernoulli equation. Normal debris flows generated by cliff failure should therefore not show downwardly injected sandstone dykes. On the other hand, a possible mechanism to explain this feature is the collision of a debris flow generated by the backflow of a first tsunami wave with an approaching second wave. As both flows would be travelling at least a hundred kilometers per hour, a strong instantaneous pressure would be generated within the flow itself. A tsunami wave shoaling over the continental shelf would show an upward increase in velocity similar to that of a debris flow, but in the opposite direction. Therefore, at the sea floor the pressure caused by two colliding currents would be much less than higher up in the flow where both opposing velocities are higher, thus generating the momentary downward pressure gradient required to inject sediments into the substrate. If this is correct, the presence of downwardly injected dykes and sills can be used to distinguish between normal debris flows and backflows associated with multiple tsunami waves. Figure 7b of Spiske *et al*. (2014) shows a sandstone dyke injected, according to them, from the underlying unit into a large substrate rip-up slab. However, this dyke is clearly much coarser than the immediately underlying deposits and also shows a sharp contact with them, making this interpretation doubtful. On the other hand, it seems to be very similar to the debris flow material itself, as depicted in their figures 7a and c. Unfortunately, the upper part of the dyke has been eroded by the overlying unit, so that its nature is uncertain. Nonetheless, if the proposal of Le Roux *et al*. (2004) that downwardly injected dykes can assist in ripping blocks and beds from the substrate is accepted, this would support a tsunami backflow origin for the Mejillones deposits. In particular, such injections commonly proceed along bedding planes (Le Roux *et al*., 2004; Fig. 3), which would explain the presence of very large, elongate substrate slabs within the mega-breccia.

Calculations of the possible wave heights generated by tsunamis along the Chilean coastline are clearly

FIG. 3. Sandstone dyke injected from base of debris flow at Carrizalillo (see Fig. 1 for location).

contradictory, as demonstrated in the lengthy discussion of Spiske *et al*. (2014). The depth of breaking cannot be determined using wind-generated wave models, for example, and is affected strongly by the offshore bathymetry. Without knowing the exact location of the shoreline at the time, which could easily have changed considerably in the light of continuing tectonism, and given our incomplete knowledge on the hydrodynamics of tsunami waves, it is doubtful if any of the proposed breaking depths are reliable. It should also be remembered that most of the energy of a tsunami is contained in its wavelength (kinetic energy) and not in its height (potential energy), a fact ignored by Spiske *et al*. (2014). It is also doubtful that the Mejillones Peninsula would have protected the mega-breccia site from a tsunami, given its location about 26 km northeast of the northernmost tip of the latter. Even a tsunami generated in the south would easily refract around the peninsula and impact directly on this part of the coastline. Furthermore, if such an event occurred during the Messinian (7.2-5.3 Ma), it is irrelevant that the Mejillones Peninsula started to develop at 3.4 Ma.

3. Conclusions

To summarize, the arguments put forward by Spiske *et al*. (2014) against a tsunami origin for the mega-breccia at Hornitos are unfounded in the light of the fact that tsunamis do generate mass flows which would be difficult to discern from gravity-generated debris flows, especially in the absence of extensive outcrops. The presence of downwardly injected sandstone dykes might even directly support a tsunami origin. A reinterpretation of the age of the La Portada Formation as well as that of similar deposits further north and south along the Chilean coastline, based on recently extended ranges of the foraminifer index species used to date them, confirms that the Eltanin impact could not have been responsible, but opens up the possibility of another mega-event during the Messinian. This can only be confirmed by more precise dating of the respective deposits.

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