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GEOLOGICAL NOTE

A possible Plio-Pleistocene tsunami deposit, Hornitos, northern Chile

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ABSTRACT

A section equivalent to the Pliocene La Portada Formation exposed in the coastal cliff at Hornitos, northern Chile, contains a *ca.* 7-10 m thick conglomerate bed. The bed occurs within a succession of shallow marine sandstones and has an erosional contact with underlying strata. The largest boulders of basement (5 m) are angular to very angular and are set within a matrix of very poorly sorted fine to very coarse grained shell-rich sandstone. Also present are very well rounded granodiorite pebbles and shallow marine sandstone intraclasts (maximum 10 m). The clast size, erosional contact, associated facies and bed thickness suggests that the conglomerate bed is a shallow marine tsunami deposit. The angular clasts indicate limited transport and no marine reworking prior to deposition. They represent alluvial fan sediment incorporated into the bed during tsunami backflow. Intraclasts of shallow marine sandstone are thought to have been ripped up and included in the bed during the seaward passage of the tsunami across the shoreface.

Key words: Tsunami, northern Chile, Pliocene, shallow marine

RESUMEN

Un posible depósito de tsunami Plio-Pleistoceno, Hornitos, norte de Chile. Una sección equivalente a la Formación La Portada de edad pliocena, expuesta en el acantilado costero en el sector de Hornitos, norte del Chile, expone un estrato de conglomerados de *ca.* 7-10 m de potencia. El estrato ocurre dentro de una sucesión de areniscas marinas someras y tiene un contacto de erosión con los estratos infrayacentes. Los clastos mayores (5 m) de basamento son angulares a muy angulares y se emplazan en una matriz arenisca de grano fino a muy grueso, pobre a muy pobremente seleccionada y con abundantes conchas. También están presentes clastos bien redondeados de granodiorita junto a intraclastos de areniscas marinas someras. El tamaño de los clastos, el contacto erosional, las facies asociadas y la potencia del estrato sugieren que el estrato de conglomerados es un depósito marino somero correspondiente a un tsunami. Los clastos angulares indican un transporte limitado sin retrabajo marino con posterioridad a su depositación. Ellos representan sedimentos de un cono aluvial incorporados al estrato durante el flujo de retroceso del tsunami. Los intraclastos de la arenisca marina somera se consideran que son producto de la erosión e inclusión en los conglomerados durante la etapa de avance del tsunami a través de la zona de anteplaya.

Key words: Shallow marine, Tsunami, Pliocene, Northern Chile.

INTRODUCTION

The present day coastline of northern Chile and southern Peru is considered to have the highest seismic and tsunamogenic potential of any region along the coast of South America (Lockridge, 1985). However, despite the common occurrence of tsunamis in northern Chile since historical records began (*e.g.*, Lomnitz, 1970), few descriptions of tsunami deposits are known from either the historical or the recent geological (Plio-Pleistocene) record, with the exception of Paskoff (1991). Here the authors describe a conglomerate bed from the Pliocene succession at Hornitos, northern Chile (Fig. 1). On the basis of its content, internal organisation, associated facies and geographic position with respect to the Cordillera de la Costa the bed is interpreted to represent the shallow marine deposit of a major Pliocene tsunami. It is thicker than previously documented tsunami deposits.

LOCATION AND STRATIGRAPHY

The studied section is located within the 25 m high sea-cliff at Hornitos, northern Chile (Figs. 1 and 2). A summary of the stratigraphy at Hornitos is shown in figure 3. The oldest exposed rock type comprises basaltic andesites of the Jurassic La Negra Formation (Ferraris and Di Biase, 1978). The andesites are unconformably overlain by an approximately 30 m thick succession of yellow sandstones that contain the studied conglomerate bed. In places, up to 5 m of relief can be seen on the basal unconformity surface. The sandstones contain shell fragments and rare locally derived pebbles; they are reasonably well cemented and locally fractured. Bedding where visible indicates that this succession dips gently (5-10°) towards the north-northwest. A horizontally bedded, shell-rich conglomerate truncates and unconformably overlies the yellow sandstones. This shell-rich conglomerate forms the lowest of a series of discontinuous Pleistocene marine terraces that are well known from the Hornitos area and Mejillones Peninsula (*e.g.*, Ortlieb, 1995). These terrace deposits have been given formation status and are referred to as the Mejillones Formation (Ferraris and Di Biase 1978).

The yellow sandstones that include the studied conglomerate bed are considered to be equivalent to the Pliocene succession referred to as the La Portada Formation (Ferraris and Di Biase, 1978). This formation crops out over the southern half of the Mejillones Peninsula and extends further southwards to the northern edge of Antofagasta (Fig. 1). At the type locality, La Portada, the formation consists of 40 m of shallow marine sandstones that unconformably overlie the La Negra Formation and are themselves truncated by Pleistocene marine terrace deposits (Herm, 1969; Ferraris and Di Biase, 1978), an identical succession to that present at Hornitos.

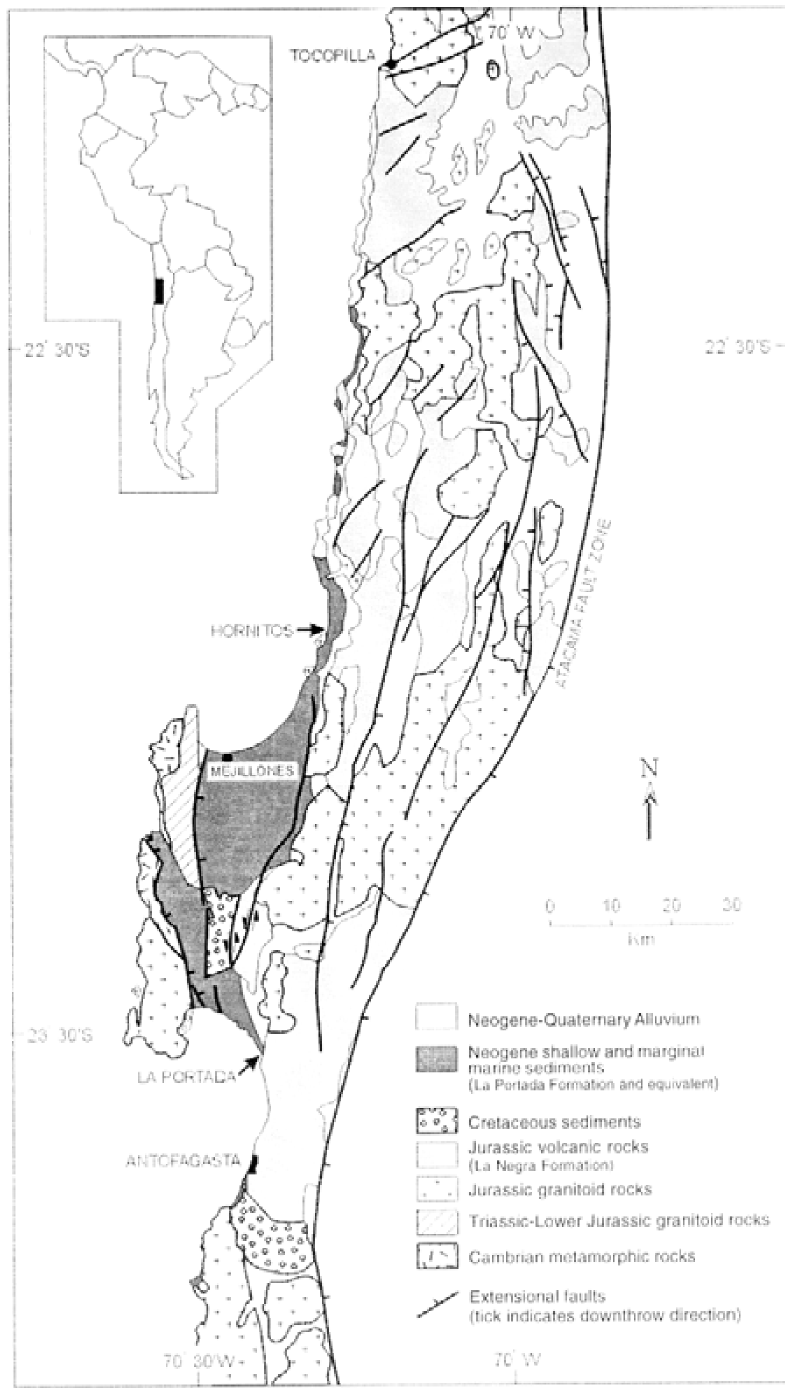

FIG. 1 General geology of the Cordillera de la Costa of northern Chile, showing the location of Hornitos and other Neogene shallow marine deposits (after Ferraris and Di Biase, 1978; Boric *et al.*, 1991).

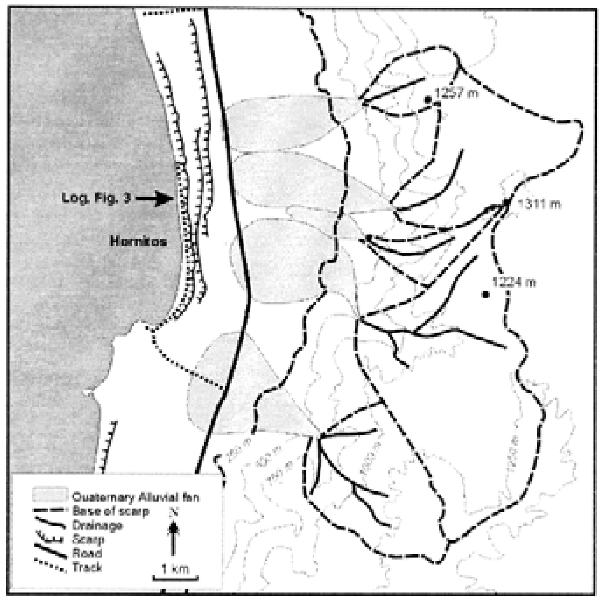

FIG. 2. Topographic setting of the tsunami deposit, drawn from 1:50.000 topographic maps and aerial photographs. Note that the catchment areas for the Quaternary fans are very similar to the catchment areas that existed in the Pliocene, in this part of the cordillera.

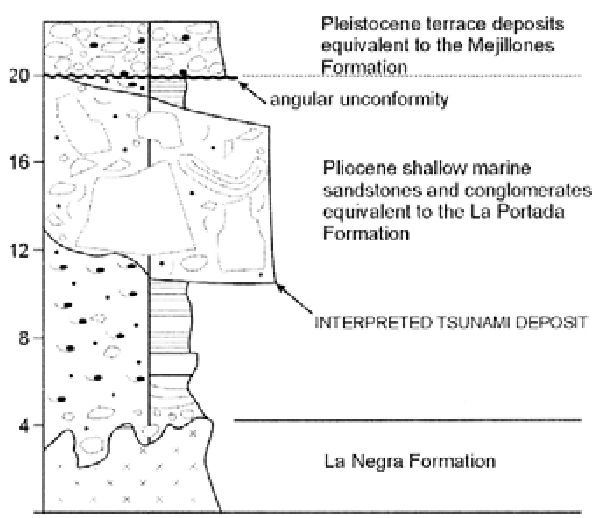

FIG. 3. Simplified stratigraphic section of the strata exposed in the sea-cliff at Hornitos.

SEDIMENTOLOGY OF THE PLIOCENE SUCCESSION

A *ca.* 7 m thick conglomerate bed is exposed towards the cliff top at 70°53'50"W, 22°17'00"S and dips gently to the north over a distance of 1,400 m. For much of the outcrop the top of the bed is truncated beneath the overlying horizontal Pleistocene marine terrace. In addition at the northern end of the outcrop the top of the bed is typically obscured by recent scree, thus as such a complete section is not always present. In addition, at the northern end of the outcrop the bed top is partially obscured by recent scree. The sandstone succession present above and below the conglomerate is described first in order to provide a context for the environment in which the conglomerate was deposited.

SANDSTONE DESCRIPTION AND INTERPRETATION

The deposits present both above and below the conglomerate bed consist of poorly to very poorly sorted, fine to very coarse grained yellow sandstone (coarse is the average grain size) with occasional scattered granules and pebbles. Broken and partially broken shell fragments (particularly barnacles) are commonly distributed throughout the sandstone. The sandstone appears to be massive, partially due to weathering but also due to extensive bioturbation. Where sedimentary structures are present they include poorly developed horizontal to sub-horizontal stratification and probable low angle cross-stratification often picked out by pebble- and granule-rich horizons. Where observed, at the northern part of the outcrop, the unit overlying the conglomerate bed shows a poorly defined upward coarsening grain size profile.

The coarse grained, shell-rich nature of the sandstones suggests a relatively high energy, shallow marine environment. The lack of mud and silt grade material indicates deposition above fair weather wave base, although the intensive bioturbation indicates relatively quiescent conditions. The absence of trough cross-stratification representing bar development in the shoaling wave to breaker zone of the shoreface (*e.g.*, Hunter *et al.*, 1979) indicates that these sediments do not represent upper shoreface deposits. In addition the lack of mm.-scale, low angle (6°) planar to sub-horizontal lamination with heavy mineral horizons and inverse grading (*e.g.*, Clifton, 1969) suggests that they do not represent foreshore deposits. Consequently a mid-shoreface environment, seaward of the breaker zone, is envisaged. This environment prevails at the present day along the north Chilean coastline and is unlikely to have changed substantially since the Pliocene (*e.g.*, Hartley and Jolley, 1995, 1999).

CONGLOMERATE DESCRIPTION AND INTERPRETATION

The conglomerate bed has an erosional contact (up to 21 m of relief) with the underlying shallow marine sandstones (Fig. 4). The dip of this contact varies from less than 10° to sub-vertical. In some areas the contact appears to have been disrupted by post-depositional soft-sediment deformation. The conglomerate is extremely poorly sorted and may be clast- or matrix-supported (Fig. 5). Discontinuous matrix-rich horizons can be traced laterally for 10 m. No obvious imbrication, sorting or grading was observed. Clasts within the conglomerate comprise 3 types: **1-** angular to very angular clasts of La Negra Formation andesite, ranging from granules to large boulders up to 5 m in diameter; **2-** very well rounded pebbles and cobbles of granodiorite; **3-** blocks of shallow marine

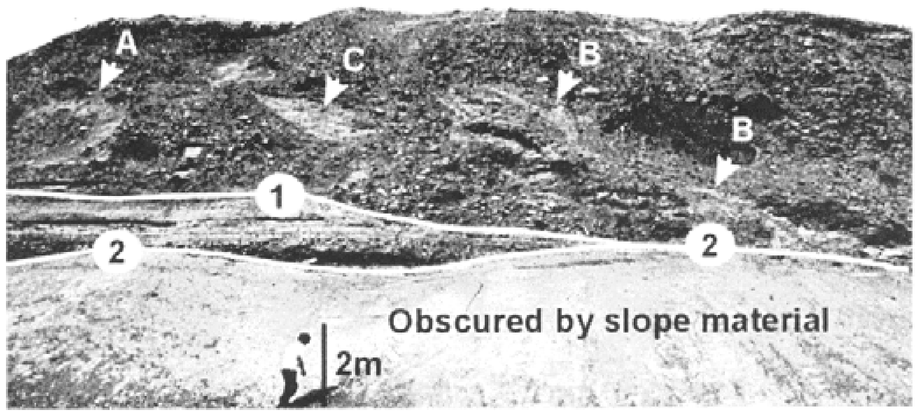

FIG. 4. General view of tsunami deposit at Hornitos displaying shallow marine sediments incorporated in a conglomerate as recumbent folds (A); thrust sheets (B), and rip-up clasts (C). Note the erosive base of the deposit (1) partially obscured by slope material (2).

sandstone identical to the underlying sediment (Fig. 5). Sandstone clast long-axes range in length from 0.05 to 10 m and often coincide with the original bedding fabric. Larger clasts may be folded and lie parallel or sub-parallel to the regional bedding (Fig. 4). Folds may be gentle or recumbent. Clasts whose long axes are generally less than a metre may have a vertical to sub-vertical orientation. Large scale soft sediment deformation features occur around the larger clasts.

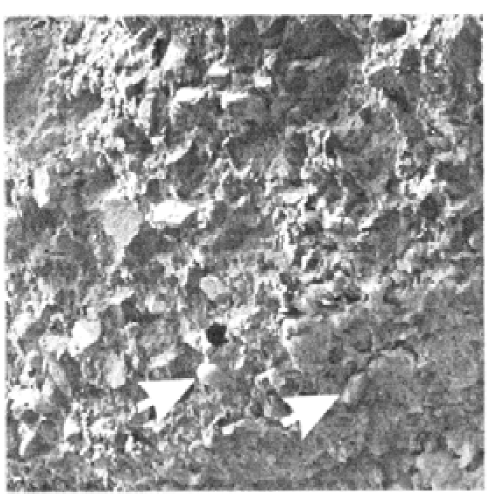

FIG. 5. Detailed view of conglomerate showing intermixing with well rounded clasts (arrowed). Lens cap for scale.

The conglomerate matrix consists of very poorly sorted fine to very coarse grained sandstone with numerous broken shell fragments, scattered granules and small pebbles of granodiorite and La Negra Formation material. Matrix-rich areas appear massive in most parts of the outcrop, although in some cases poorly defined horizontal to sub-horizontal stratification can be observed.

The thickness, variety of clast sizes, as well as the ungraded and unsorted nature of the conglomerate bed suggest that it represents a single depositional event. The sandstone clasts represent intraclasts derived from erosion of the underlying sandstone. The folded nature of the clasts and the vertical contact of the erosion surface at the base of the conglomerate indicate that the sandstone was partially-lithified prior to incorporation into the conglomerate bed. The very well rounded granodiorite pebbles are considered to have been derived from a contemporaneous beach. This interpretation is based on an analogy with modern day pebbly shorelines in northern Chile, where very well rounded pebbles of granodiorite form small beach cusps (Hartley & Jolley 1999). The conglomerate matrix is identical to that of the encompassing shallow marine sandstones, comprising very poorly sorted, shell-rich sandstone, indicating derivation from unconsolidated shoreface sediment. Thus the matrix, well rounded pebbles and sandstone intraclasts all indicate derivation of material from the shoreface and foreshore environment. In contrast the angularity of the andesite clasts indicates that they were not derived from a beach or shoreface setting. However, similarly angular andesite clasts are present within adjacent, recent, alluvial fan deposits 1 km to the east of Hornitos. It is suggested therefore, that alluvial fan material up to 5 m in diameter was incorporated into a single event bed containing sediment derived from a shoreface and foreshore environment.

Many features of the Hornitos conglomerate bed are considered to be characteristic of a tsunami deposit according to the criteria identified by Einsele (1998). These criteria include: an erosive base, an unusually coarse grain size in comparison with surrounding sediment and a mixture of clasts derived from shallow water, the beach zone and inundated land. An alternative interpretation as a large debris flow deposit derived from the adjacent alluvial fans is unlikely, as: **1-** it is difficult to envisage how a debris flow could result in subaqueous scouring of the shoreface and incorporate shell material, sandstone intraclasts and foreshore-derived pebbles into the resulting deposit; **2-** any debris flow deposit is likely to be eroded and reworked by subsequent storm and fairweather processes, and **3-** the location of the conglomerate deposit ranges from 3-5 km from the coastal scarp and its associated drainage system (the top of the scarp is taken at the 1,000 m contour, Fig. 2). The Plio-Pleistocene drainage is still preserved along the coastal cordillera (Fig. 2) and is of insufficient size to develop such a high magnitude event.

The conglomerate bed is therefore interpreted as the deposit of a single Pliocene tsunami. Following this interpretation, a scenario can be envisaged where the tsunami passed across the Pliocene shoreface and foreshore and inundated the contemporaneous alluvial fan covering the adjacent coastal plain. Einsele (1998) noted that the backflow of a tsunami is commonly focussed by the coastal morphology into a channelised flow, thus becoming more powerful and therefore more erosive than the landward-directed flow. As a consequence of this, it is likely that the majority of the alluvial fan material and foreshore pebbles, together with shoreface scouring and incorporation of sandstone intraclasts took place during tsunami backflow. This is supported by the presence of large blocks of alluvial fan material being transported into the shoreface environment and the thickness of the conglomerate.

DISCUSSION

The Pliocene tsunami deposit at Hornitos is unusual in that it is preserved within a high energy, wave-dominated, shoreface environment. In this environment, it is likely that the deposit would be rapidly reworked by storm and wave processes. A further unusual feature is the bed thickness, tsunami deposits interpreted from shallow marine or terrestrial settings are generally less than a metre or at the most three metres thick (e.g. Long *et al.*, 1989; Minoura and Nakaya, 1991; Shiki and Yamazaki, 1996; Massari and DíAlessandro, 2000). Indeed the Hornitos conglomerate appears to be one of, if not the thickest described tsunami deposit associated with shallow marine or terrestrial sediments that has been recorded.

A possible explanation for both the depositional environment and thickness of the Hornitos conglomerate bed is that the Pliocene tsunami was an extremely large magnitude event. This interpretation is supported by the size of the clasts incorporated within the flow that were transported from the alluvial fan into the shoreface. In addition a particularly powerful current would have been required to remove unconsolidated sand, scour at least a metre down into the shoreface and rip-up large clasts of semi-lithified sandstone. This powerful event left a substantial deposit in the upper shoreface, however, because of the size of the deposit only limited reworking took place prior to deposition of the next bed. As the top of the conglomerate appears to be abruptly overlain by shoreface sandstones, it is likely that some reworking has taken place. This hypothesis is based upon the fact that most interpreted tsunami deposits display a graded bed top (Einsele, 1998) associated with waning flow following passage of the tsunami wave. A graded top to the Hornitos deposit was either not deposited which appears unlikely in comparison with other tsunami deposits, or it was not preserved. The latter scenartio is preferred here where it is inferred that subsequent storm and fair weather processes removed the graded bed top. It is also significant to note that without the geographic context, the Hornitos conglomerate may have been interpreted as a large debris flow deposit or seismite. It is possible that the processes that deposited other, comparable, beds may have been misinterpreted.

The large scale of the Hornitos conglomerate bed, as previously noted, suggests that it represents a very large magnitude event deposit. As such this event bed should form a useful stratigraphic marker correlatable throughout the Pliocene succession of northern Chile.

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REFERENCES

Boric, R.; Díaz, F.; Maksaev, V. 1990. Geología y Yacimientos Metalíferos de la Región de Antofagasta. *Servicio Nacional de Geología y Minería, Boletín*, No. 40, 246 p.

Clifton, H.E. 1969. Beach lamination: nature and origin. *Marine Geology*, Vol. 7, p. 553-559.

Einsele, G. 1998. Event stratigraphy: recognition and interpretation of sedimentary event horizons. *In* Unlocking the stratigraphical Record: advances in Modern Stratigraphy (Doyle, P.; Bennet, M.R.; editors). *Wiley*, p. 145-193. Chichester, England.

Ferraris, F.; Di Biase, F. 1978. Hoja Antofagasta. *Instituto de Investigaciones Geológicas de Chile, Carta Geológica de Chile*, No. 30, 48 p.

Hartley, A.J.; Jolley, E.J. 1995. Tectonic implications of Late Cenozoic sedimentation from the Coastal Cordillera of northern Chile (22-24°S). *Journal of the Geological Society of London*, Vol . 152, p. 51-63.

Hartley, A.J.; Jolley, E.J. 1999. Unusual coarse, clastic, wave-dominated shoreface deposits, Pliocene to Middle Pleistocene, northern Chile: implications for coastal facies analysis. *Journal of Sedimentary Research*, Vol. 69, p. 105-114.

Herm, D. 1969. Marines Pliozän und Pleistozän in Nord und Mittel-Chile unter besonderer Berücksichtigung der Entwicklung der Mollusken-Faunen. *Zitteliana*, Vol. 2, 159 p. München.

Hunter, R.E.; Clifton, E.; Phillips, R.L. 1979. Depositional processes, sedimentary structures, and predicted vertical sequences in barred nearshore systems, southern Oregon coast. *Journal of Sedimentary Petrology*, Vol. 49, p. 711-726.

Lockridge, P.A. 1985. Tsunamis in Perú-Chile. *National Geophysics Data Centre and World Data Center A for Solid Earth Geophysics, NOAA*, Report SE-39, 79 p. Boulder, Colorado.

Lomnitz, C. 1970. Major earthquakes and tsunamis in Chile during the period 1535 to 1955. *Geologische Rundschau*, Vol. 59, p. 938-960.

Long, D.; Smith, D.E.; Dawson, A.G. 1989. A Holocene tsunami deposit in eastern Scotland. *Journal of Quaternary Science*, Vol. 4, p. 61-66.

Massari, F.; D' Alessandro, A. 2000. Tsunami-related scour-and-drape undulations in Middle Pliocene restricted-bay carbonate deposits (Salento, south Italy). *Sedimentary Geology*, Vol. 135, p. 265-281.

Minoura, K.; Nakaya, S. 1991. Traces of tsunami preserved in inter-tidal, lacustrine and marsh deposits: some examples from Northeast Japan. *Journal of Geology*, Vol. 99, p. 265-287.

Ortlieb, L. 1995. Late Quaternary coastal changes in northern Chile: fieldguide for International Geological Correlation Program Project 367, Late Quaternary records of Coastal Change, Annual Meeting, 1995. *Orstom*, 175 p. Antofagasta, Chile.

Paskoff, R. 1991. Likely occurrence of a mega-tsunami in the middle Pleistocene near Coquimbo, Chile. *Revista Geológica de Chile*, Vol. 18, p. 87-91.

Shiki, T.; Yamazaki, T. 1996. Tsunami-induced conglomerates in Miocene upper bathyal deposits, Chita Peninsula, central Japan. *Sedimentary Geology*, Vol. 104, p. 175-188.

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