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Hydraulic behavior of tsunami backflows: insights from their modern and ancient deposits

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Abstract Tsunamis are unpredictable, catastrophic events, and so present enormous difficulties for direct studies in the field or laboratory. However, their sedimentary deposits yield evidence of a wide variety of hydrodynamic conditions caused by flow transformations on a spatial and temporal scale. Tsunami deposits ranging from the Miocene to modern times identified at different localities along the Chilean coast are described to provide a database of their characteristics. Among the typical features associated with tsunami deposits are well-rounded megaclasts eroded from coastal alluvial fans or beaches by very dense, competent flows. Sand injections from the base of these flows into the substrate indicate very high dynamic pressures, whereas basal shear carpets suggest hyperconcentrated, highly sheared flows. Turbulence develops in front of advancing debris flows, as indicated by megaflutes at the base of scoured channels.

Keywords Tsunami · Bingham fluid · Sandstone dikes

Introduction

One of the oldest working hypotheses in geology was formulated by Sir James Hutton in 1785: "The present is the key to the past". The observation of sedimentary transport and depositional processes along modern rivers, coastlines and in the marine realm greatly assists in the interpretation of their ancient deposits, where sedimentary structures similar to those forming presently are commonly preserved. Civil and hydraulic engineers have made a vast contribution to the knowledge of sedimentologists concerning sediment transport in these environments. However, the average engineer is probably unaware of the potential contribution of hard-rock sedimentologists to the understanding of certain hydraulic processes. Under some circumstances, the past can actually be a key to the present, as observed by Kelling and Stanley (1978). This is particularly true in the case of unpredictable, catastrophic events occurring on a scale far too large to simulate accurately in the laboratory. In this category can be included mud and snow avalanches, pyroclastic flows and tsunamis. All of these pose a great risk to the world's inhabitants, as demonstrated again by the tsunami that devastated parts of southeast Asia in December 2004. It is therefore vital to understand the hydraulic processes involved. In this article we describe the sedimentary deposits left by tsunamis all along the Chilean coast, in an endeavor to record their characteristics and to obtain better insights into the processes and possible magnitude of these events.

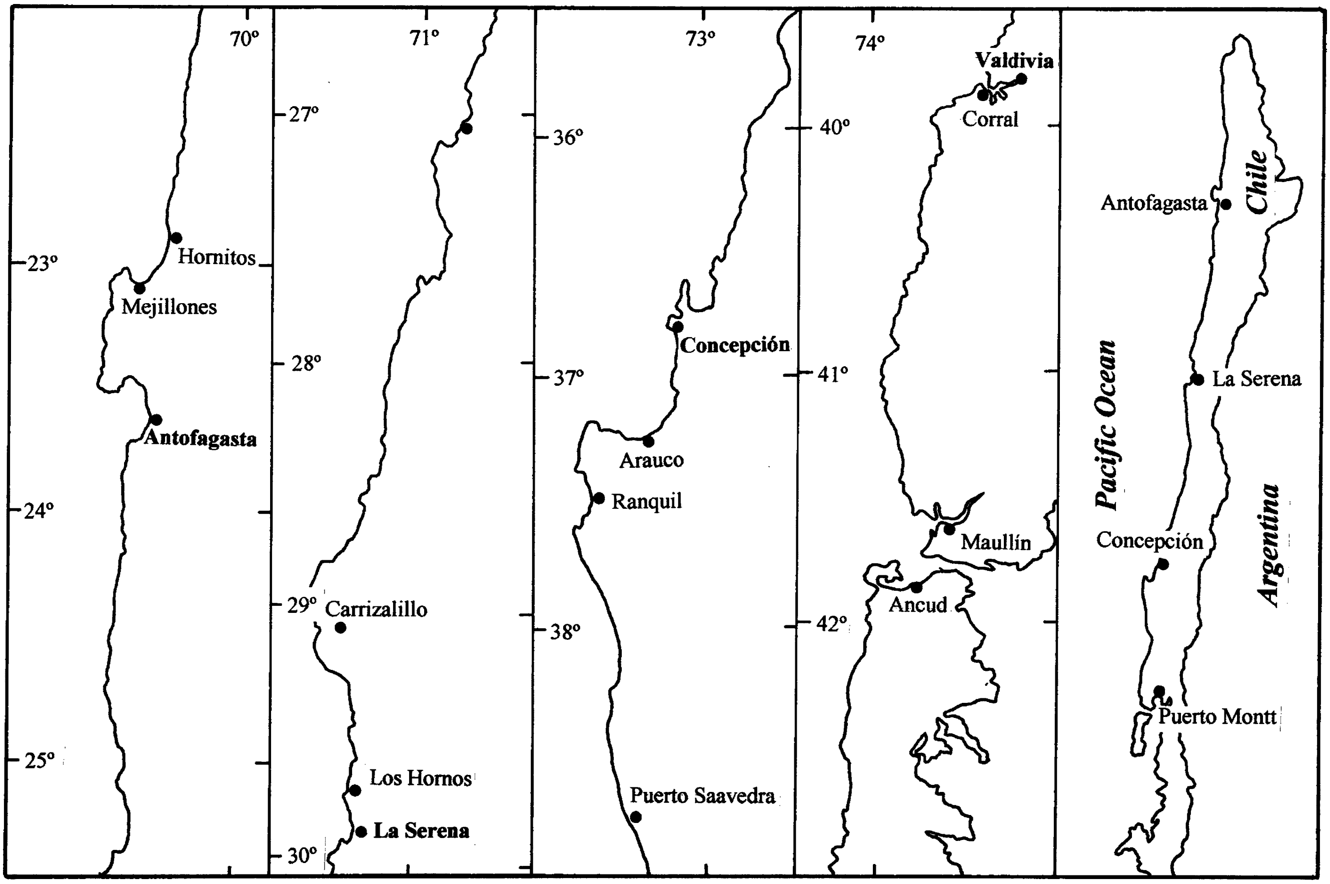


Fig. 1 Locality map of tsunami deposits and other localities mentioned in the text

Modern tsunami deposits

As one of the seismically most active regions in the world, Chile is a great natural laboratory where both recent and ancient tsunami deposits abound. The largest earthquake ever recorded in modern times, measuring 9.5 on the Richter scale, took place on 22 May 1960 near the town of Valdivia and caused a tsunami that devastated coastal towns such as Puerto Saavedra, Corral, and Ancud (Fig. 1). In the Maullín Estuary, eight waves reaching a maximum height of about 14 m advanced upstream and deposited a layer of sand up to 9 km inland (Cisternas et al. 2000). A similar sand bed was also deposited by the same event elsewhere along the coast (Watanabe and Karzulovic 1960; Wright and Mella 1963; Bartsch-Winkler and Schmidt 1993). In the Maullín Estuary, the tsunami bed is described by Cisternas et al. (2000) as a fine-grained quartz sand varying in thickness between 3 and 10 cm, overlying organic-rich muds with an erosional contact. No sedimentary structures were observed, so that the direction of transport during its deposition cannot be determined directly. However, Cisternas et al. (2000) tabulate the granulometric characteristics of 65 sand samples taken from the bed on a marsh, east of the confluence of the Maullín and Cariquilda Rivers. This can be analyzed using methods developed by Le Roux (1994) and Le Roux et al. (2002) to determine the transport direction. Figure 2 indicates that the tsunami onrush and backwash took place along well-defined zones. The strong northern onrush zone lies just south of the Maullín River, suggesting that the tsunami advanced rapidly up the latter. The existence of a backwash zone in the north-central part of the marsh between the northern and weaker southern onrush zones indicates the development of a kind of rip current in this area. Einsele (1998) noted that the backflows of tsunamis are commonly focused by the coastal morphology into channelized flow. Reflection off the mainland bordering the Cariquilda River to the south is in fact suggested by the northerly current directions within the southern backwash zone. Rip currents such as the one that possibly developed in the central backwash area may attain very high velocities and should be capable of transporting large volumes of sediment out to the sea.

The Bay of Mejillones (23°S), north of Antofagasta (Figs. 1, 3), is a sedimentary basin dominated by

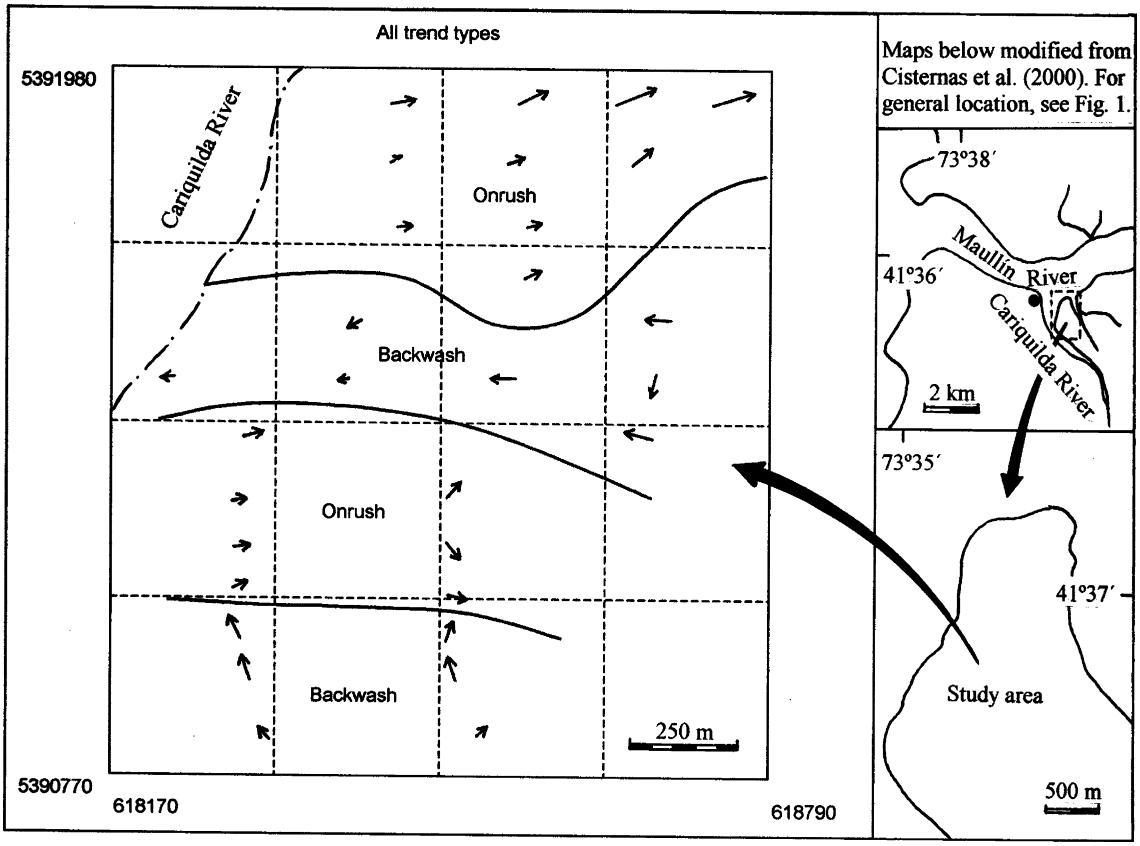


Fig. 2 Current directions and rush-up/backwash zones of 1960 tsunami as determined by grain-size granulometry along the Maullín Estuary

hemipelagic sedimentation of organic-rich diatomaceous mud (Ortlieb et al. 2000; Vargas et al. 2004). The analysis of several short sediment cores obtained from a water depth of 75–110 m in the central part of the bay revealed some conspicuously anomalous sedimentological features, such as an angular unconformity and a slump deposit. As shown by Vargas et al. (2005), these features are associated with discontinuous, lenticular beds, a few cm thick, which are anomalously enriched in coarse lithic grains (Fig. 4). These characteristics suggest local reworking of the material eroded from shallower areas (generally less than 50 m) along the basin margin, which could be associated with tsunami backwash currents after strong seismic events. From detailed geochronological models based on the analysis of ^{14}C and ^{210}Pb downcore data and lateral correlation of cores, Vargas et al. (2005) inferred the ages as between A.D. 1409 and 1449 for the first event and between A.D. 1754 and 1789 for the second. As no anomalous features were observed in the top of the succession that could be associated with the last great subduction earthquake and tsunami in northern Chile during 1877, this suggests that the fifteenth and eighteenth century events had a higher intensity or were of local origin. Both tsunami events inferred from the cores were probably due to the reactivation of the Mejillones Fault during earthquakes. The first event occurred about 100 years before the 1543 historical earthquake, whereas the second probably correlates with the great historical earthquake of 1768 in northern Chile (Comte and Pardo 1991).

Acoustic profile data recently obtained from the same basin (Vargas et al. 2005) reveal the occurrence of a several meters thick, widely distributed slump deposit within the Holocene sedimentary infill of the bay (Fig. 5). Taking into account the sedimentation rates inferred from the analysis of short sediment cores from the central part of the basin and considering the dimensions and location of the slump in the upper part of the sedimentary infill, we suggest that this records the most important tsunami event in the area, most probably during the Middle to Late Holocene, a few thousand years ago (Vargas et al. 2005). Detailed mapping and characterization of this deposit will be required to evaluate the role of different processes in its development.

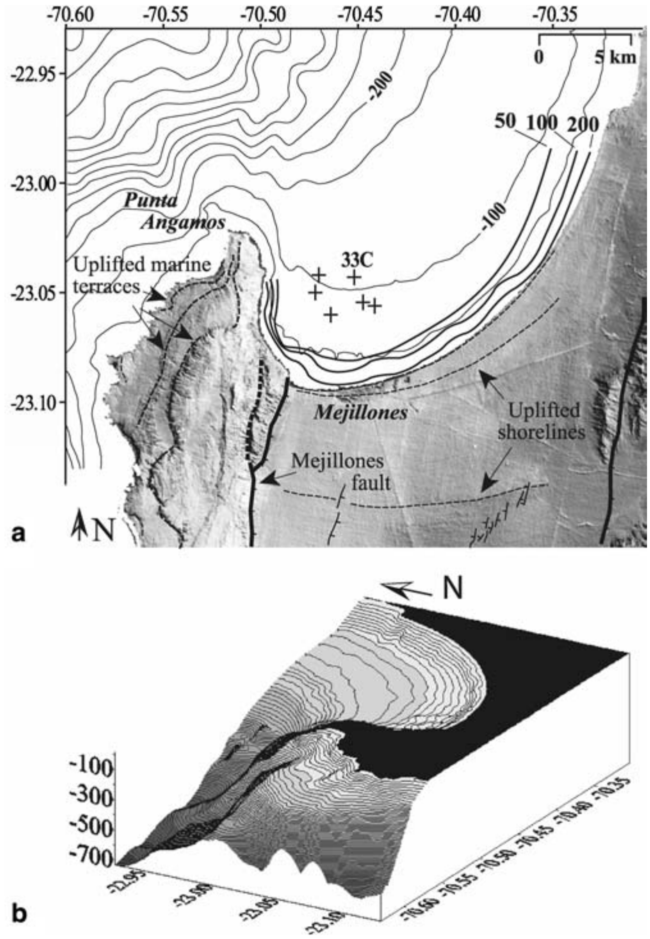


Fig. 3 **a** Bathymetry and geomorphology of Mejillones Bay in northern Chile, showing major morphotectonic features as uplifted marine terraces and shorelines, recent fault scarps, and the location of the short sediment cores previously studied. The maximum depth of the mean grain sizes corresponding to 50, 100, and 200 µm are also shown. **b** Three-dimensional view of the bathymetry. The basin constitutes a small platform oriented towards the north

Ancient tsunami deposits

Modern tsunami deposits described in the literature, including those mentioned above, rarely exceed 3 m in thickness (Minoura and Nakaya 1991; Shiki and Tamazaki 1996; Massari and D′Alessandro 2000) and seem to be dwarfed by the scale of beds attributed to tsunamis in the geological past. For example, a probable Plio-Pleistocene tsunami deposit described at Hornitos (northern Chile) by Hartley et al. (2001) and Cantalamessa and Di Celma (2005) is 7–10 m thick. This deposit, also examined by us, shows many of the characteristics typical of tsunami beds, including extremely poor sorting, angular basement boulders, large rip-up intraclasts reaching up to 10 m in length, and an erosional base. In this case the tsunami seems to have also incorporated well-rounded alluvial boulders up to 5 m in diameter from a contemporaneous alluvial fan on the adjacent coastal plain (Hartley et al. 2001), but the bed itself is preserved in middle shoreface deposits formed beyond the breaker zone.

Our observations of Miocene–Pliocene tsunami beds at different localities along the Chilean coast reveal a wide range of features that reflect the hydrodynamic behavior of tsunami backflows.

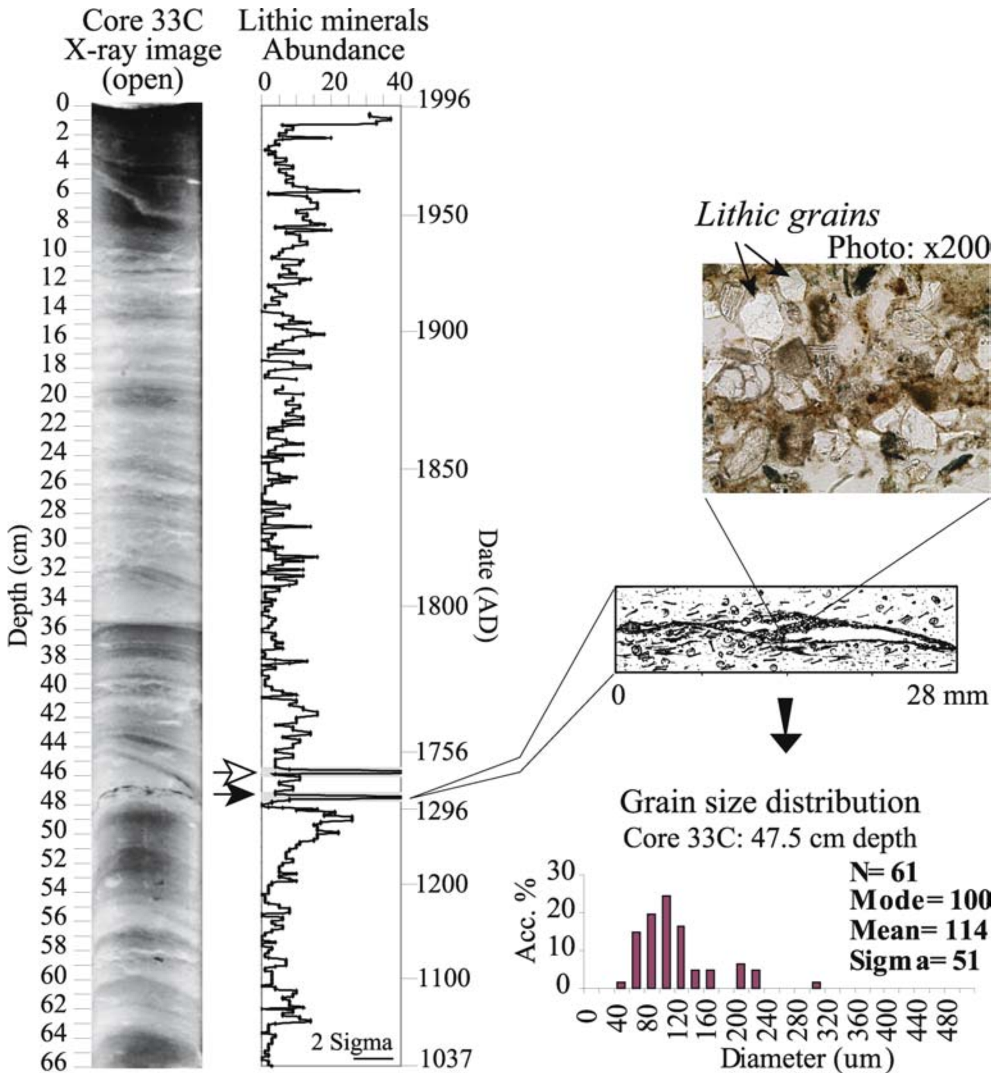
Sedimentologic characteristics

One of the features that we consider to be the most reliable evidence for tsunamis is the presence of sandstone injections and dikes penetrating the underlying strata, commonly associated with large intraclasts within the deposit itself (Le Roux et al. 2004). These injections evidently develop when sand under high pressure enters cracks in the top of the substrate, usually composed of very fine sandstone, siltstone, or mudstone. The fractures are clearly not mudcracks, so they are attributed to the shattering effect of an earthquake on semi-consolidated sediments, followed shortly thereafter by a sediment-laden tsunami backflow. At Carrizalillo about 100 km north of La Serena (Fig. 1), Le Roux et al. (2004) describe coarse sandstone injections emanating from the base of a channelized tsunami bed loaded with large, fine-grained sandstone intraclasts (Fig. 6). The injections reach over a meter in length (Fig. 7), widening the fractures and proceeding along the bedding planes of the underlying fine sandstone. Large clasts were evidently plucked from the latter as the injections deflected again to the substrate surface.

In the Miocene Ranquil Formation south of Arauco (Fig. 1), a thick mudstone unit is criss-crossed in places by unusually large sandstone dikes and sills proceeding from the base of a massive, coarse to a very coarse sandstone bed (Fig. 8). In this case the injections reach lengths exceeding 15 m, suggesting very high dynamic pressures probably due to an extremely violent event. Enormous blocks of mudstone floating within the sandstone are cracked and injected around their margins, in some cases forming a distinct mudstone breccia (Fig. 9).

At Carrizalillo and Hornitos, many of the substrate intraclasts are parts of sandstone beds that had been folded within the tsunami deposit (Fig. 6). This indicates that the substrate beds were at least partially consolidated, but retained enough flexibility not to break up completely within the debris flow itself. The folds indicate a strong shearing action within the flow, but apparently not competent enough to shatter the clasts completely. The flows must also have been dense enough to prevent these intraclasts from sinking to the bottom of the unit, thus suggesting hyperconcentrated flow. A lack of turbulence is indicated by the absence of traction structures such as cross-lamination.

Fig. 4 X-ray radiograph (positive phase) of sediment core 33C and relative abundance of lithic minerals (N°. 7 mm^{-2}) estimated from microscopic observations. *Black* and *white arrows* indicate lenses anomalously enriched in coarse lithic grains, interpreted as tsunami deposits after strong seismic events. These deposits are possibly associated with local reworking by backflows from shallower zones in the bay (see Fig. 3)



The presence of well-rounded basement megaclasts within debris flow deposits, which are generally characterized by angular clasts, can also be considered as good evidence for tsunamis. These rounded boulders may have been eroded from alluvial fans as at Hornitos or may be wave-smoothed beach material incorporated into the tsunami backflows. The enormous size of some of these boulders, e.g. in the Coquimbo Formation south of Caldera (Fig. 1) where they reach a diameter of more than 5 m and a weight of around 200 metric tonnes (Fig. 10), implies that they are unlikely to have been moved by storm waves. To sculpt and polish these blocks by wave action probably requires centuries within the breaker zone, during which time they must have been subjected to many major storms unable to move them into deeper water. In some cases, as for example described by Le Roux et al. (2004) at Carrizalillo, large protruding megaclasts riding on top of debris flow deposits may be produced by the collapse of submarine canyon walls or beach cliffs, but they are usually angular or subangular.

Some channelized debris flow deposits show megaflutes at their base, which evidently formed in highly turbulent flows unrelated to and preceding the debris flow itself. A ca. 300 m wide, more than 15 m deep channel described by Le Roux et al. (2004) at Carrizalillo can be attributed to a tsunami event because of the presence of large intraclasts plucked from the substrate in the central part of the channel. The giant flutes are up to 60 cm wide, 80 cm long, and 15 cm deep (Fig. 11), being oriented along the trend of the channel and the submarine canyon in which the latter is located. A shear carpet at the base of the overlying debris flow deposit, described below, follows the contours of the flutes without any significant change in thickness, indicating a subsequent, highly sheared flow succeeding the turbulent flow. Le Roux et al. (2004) suggested that large volumes of sediment, moving rapidly down channels and canyons

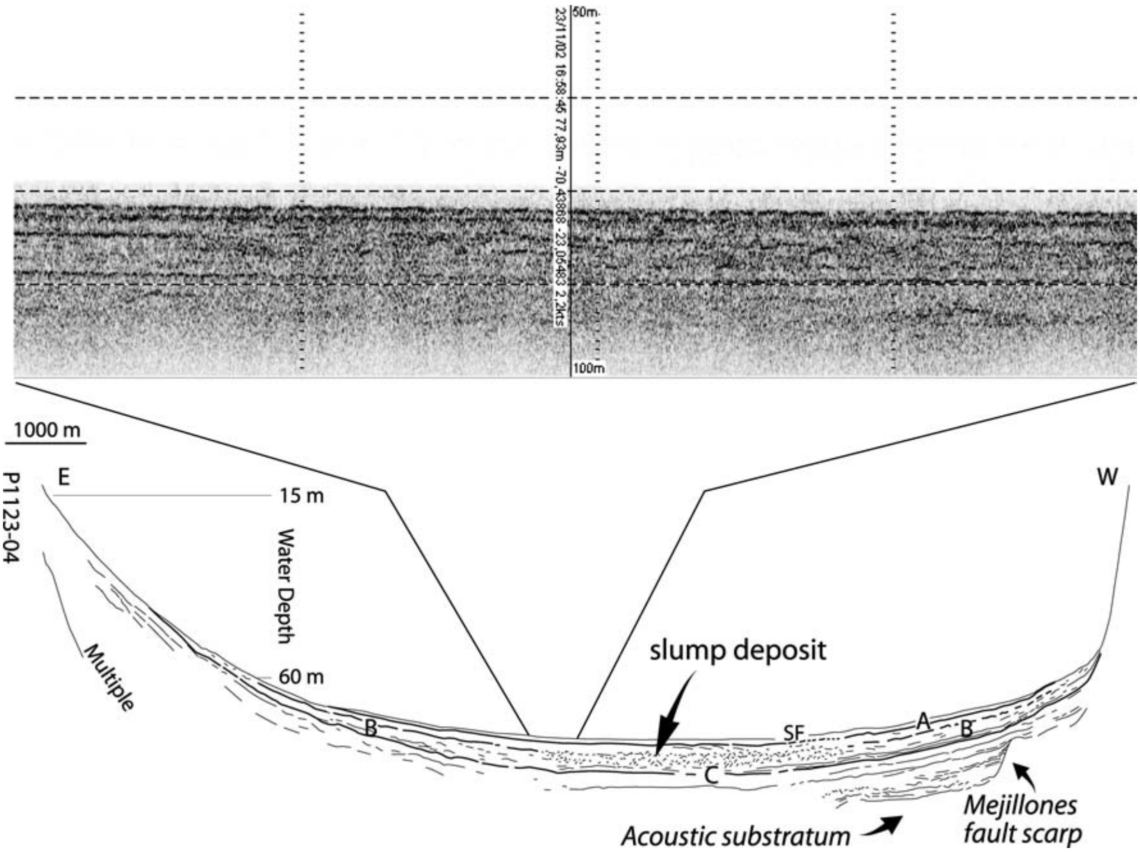


Fig. 5 Interpretation of acoustic profile P1123-04, obtained with a 12 ± 2 kHz transducer, showing the development of a large slump deposit interpreted as an important seismic and tsunami event that probably occurred a few thousand years ago. A morphologic scarp in the acoustic substrate, probably associated with the northward projection of the active Mejillones Fault, is also shown. *SF* Sea floor. **a**–**c** are major reflections observed in this profile. The slump is shown in reflection (**b**)

as semirigid plugs, would displace the water ahead of them, causing clear turbulent flow without depositing any sediments. This seems to be the most likely origin of the flutes, which would be difficult to explain if they were formed by normal sediment-laden turbidity currents.

Shear carpets also seem to be a common feature at the base of tsunami deposits, as we have observed at Carrizalillo (Fig. 11), Caldera, and Los Hornos (Fig. 12). They are usually only a few centimeter thick, coarsening upward, and distinctly finer grained than the overlying debris flow deposits. The size grading is produced by kinematic sieving (Middleton 1967) and squeezing (Le Roux 2003), as well as dispersive pressure (Bagnold 1954) caused by the intense shearing action of the overlying debris or hyperconcentrated flows.

Fluid escape structures, another feature typical of tsunami deposits, may be found in sandstones as dish structures or vertical pipes (Mohrig et al. 1998). In coarse, shelly conglomerates such as at Carrizalillo, bivalves are commonly orientated with their concave side up (Le Roux et al. 2004), in contrast to the hydrodynamically more stable convex-up orientation characteristic of turbulent flow.

Although debris flow deposits related to tsunamis are generally massive, traction structures such as trough cross-lamination or upper flow-regime plane lamination may be present in the deeper parts of the channels or towards the tops of tsunami beds. These structures reflect turbulent flow, which commonly arise out of the flow transformation processes described below.

Hydraulic processes

Tsunamis are probably not only capable of directly eroding large volumes of material from the coastal plain, but can also cause the partial collapse of beach cliffs or submarine canyon walls already fractured and weakened by the preceding earthquakes. This would result in a very dense flow with a much higher capacity to transport large boulders than clear seawater, accounting for the enormous size of rounded megaclasts within tsunami

Fig. 6 Sandstone intraclasts ripped up from the base of channel by sandstone injection, Carrizalillo. Note that the large clast in the *center* of the photo is folded

deposits. Such very dense sediment–water mixtures may initially behave as Bingham fluids dominated by frictional grain interactions and shearing, so that shear carpets may develop locally at their base.

As tsunami backflows advance offshore from the coastline, they will undergo several changes known as flow transformation (Fisher 1983). Channelization of the flow induced by the coastal or submarine topography

Fig. 7 Coarse-grained sandstone injections in fine-grained sandstone substrate underlying tsunami bed, Carrizalillo

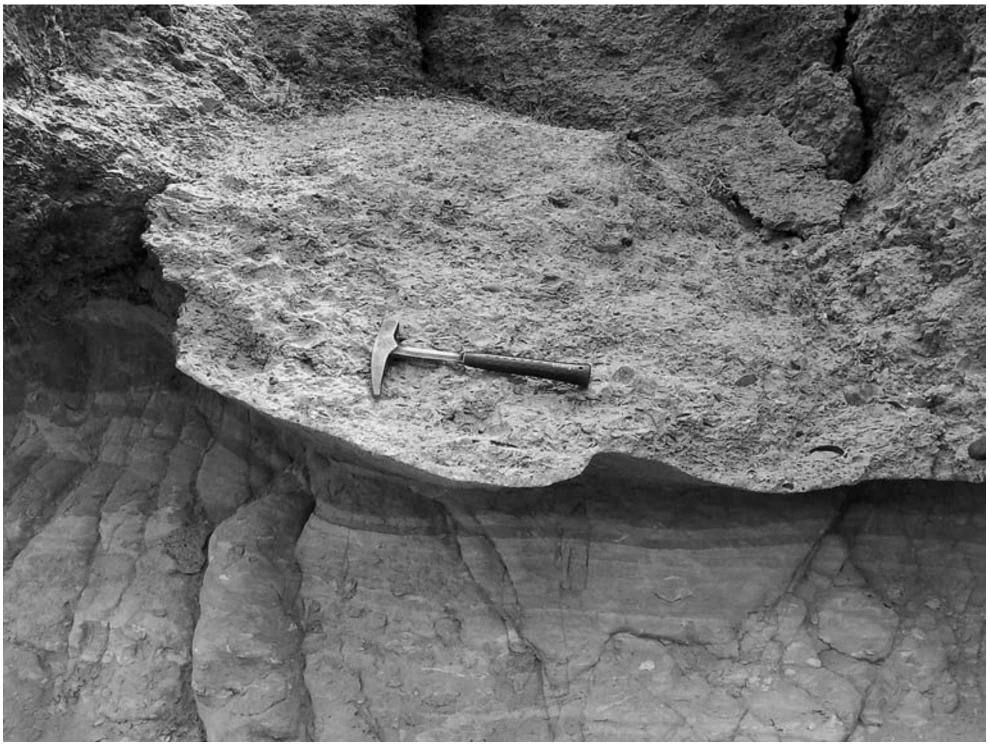
Fig. 8 Large sandstone dikes in mudstones underlying tsunami bed, Ranquil

would also cause lateral, across-current flow transformation, as demonstrated within the channel at Carrizalillo, described above. Here, the central, deepest part of the channel, where the deposit exceeds 15 m in thickness, is characterized by large rip-up intraclasts at the base, followed higher up by trough cross-lamination, crude horizontal bedding, and bivalves orientated with their convex side up. The deposit is overlain by a fine-grained sandstone lens with textural characteristics similar to the matrix of the underlying shelly

Fig. 9 Mudstone breccia formed by fractured and injected intraclasts, Ranquil

Fig. 10 Well-rounded, protruding megaclast in tsunami bed, Caldera

Fig. 11 Cross-section of megaflute at the base of channel filled with tsunami deposits, Carrizalillo. Note the thin shear carpet along flute base



conglomerate. The rip-up intraclasts indicate very high dynamic pressures and sandstone injection into the substrate, probably from a hyperconcentrated flow, as suggested by the fact that these clasts did not sink to the very bottom of the channel. The traction structures and convex-up bivalves higher up indicate the development of turbulence, whereas the fine sandstone lens is interpreted to represent elutriation deposits, i.e. matrix material expelled from the debris flow by fluids escaping to the surface (Fisher 1983). The channel sides have megaflutes and a well-developed shear carpet at the base, which indicate turbulent flow followed by a dense, highly sheared fluid with possible Bingham characteristics. The concave-up orientation of the bivalves suggests that turbulence was absent during this second flow phase.

It is envisaged that the deepest part of the channel was characterized by higher velocities and the possible development of hydroplaning. According to Mohrig et al. (1998) the densiometric Froude number, given by

$$Fr_{\mathrm{d}} = V/\sqrt{[(\rho_{\mathrm{d}}/\rho_{\mathrm{f}} - 1)gh]\cos\phi},$$

Fig. 12 Shear carpet at the base of tsunami deposit, Los Hornos

where V is the flow velocity, ρ_d the flow density, ρ_f the density of the ambient fluid, g the acceleration of gravity, h the flow thickness, and ϕ the slope angle, should exceed 0.4 for hydroplaning to develop, which is more likely to have occurred where the velocity was the highest. Another prerequisite for hydroplaning, the time scale of pore pressure decay R (Iverson and LaHusen 1989), given by

$$R = \delta^2 \mu / kE,$$

where δ is proportional to the average flow depth, μ is the viscosity of the interstitial fluid, k the permeability of the debris, and E the uniaxial compression modulus or stiffness of the debris, is also more likely to have been higher in the deeper part of the channel.

Hydroplaning, where the front of the debris flow runs on a cushion of water, can cause an acceleration of the front with its eventual detachment from the slower debris body. The uptake of water from the developing basal fluid pockets would also cause a rapid dilution of the flow density. Hyperconcentrated flow conditions may therefore develop within the deepest channel zone, accompanied by the rip-up of intraclasts from the substrate. Large-scale fluid escape would elutriate the fine matrix, which would ride as a cloud on top of the debris flow and be deposited well after the latter had passed any particular locality. Before this happens, however, further dilution of the debris flow would lead to the development of turbulence, as indicated by the traction structures observed within this part of the channel.

Conclusions

Much can be learned about the hydrodynamic behavior of tsunamis by a careful study and interpretation of their deposits. Their backflows are obviously characterized by a wide range of processes, which change in time and space during a single event. Flow channelization seems to play an important role in lateral flow transformations and may lead to deposits exceeding 15 m in thickness. In the geological past, some tsunamis have left deposits and injection structures of a magnitude as yet unheard of in historic times. Although such tsunamis probably have a frequency of the order of millions of years, they can and will strike again in future. For the sake of coastal communities, one can only hope that the latter is very distant.

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References

Bagnold RA (1954) Experiments on gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Roy Soc (Lond) Proc A 225:49–63

Bartsch-Winkler S, Schmoll HR (1993) Evidence for Late Holocene relative sea-level fall from reconnaissance stratigraphic studies in an area of earthquake-subsided intertidal deposits, Isla Chiloé, southern Chile. Special publication 20. International Association of Sedimentologists, pp 91–109

Cantalamessa G, Di Celma C (2005) Sedimentary features of tsunami backwash deposits in a shallow marine Miocene setting, Mejillones Peninsula, northern Chile. Sediment Geol 178:259–273

Cisternas M, Contreras I, Araneda A (2000) Reconocimiento y caracterización de la facies sedimentaria depositada por el tsunami de 1960 en el estuario Maullín. Rev Geol Chile 27:3–11

Comte D, Pardo M (1991) Reappraisal of great historical earthquakes in the Northern Chile and Southern Peru seismic gaps. Nat Hazards 4:23–44

Einsele G (1998) Event stratigraphy: recognition and interpretation of sedimentary event horizons. In: Doyle P, Bennett MR (eds) Unlocking the stratigraphic record: advances in modern stratigraphy. Wiley, Chichester, pp 145–193

Fisher RV (1983) Flow transformation in sediment gravity flows. Geology 11:273–274

Hartly A, Howell J, Mather ME, Chong G (2001) A possible Plio-Pleistocene tsunami deposit, Hornitos, northern Chile. Rev Geol Chile 28:117–125

Iverson RM, LaHusen RG (1989) Dynamic pore-pressure fluctuations in rapidly shearing granular materials. Science 346:796–799

Kelling G, Stanley DJ (1978) In: Stanley DJ, Kelling G (eds) Sedimentation in submarine canyons, fans and trenches. Dowden, Hutchinson & Ross, Inc., Stroudsburg, pp 377–388

Le Roux JP (1994) An alternative approach to the identification of sediment transport paths based on grain-size trends. Sediment Geol 94:97–107

Le Roux JP (2003) Can dispersive pressure cause inverse grading in grain flows?—discussion. J Sediment Res 73:331–332

Le Roux JP, O'Brien RD, Ríos F, Cisternas M (2002) Analysis of sediment transport paths using grain-size parameters. Comput Geosci 28:717–721

Le Roux JP, Gómez C, Fenner J, Middleton H (2004) Sedimentological processes in a scarp-controlled rocky shoreline to upper continental slope environment, as revealed by unusual sedimentary features in the Neogene Coquimbo Formation, north-central Chile. Sediment Geol 165:67–92

Massari F, D'Alessandro A (2000) Tsunami-related scour-and-drape undulations in Middle Pliocene restricted-bay carbonate deposits (Salento, south Italy). Sediment Geol 135:265–281

Middleton GV (1967) Experiments on density and turbidity currents—III: deposition of sediment. Can J Earth Sci 3:523–546

Minoura K, Nakaya S (1991) Traces of tsunami preserved in inter-tidal, lacustrine and marsh deposits: some examples from northeast Japan. J Geol 99:265–287

Mohrig D, Whipple KX, Hondzo M, Ellis C, Parker G (1998) Hydroplaning of subaqueous debris flows. Geol Soc Am Bull 110:387–394

Ortlieb L, Escribano R, Follegati R, Zuñiga O, Kong I, Rodríguez L, Valdés J, Guzmán N, Iratchet P (2000) Recording ocean-climate changes during the last 2,000 years in a hypoxic marine environment off northern Chile (23°S). Rev Chilena Hist Nat 73:221–242

Shiki T, Yamazaki T (1996) Tsunami-induced conglomerates in Miocene upper bathial deposits, Chita Peninsula, central Japan. Sediment Geol 104:175–188

Vargas G, Ortlieb L, Pichon JJ, Bertaux J, Pujos M (2004) Sedimentary facies and high resolution primary production inferences from laminated diatomaceous sediments off northern Chile (23°S). Mar Geol 211:79–99

Vargas G, Ortlieb L, Chapron E, Valdés J, Marquardt C (2005) Paleoseismic inferences from a high resolution marine sedimentary record in northern Chile (23°S). Tectonophysics (in press)

Watanabe T, Karzulovic J (1960) Los movimientos sísmicos del mes de mayo de 1960 en Chile. Universidad de Chile Anales 17:43–87