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The camouflaged tsunami record of arid coasts: Looking for sand in the Atacama Desert

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The poor preservation potential of tsunami records in arid environments has prevented detailed studies of tsunami-washed sand deposits along these coasts. However, recent studies have shown that evidence of these high-energy marine events is camouflaged within (hyper)arid landscapes.

In general, the study of recent paleotsunamis has been based on the identification and analysis of their onshore deposits, in the absence of historical or archaeological evidence (e.g. Engel et al. 2020; Prizomwala et al. 2024). High-energy waves mix the marine sediments they drag from the seabed with the continental deposits they flood, resulting in a layer of sand containing a melting pot of grains and microfossil remains.

Scientists studying paleotsunamis look for areas where these sediments are trapped and, in most cases, they find them in very similar environmental scenarios: coastal wetlands and lagoons near river mouths, or even continental lakes near the shoreline where waves can reach and deposit the sediment they transport.

The presence of large bodies of freshwater is a common characteristic, as it favors the accumulation of the tsunami deposits. In addition, the subsequent, and continuous sedimentary dynamics buries them, allowing their preservation in the sedimentary record. But, what happens when a tsunami impacts coasts where these freshwater bodies do not exist, such as in the Atacama Desert in Chile, the driest place in the world? Without wetlands, lagoons, estuaries, or deltas, how are the tsunami deposits preserved?

Why study the tsunami record of the southern Atacama Desert?

The Chilean coast is a highly seismic and tsunami-prone hazard zone, owing to the convergent boundary where the Nazca Plate subducts below the South American Plate (Fig. 1). In this setting, tens of earthquakes with focal mechanisms and magnitudes large enough to trigger highly destructive tsunamis must have been generated during the Late Holocene, although no great earthquakes (moment magnitude [M_w] ≥8.6; Klein et al. 2017) have been reported in the historical chronicles of the southern edge of the Atacama Desert (Fig. 1). In fact, only two large-magnitude earthquakes that triggered destructive tsunamis occurred in historic times; in 1819 and 1922 CE (Ruiz and Madariaga 2018).

There is still great uncertainty regarding the number and magnitude of large paleotsunami events in this sector of the Atacama Desert during the Late Quaternary, caused by the challenging accessibility and long distances from major cities that have prevented exploration of these coasts. The less-evident record of tsunami deposits linked to environmental constraints when compared with other zones of Chile contributes to this uncertainty (Fig. 1).

The tsunami record on arid coasts: Boulder deposits

On arid, rocky coasts, such as those of northern Chile, tsunamis are not commonly recorded as sand layers interbedded with finer sediments, but as boulder fields on top of cliffs. Some of these reach weights of hundreds of tons and were moved from areas located up to 10 m above sea level (Abad et al. 2020). These deposits form when the tsunami waves impact the rocky cliff, detach a boulder, creating a boulder niche, and transport it landwards tens to hundreds of meters. The orientation of the boulders can be used to interpret the wave direction, and their size and mass can be used to model the scale of the extreme

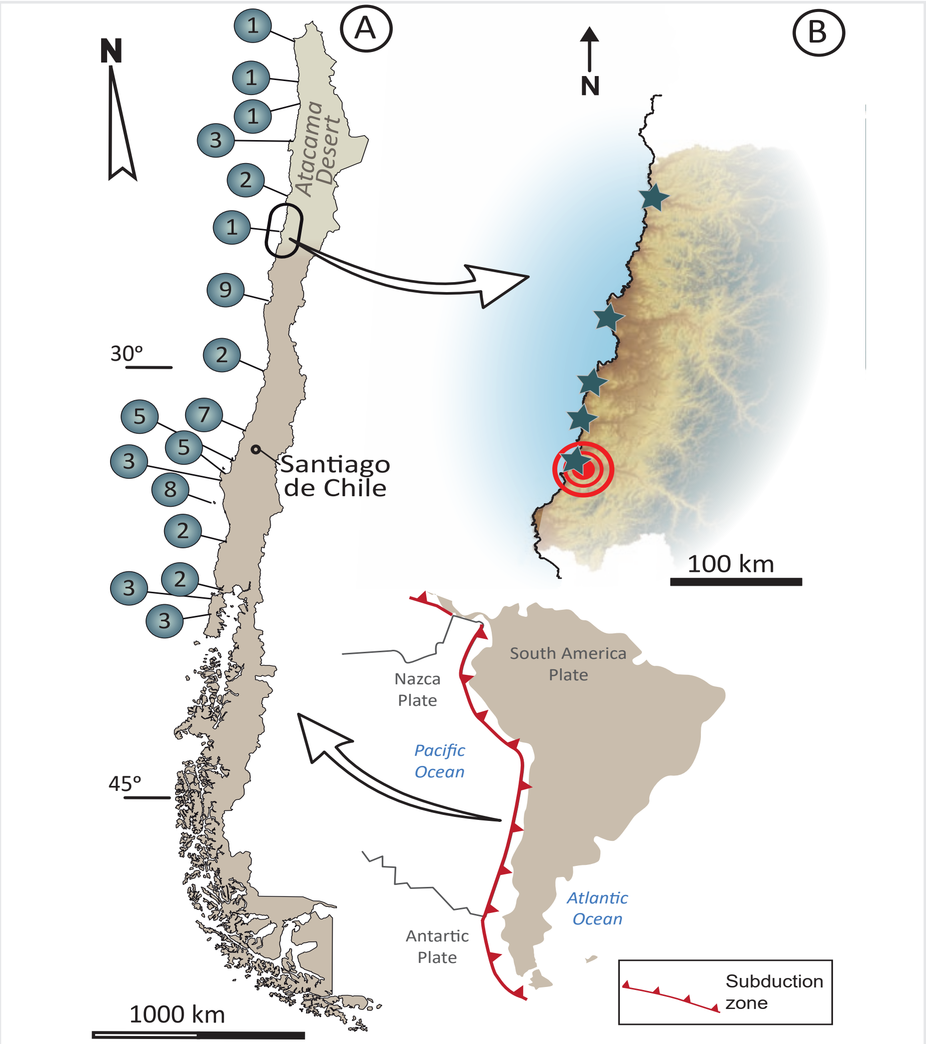

Figure 1: (A) Location of the places where records of paleotsunamis have been described on the coast of Chile. The number inside the colored circle indicates the number of works carried out on this topic (based on León et al. 2022). **(B)** Detail of the southern Atacama Desert coast. Stars indicate potential sites for tsunami research and the red circle indicates the epicenter of the 1922 CE Atacama earthquake.

waves and their flow velocities. The advantage of these deposits is that they cannot be reworked by the wind after their deposition; thus, they provide exceptional tsunami evidence on arid coasts that prevail in the landscape without being practically modified over time. Unfortunately, the scenario in which this type of evidence is formed is very specific, and the recording of events through these records is very incomplete. In some cases, a boulder field can even be the result of successive large tsunamis.

The tsunami record on arid coasts: Fine grained deposits

In the absence of cliffs and freshwater bodies that may preserve the large volumes of sand brought from the sea to the coasts of the Atacama Desert, the sediments are deposited on vast coastal plains and become part of the dune fields, which bear little resemblance to the classic description of "tsunamiites" in scientific literature (Shiki and Yamazaki 2008). The apparent absence of this geological evidence should not be interpreted as evidence of its absence. This is perhaps one of the last challenges that remains to be overcome in tsunami science, and it must be addressed from a holistic perspective, in order to determine the tsunamigenic origin of camouflaged morphogenic and sedimentary evidence.

So, where, and how, do we look for "classic" and probably clearer evidence of paleotsunami(s) in the Atacama Desert? Along thousands of kilometers of arid coast there are a few exceptional places in which a combination of geomorphological, climatic and geological factors exist, and small coastal wetlands have been formed, owing to the emergence of groundwater in the permanent absence of surface waters that reach the sea. Nevertheless, the probability of marine high-energy events being recorded and preserved in these environments is low, because several processes may alter them.

Firstly, after the marine flooding occurs and seawater retreats, evaporation of the wet marine sediments begins. This newly deposited material includes sea salts that precipitate, as evaporation continues, forming saline crusts and nodules that will mask the tsunami deposit in the geological record (Fig. 2). In fact, tsunami sand or mud deposits can be misinterpreted as paleosoils in the field. If this salt precipitation process does not occur, the absence of sedimentation in arid environments will not protect them from eolian processes, leading to an incomplete tsunami record.

Finally, ephemeral rivers, where coastal wetlands are formed, are occasionally activated when intense El Niño-Southern Oscillation-related rain occurs in the desert. These continental flows present a strong erosive capacity, even near the river mouth, and can dramatically change the coastal wetland configuration, as occurred after the March 2015 CE rains in Atacama (Abad et al. 2017).

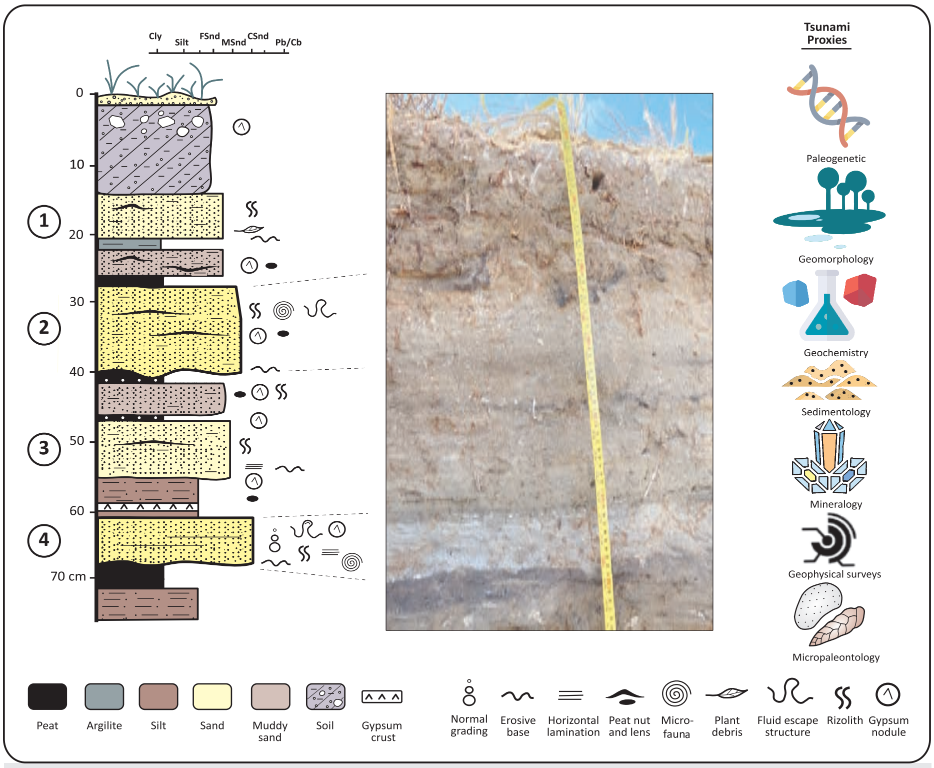

Figure 2: Detailed sedimentological section elaborated in an arid coastal wetland in the southern Atacama Desert. Numbers indicate sand layers of a distinctive lighter color formed by tsunamis. The formation of saline crusts and gypsum nodules, as well as the burrowing of roots, usually mask these records.

A multi-proxy solution

The solution to these issues is neither simple nor straightforward. Only a few sectors of the Atacama Desert coastal segment seem to fulfill the geomorphic requirements, and even at those locations, a multi-proxy detailed study is needed to untangle the paleotsunami record of the last 4000 years. At these locations, each layer, generally less than 10 cm thick, must be sampled and subjected to a variety of analyses looking for the proxy or their combination, which allows us to classify the deposit as sediments formed by a tsunami.

At temperate latitudes, the combination of grain size and micropaleontology or geochemistry is normally sufficient to claim a deposit as a tsunami layer. However, on these arid coasts, grain size may have been modified by eolian rework, microfauna may have been dissolved, and the geochemistry of the sediment may have been altered by later precipitation of gypsum. Thus, we will have an answer only if we consider a more holistic solution. Geomorphological and sedimentological analyses are still key, but they must be combined not only with microfossil and geochemical analyses, but also with mineralogical, geophysical and even environmental DNA analysis to be sure that this sand layer was formed by a paleotsunami (Fig. 2). The effort to unmask this evidence is enormous, and requires the participation of multidisciplinary teams formed by geologists, paleontologists, biologists, and geophysicists, without whom it would be impossible to achieve the ultimate goal of assessing the tsunami hazard to which the southern Atacama coast is exposed.

To date, the low number of tsunami studies on arid coasts has not only led to a misunderstanding of the tsunami events on these coasts compared to temperate and humid areas, but also to underestimating the risk that coastal communities are exposed to by ignoring the recurrence of these high-energy marine events and their magnitude throughout the geological record. Until we understand them, we will continue to search for sand in the desert.

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