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Bimodal tsunami deposits – a neglected feature in paleo-tsunami research

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Abstract

Within the last two decades field research has demonstrated that tsunami may leave a broad variety of different deposits ranging from fine sediments, widely distributed but in thin layers and hidden in other sediment units, to boulder deposits as significant landscape marks. Hitherto, the accumulation of bimodal sediments, a mixture of fine and coarse grain sizes, was neglected in its relevance for the discussion of tsunami sedimentation despite the widespread occurrence of such bimodal sediments. This paper will overview the role of these mixed deposits in tsunami sedimentation history.

1 Introduction

The state-of-the-art of the nature of tsunami deposits is summarized in two recent publications. Dawson & Shi (2000) name sand, boulders and microfossils as frequent tsunami relics and emphasize the difficulty of understanding the mechanism of boulder transport and the distinction between storm and tsunami sediments. The authors state that boulders incorporated in a sandy matrix (i.e. a bimodal mixture) occur only rarely and highlight the need of further detailed analyses.

On the basis of a thorough literature review Bryant (2001) classified tsunami deposits into

- buried sand and anomalous sediment layers. They consist mostly of coarser sand in thicker units, incorporated in marshes etc., e.g. the Storegga deposits;
- boulder floaters in a sandy matrix. Mostly difficult to detect. Boulders normally represent only 0,1 % or less of the volume of the deposit. Such a distribution can be excluded for storm deposits.
- dump deposits with a chaotic sediment mixture and minimal sorting, pointing to a very short time span for the depositional process. Congruent with this rapid event is the deposition of broken fragile particles (e.g. foraminifera, shells). Their internal characteristics or fabric are similar to pyroclastic density currents. These dump deposits are very similar to the bimodal units described below;
- smear deposits with mud and clay, mostly from local sources like soil;
- and large boulders or piles of imbricated boulders without fine sediments.

During extensive field research on paleo-tsunami deposits in the Mediterranean, the Caribbean and Bahamas (Kelletat & Schellmann 2001, 2002; Bartel & Kelletat 2003; Whelan & Kelletat 2003; Scheffers 2002; Scheffers & Kelletat 2003 a-d) with systematic mapping of longer coastal sections we realized that a bimodal sediment distribution is not the exception, but the standard for all tsunami deposits, which have interacted with rocky environments like cliffs, coastal platforms or coral reefs during the impact. Subsequent to the deposition of the bimodal sediments, the sandy matrix is often removed to various amounts by erosion depending on vegetation cover, slope, or intensity of precipitation resulting in exhumed, bare boulder deposits.

Hitherto, the distinction between fine and coarse tsunami sediments in the scientific literature neglect the fact that at many locations tsunami predominantly accumulate fine and coarse sediments contemporaneously. In so far, this strict separation seems not justified.

At many locations, boulder assemblages and boulder ridges accompany sandy deposits, mostly along their seaward margin (Fig. 6-8). The sands often have been misinterpreted as coastal dunes due to their position and forms or they have been overlooked because of vegetation cover. Nevertheless, at several sites tsunami boulder deposits may lack any evidence of fine sediments as is documented by Scheffers (2002), Whelan & Kelletat (2003), Kelletat & Schellmann (2001), Bryant (2001) and others. However, the impressive boulder accumulations in the Caribbean and on the Bahamas clearly document the morphological relation of sandy and coarse deposits, which is confirmed by absolute dating of the deposits to the same event.

2 Descriptive characteristics and field examples of bimodal sediments

2.1 Mediterranean

In the southeastern part of Mallorca island (Cabo de ses Salines) (Bartel & Kelletat 2003; Scheffers 2003) densely vegetated dune-like deposits with a height of approx. 15 m exist, which are accumulated subsequent to extensive boulder rigdes. At present, no beaches as source areas for these sandy deposits have been developed, but abundant sand deposits exist in the foreshore area. On the upper slopes, sand is the dominant sediment, but occasionally small boulders and shell fragments can be found incorporated or on top of the sandy deposits. On the lower slopes as well as in the supratidal zone, boulders (~20 t) have been accumulated. A detailed investigation of the boulder ridges revealed that they represent paleo-tsunami deposits, which could be dated to 500 BP and 1400 BP by radiocarbon dating. Therefore, we assume that these dune-like deposits represent the sedimentologic imprint of one or two paleo-tsunami.

Comparable deposits can be found at Cabo de Trafalgar in southern Atlantic Spain (Whelan & Kelletat 2003). Here, shifting sands cover a headland up to 19 m asl. and contain shell fragments, rounded pebbles and cobbles as well as rounded boulders up to several 100 kg (Fig. 1). But in total, these coarse sediments represent only less than 1% of the deposit. Strikingly most of the pebbles and cobbles are broken. Their fresh appearance, their altitude above sea level and the existance of huge boulders (up to 90 t) on the intertidal platform, point to a tsunami accumulation during the Lisbon event in 1755 AD. North of these deposits, cobbles and smaller well-rounded boulders were accumulated into an older beach ridge (sand content ~ 60-70%). Subsequent to the tsunami, a broad sandy beach has aggradated in front of this older ridge.

Fig. 1: Rounded boulders in a sandy matrix at 16 m asl on Cabo de Trafalgar, southern Atlantic Spain.

In contrast to these chaotic distribution, a bimodal tsunami sediment with a sandy matrix but accompanied by well rounded flat pebbles and cobbles, which show an orientation of their longest axes, is present along the west coast of the Akamas peninsula on Cyprus island (Kelletat & Schellmann 2001, 2002). The tsunami could be dated to 1650 – 1700 AD. Sediment units south of the Lara peninsula with large well-rounded boulders derived from the foreshore resemble the same orientation of the long axes of the boulders. Here, the coarse fragments may constitute 30-60% of the tsunami sediments. Several bays in west Cyprus were filled by the tsunami with a similar mixture of sand and well rounded floating pebbles from the foreshore, but here sand dominates the deposits with at least 80%.

2.2 Caribbean and Bahamas

Along the east coast of Guadeloupe (French Lesser Antilles) at Anse Maurice and Anse Ste-Marguerite, swash-like accumulations of sand form an undulating ridge between 3-8 m above sealevel. At its northern range, these sands are adapted to hill slopes (Scheffers et al. 2003a). The hills, resembling coastal dunes, are densely vegetated and show a good soil development. On top of this sediment unit, large coral heads or fragments as well as boulders from an interglacial coral reef with weights of many tons are accumulated. Diggings in the sandy deposits reveal the absence of any stratification, but instead a chaotic mixture of sand (finer and coarser), shells and shell fragments, coral branches, Strombus gastropods, and boulders from older reef rock. Overall, the amount of these coarser grain sizes form several percent of the sediments (Fig. 2). Larger boulders are distributed at the seaward margin of these sandy hills. Radiocarbon dating yielded a tsunami deposition at about 2800 BP.

Fig. 2: Chaotic sand deposits with coral fragments of different size in Anse Ste-Marguerite, east coast of Guadeloupe.

Bimodal sediments with chaotic structure, but of much older age than the described above, can be found on the islands of Grenada and St. Lucia (Lesser Antilles, Scheffers et al. 2003a). Here, the bimodal tsunami deposits are embedded into tephra layers of Pleistocene age at a height of 50 m asl. (Fig. 3). The boulders may reach a weight of up to 10 tons and are mostly well rounded. They are evenly distributed in a matrix of sand and fine gravel without contact, giving the impression of floating in the matrix.

Fig. 3: Chaotic tsunami deposits with well-rounded littoral boulders floating in sandy and gravelly matrix between tephra units at 50 m asl., St. Lucia, Lesser Antilles.

In the south of the Antillean Island Arc, on the islands of Aruba, Curaçao and Bonaire, Holocene paleo-tsunami have deposited bimodal sediments of different types. Along the southernmost tip of Aruba (NW of the Seru Colorado promontory), a double sand ridge has been accumulated (Scheffers 2002). Within this predominantly sandy deposits smaller and larger coral fragments are intermingled in negligible quantities (Fig. 4), which may originate from the youngest tsunami event on this island, dated around 450-500 BP. On Bonaire and Curaçao, coarse boulder deposits in form of elongated ridges or ramparts are the most prominent deposition type (Scheffers 2002). On the surface they expose mostly coarse fragments with a size of several decimeters to about 1 meter. However, cross-sections exhibit that in lower sections substantial amounts of sand including shell is present. This distribution is the result of erosion of the finer grain sizes (Fig. 5) and may indicate the relative age of the deposit.

Fig. 4: Tsunami ridges with a mixture of sand and coral debris, southeast coast of Aruba, Netherlands Antilles.

Fig. 5: Boulder ridges at the south end of Bonaire (Netherlands Antilles), where sand is outwashed from the upper parts but still present in the lower sections.

The erosional process is also demonstrated by sand sheets often found along the seaward margin of boulder rigdes, as e.g at the north-east point of Curaçao (Scheffers 2002) or on the Lara peninsula of Cyprus (Kelletat & Schellmann 2001, 2002). These sand sheets have been misinterpreted as the sedimentologic relics of strong storms, which pick up sands form the foreshore area, but were to weak to rework the boulder deposits. The common interpretation stated, that due to their barrier function, the sand was accumulated in front of the deposits. We assume, that the sand sheets are the remains from initially extended amounts of sand accumulated with and in the boulder ridges. The older age of the above described sand sheets is also noticable by their darker colors due to soil development. Nevertheless, the character of the sediment will dissimulate a rather young age by a rather fresh appearance, if constantly washed out by strong rains or splash. This kind of fresh looking sand can be found as a strip in front of a weathered one, e.g. on the Whale Point peninsula in North-Eleuthera (Scheffers et al. 2003 b). We can exclude any recent sedimentation even during hurricanes because of deep water in the foreshore area (> 10 m).

Chaotic mixture of shell, coral and smaller boulders is also characteristic for a tsunami relic at Clarence Town on Long Island (Bahamas) (Fig. 6). Here, radiocarbon dating determined an rather young absolute age of 400 BP. Comparable tsunami deposits with a limited amount of coarse particles can be found at “The Cliffs” on Eleuthera Island, Bahamas (Scheffers et al. 2003b). But here, as well as in the vicinity of Cape Sta. Maria at the most northern tip of Long Island (Bahamas), the coarser fragments are mostly concentrated in the most lower section of the deposits (Fig. 7), whereas the upper parts (with a thickness of several meters) lack any coarser particles. Overall, no stratification between the two units could be found.

Fig. 6: A “dump deposit” with a chaotic mixture of sand, shell fragments, sailship ballast boulders and coral at Clarence Town, Long Island, Bahamas.

A study of coarse Holocene tsunami deposits on the Bahamas revealed that they mostly belong to a chaotic bimodal mixture of fine and coarse particles, accumulated several meters thick and at elevations of more than 10 m asl (Scheffers et al. 2003b). Here, the deposits accompany the coastlines for kilometers and give – hidden under dense vegetation – the impression of a coastal dune ridge. At the seaward flank of the ridge large boulders have been enriched or exhumed from the sand, in particular where the coastal slope is steeper and where backward erosion of the sandy deposit increases. Behind the boulders, the bimodal mixture is often exposed in cliffs and stabilised by vegetation (see Figs. 7-10). At first sight it may strike that some of the boulders appear fresh and unweathered in between other deeply weathered ones. But a closer examination lead to may show that at the larger boulders the lower parts look fresh as well, whereas the upper ones show a longer impact of karstification. Sometimes on a fresh looking white carbonate boulder at the upper dark and weathered surface old woody bonsai shrubs are growing, clearly documenting that the boulders have not been moved during the last century or so. Overall, it can be stated that the rather large amount of sand sheets on higher rocky ground above coastal cliffs or rocky shorelines along the Atlantic coastlines of Bahaman islands are not the result of storm or hurricane deposition, but rather constitute the relics of tsunami-induced sedimentation. The hurricane-scenario can be excluded as the lower rock pools of the supratidal, representing thousands of large and deep sediment traps, do not contain any sediment. Evidently storm waves are too weak (or water depth is to deep) to transport fine or coarse sediment from the foreshore area onshore. Our absolute data exclude young sedimentation at these places as well.

Fig. 7: Tsunami deposits dominated by sand with some boulders in the base section. Cape Sta. Maria, Long Island, Bahamas.

Fig. 8: Along the Whale Point peninsula in northern Eleuthera (Bahamas) big boulders are exhumed from sand deposits at about 10-15 m asl..

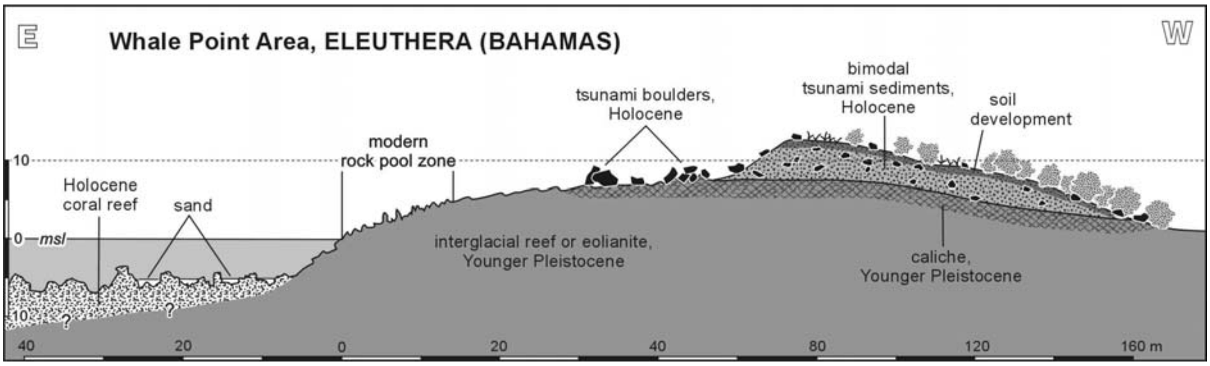

Fig. 9: Profile across the boulder-containing sandy tsunami ridges on the Bahaman islands of Eleuthera and Long Island.

Fig. 10: East coast of Aruba (Netherlands Antilles) with a mixed sand-and-boulder-ridge from tsunami in the Younger Holocene.

3 Conclusions

Bimodal sediment distribution is a common characteristic of tsunami-induced depositions. Figure 11 visualizes the different types of bimodal tsunami deposits depending on the relation of fine to coarse particles and the degree of erosion. The grain size distribution may vary from few, small floating coarser particles in a sandy matrix to boulder size dominating the accumulation enclosed in thin veneers of sand. The sediment structure is in the majority of cases chaotic, but occasionally coarser fragments may be enriched at the base of the units, presumably representing a base surge during the tsunami. The degree of erosion due to rainfall or splash alters the appearance over time. Today we may encounter completely or partly washed out units or large boulders still enclosed entirely in sand. Moreover, the wide variability of the sediment character depends locally e.g. on the availability of sand and boulders, the energy of tsunami waves (see the weight of the boulders) or the depth of the foreshore area.

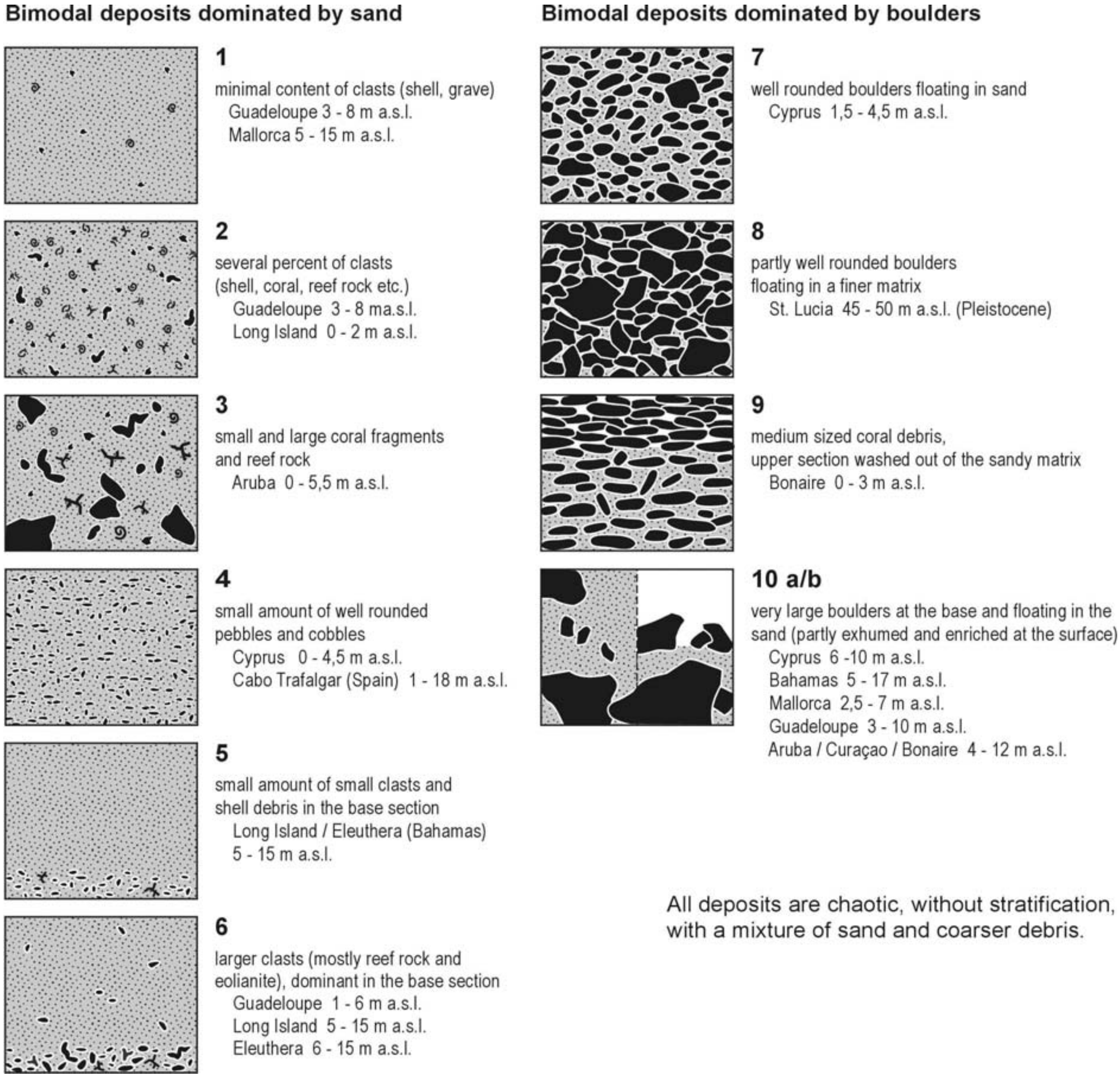

Fig. 11 Ten main types of unstructured tsunami deposits with a mixture of fine and coarse particles.

The recognition of the tsunamigenic origin of these widespread Holocene sediments, which accompany in many parts of the world elongated coastal sections at elevations out of the reach of storm waves, is essential for the interpretation of the Holocene landscape history of a certain region. So may the misinterpretation of an extended tsunami deposit of about 3000 years BP deposited at altitudes of 10-18 m asl lead to the assumption of a higher Holocene sea level, with all consequences for constructing sea-level curves, neotectonic movements or even climatic changes. This pitfall can be transferred to coastal deposits of interglacial times. We would like to emphasize the necessity to review debatable high-lying littoral accumulations with respect to their possible origin as tsunamigenic sediments from paleo- events with unknown energy and run up.

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