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Boulder transport by high-energy wave events at Cap Bon (NE Tunisia)

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Abstract

The Mediterranean is characterized by a considerable seismic and geodynamic activity resulting in a high tsunamigenic potential, particularly for the central and eastern Mediterranean. Within the last decades, numerous studies dealing with deposits caused by extreme events revealed recurrent tsunami events in the Mediterranean throughout the Holocene. In general, two main types of extreme wave event deposits have been described so far: (i) fine-grained allochthonous marine sediments found in near-coast geological archives and (ii) wave-emplaced block deposits along rocky shorelines. However, in many cases, there is an ongoing debate on whether these deposits were accumulated by tsunami or storm events.

This paper presents, for the first time, evidence of block accumulations from the north-eastern coasts of Tunisia induced by extreme wave events. Along the north-western coast of Cap Bon, several block fields and wave-transported boulders were detected. The blocks are partly arranged in the form of imbrication trains up to 4 m a.s.l. Many boulders show two distinct rock pool generations allowing for a relative chronological interpretation. Furthermore, the presented results point to a tsunami-induced transport of the blocks rather than to a storm-induced dislocation.

1 Introduction

The devastating December 26th, 2004 Indian Ocean tsunami dramatically changed public awareness of tsunami hazards all over the world. However, the event not only showed the tremendous and catastrophic wave-induced energy of tsunami and its potential for destruction - in particular, it demonstrates the need for intensified geoscientific research on tsunami events and on extreme wave events. A comprehensive knowledge about comparable tsunami events in the past is necessary for the estimation of tsunami hazard in a distinct area and for effective coastal protection measures. Apparently, reliable information on tsunami recurrence intervals as well as on the intensity and dimension of wave inundation are inevitable for an appropriate hazard assessment (Bondevik 2008). In this context, geo–scientific investigations, besides the analysis of historical accounts, are considered as one of the most promising approaches in palaeo-tsunami and palaeo-event research.

First sedimentary studies about tsunami imprints in geological archives were carried out in the late 1980s (Atwater 1987). Since then, two main types of extreme wave event deposits have been described: (i) fine grained allochthonous marine sediments found in near-coast geological archives, such as lagoons or coastal swamps, and (ii) wave emplaced block deposits along rocky shorelines. However, in many cases the determination of the event source remains problematic and only the marine origin and the high-energy nature of the deposit can be proved. Therefore, a vivid discussion on the distinguishability between tsunami and storm deposits in the geological record has evolved (for instance Goff et al. 2004, Kortekaas 2002, Kortekaas & Dawson 2007, Morton et al. 2007, Nott 1997, 2003a, 2003b, Robinson et al. 2006, Scheffers & Kelletat 2001; Scheffers 2005; Switzer & Burston 2010, Switzer & Jones 2008a, 2008b, Williams & Hall 2007).

In this paper, we present first evidence of block accumulations from the north-eastern coasts of Tunisia induced by extreme wave events. Chronological aspects of the block movement and possible event sources are discussed.

2 Palaeotsunami studies in the Mediterranean

Evidence for extreme wave events during the Holocene is known from a number of areas in the Mediterranean, and in most cases these events are associated to tsunami. In particular, numerous historical reports on tsunamis exist for the central and eastern Mediterranean, especially for Italy and Greece, summarized in tsunami catalogues (for instance Soloviev et al. 2000, Tinti et al. 2004). In these catalogues, additional information on event-related earthquakes, tsunami wave heights, inundated areas and other effects is recorded.

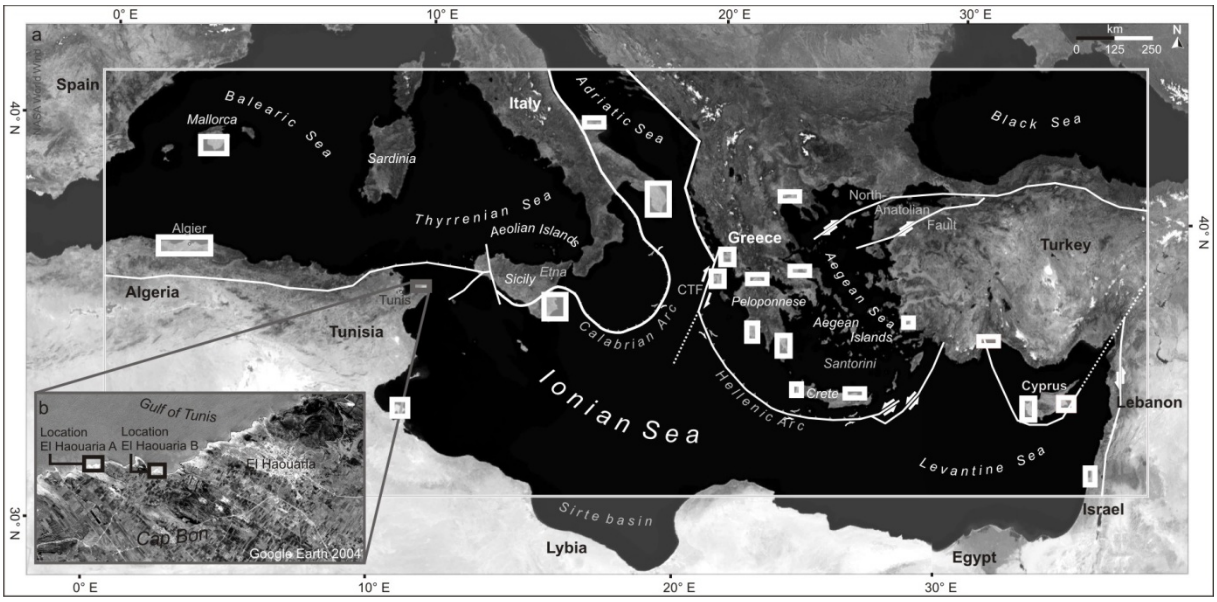

Figure 1: a) Overview of the Mediterranean with main tectonic structures (map based on Facenna et al. 2001, Wortel & Spakman 2000). White boxes mark reports on sedimentary tsunami imprints. The study area presented in this paper is marked by a grey box. b) Study area, north-western coast of Cap Bon, NE Tunisia, with presented locations of block findings. The coastal morphology shows a typical bay and headland configuration.

Sedimentary evidence for palaeotsunami events in the central Mediterranean proves the occurrence of tsunami events since the mid-Holocene. Especially the eruption of Santorini in the Bronze Age was subject to geological investigations (Bruins et al. 2008, Dominey-Howes et al. 2000a, McCoy & Heiken 2000, Minoura et al. 2000, Scheffers & Scheffers 2007). More recent events also left sedimentary signatures such as the 1956 tsunami in the southern Aegean Sea for which imbricated pebbles on the island of Astypalaea are described (Dominey-Howes et al. 2000b). Korteekaas (2002) and Kontopoulos & Avramidis (2003) gave evidence for tsunamigenic sediments in the Corinthian Gulf. Scheffers et al. (2008) found palaeotsunami imprints on the coasts of the southern and south-western Peloponnese. For northwestern Greece, Vött et al. (2006, 2007, 2008, 2009, 2010), May (2010) and May et al. (2008) presented manifold sedimentary evidence of tsunami influence on the Preveza-Lefkada coastal zone.

Several studies were also conducted on tsunami induced changes of coastal morphology such as boulder and block accumulations along rocky shorelines (Mastronuzzi & Sanso 2000, 2004; Scicchitano et al. 2007) and washover fans (Gianfreda et al. 2001) in southern Italy. Further evidence for extreme wave events was presented by Reinhardt et al. (2006) for the Israeli coast close to the ancient harbour of Cesarea, and Morhange et al. (2006) gave evidence for wave emplaced boulders at the coast of Lebanon. From the North African coast, Maouche et al. (2009) report on large boulder accumulations in northern Algeria and suggest a tsunamigenic origin and Kelletat (2005) describes wave transported boulders in southern Mallorca. Frébourg et al. (2007) describe a possible tsunami layer found within eolianites from eastern Tunisia. Block accumulations are also known from Morocco (Mhammudi et al. 2008), but may be related to event sources in the Atlantic Ocean, comparable to the 1755 earthquake and tsunami of Lisbon (Andrade 1992, Whelan & Kelletat 2005).

When considering possible source mechanisms for tsunami events in the Mediterranean, several potential triggers must be taken into account (see also figure 1). Especially the central Mediterranean exhibits a high seismic activity. Numerous strong earthquakes are reported from the subduction zone of the Hellenic Arc or major fault zones. It is well known, that vertical crustal movements of terrestrial and submarine origin have a high tsunamigenic potential in this region (for instance Benetatos et al. 2004, Pirazzoli 1986). In northwestern Greece, the Cefalonia transform fault (CF), situated west of the Ionian Islands Cefalonia and Lefkada, connects this zone of subduction with an area of continent-continent collision beginning off the coast of southern Epirus (figure 1). The CF also shows a remarkably high seismic activity and has been responsible for numerous strong earthquakes during history (Benetatos et al. 2005, Cocard et al. 1999, Louvari et al. 1999, Sachpazi et al. 2000, Papadopoulos et al. 2003). In the western Mediterranean, several tsunamigenic earthquakes are known from south-eastern Spain and North Africa (Alasset et al. 2003, Gràcia et al. 2006). Moreover, Pareschi et al. (2006) suggest that flank collapses of the Etna volcano, occurring during the middle Holocene, resulted in mega tsunami events effecting large parts of the Mediterranean. From the central Ionian Sea and the Sirte basin to the north of the African coast, several turbidite layers have been detected in the deep sea geological record. These layers suggest repeated and extensive submarine mass movements in the area that may also have produced large tsunami events in the central Mediterranean (Hieke 2000, Hieke & Werner 2000). Further potential tsunami triggers are cosmic impacts for which, however, no evidence has yet been found in the Mediterranean.

3 Study area

Field survey was carried out along the north-western coast of Cap Bon, NE Tunisia (figure 1). In general, the Geology of the low lying coastal areas at Cap Bon is dominated by Tertiary and early Pleistocene sequences, mainly consisting of marine sandstones and aeolianites (Mensching 1979). The coastal morphology is characterized by slightly elevated marine terraces, most likely of late Pleistocene origin (Jedoui et al. 1998, Morhange & Pirazzoli 2005).

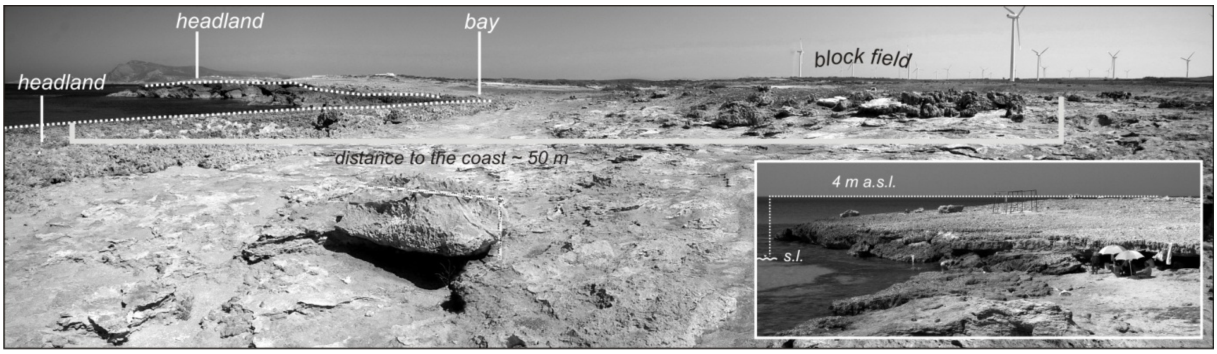

Figure 2: Cliff top platform with field of dislocated blocks, around 50 m distant from the sea. Inlay: View of Pleistocene terrace with cliff top platform reaching up to 4 m a.s.l. Elevation of cliff ~ 2 m. Note typical coastal configuration with bays and headlands.

They form, in most cases, small headlands, which are characterized by a well-developed cliff, up to 5 m high, and a cliff top platform, up to 200 m wide (figure 2). These promontories are separated from each other by small and narrow bays with, at some locations, sandy beaches. Well-defined notches document a comparatively stable relative sea level for the area for the late Holocene. The cliff top platforms are free of vegetation and characterized by intense karstification and, in the littoral and supralittoral zone, extensive rock pool formation.

4 Methods

During August 2008, a geomorphological field survey was carried out along the northern shorelines of Tunisia in order to detect geo-scientific imprints of extreme wave events. In this context, we found evidence for extreme wave emplaced blocks, up to at least ~ 5 m³ and 11 t.

Block fields detected during the geomorphological survey were documented and partly measured. The sizes of selected boulders were estimated based on measurements of the x-, y- and z-axes using a measuring tape. All the dislocated blocks and boulders were examined for rock pools on their surfaces. The number and the dimension of different rock pool generations were studied in order to get information on different phases of boulder transport. For weight calculation of the transported boulders, rock density was estimated to ~2.2 g/cm³ (Scicchitano et al. 2007). GPS points were measured for the study areas and for the sampling points.

5 Results and discussion

Location one (El Haouaria A, 37°03'9.08"N; 10°56'46.91"E, figs. 1 and 3) is situated 5.5 km west of the City of El Haouaria. Here, the cliff top platform reaches an elevation of around 4 m a.s.l. (above mean sea level) and is covered by numerous blocks and boulders, up to 3 m³ in size. The blocks are assembled in block fields and can be followed up to a distance of 50 m onshore.

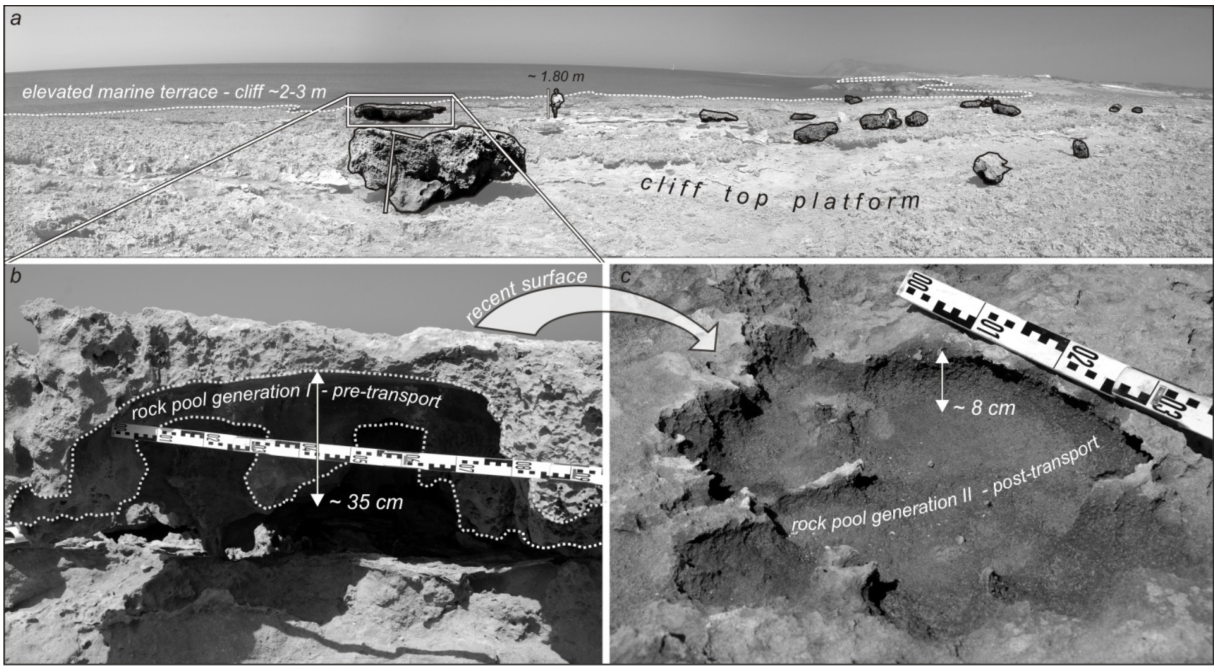

Figure 3: a) Block field at El Haouaria site A. Cliff top platform lies at around 3 m a.s.l. Note person (around 1.80 m) as scale. b) Overturned block of ca. 2.7 m³ in size with former surface (rock pool generation I) at its bottom side. c) Rock pool generation II on top of the recent surface.

Most blocks show extensive rock pools at their surface. These rock pools are usually formed by bio-erosional processes in the littoral zone (Laborel & Laborel-Deguen 1994). Found in the present constellation, they clearly prove that the blocks were transported from the littoral zone to their current position. Most probably, the rock slabs and blocks originate from the cliff front area.

Some of the dislocated blocks are overturned, with the former surface facing downwards. For the block depicted in figure 3, which is around 2.7 m³ in size and weighing approximately 6 t, this is indicated by well-developed rock pools, up to 35 cm deep and 1 m wide, found on the lower side of the block (figure 3b, rock pool generation I). A comparatively long period of rock pool formation was thus needed before the block was dislocated and transported to its recent position. Clear indications of bio-erosion by gastropods point to the formation of the rock pool in a littoral environment. Moreover, a second generation of rock pools (rock pool generation II) was observed on top of the recent surface. This rock pool generation shows a much smaller depth and width of around 8 cm and 40 cm, respectively, and must have developed subsequent to the transportation of the block (figure 3c). Thus, for this block, the period of time between the start of the formation of rock pool generation I and its displacement must have been much longer than the period of time since its transport. As not more than two rock pool generations could be observed, a displacement of the block during one singular event can be assumed.

Figure 4: a) Block field at El Haouaria site B showing several imbrication trains; the cliff top platform lies at around 1 m a.s.l. Note person (around 1.80 m) as scale. b) and c) Imbrication trains – blocks are typically tilted in wave direction. Inlay in b) shows two rock pool generations found for the second block within the imbrication train (grey – rock pool generation I, white – rock pool generation II).

Location two (El Haouaria B, 37°03'5.00"N; 10°58'9.20"E, figure 1 and 4) is located around 2 km east of location one and some 3.5 km west of El Haouaria. Dislocated blocks and boulders were encountered on top of an elevated marine terrace, about 1 m a.s.l. As illustrated in figure 4, blocks and rock-slabs are abundant and are assembled in a block field, extending approximately 3000 m². Within the block field, several trains of imbricated blocks, up to 5 m^3 in size, were found, consisting of up to 6 tilted blocks or rock-slabs. The imbrication of the blocks proves their extreme wave generated displacement and deposition.

Several blocks exhibit rock pools on their surface. Comparable to the findings at location El Haouaria A, two generations of rock pool formation can be observed, regardless of the position of the hosting blocks within the imbrication train (figures 4b and 5). Rock pool generation I appears to be deeper and wider than rock pool generation II (figure 5). Thus, the period of formation of rock pool generation I must have been longer than the one of rock pool generation II. Due to these findings we suggest that (i) the imbrication trains were arranged by only a single extreme wave event, and (ii) the blocks have not been shifted or tilted and thus remained in one and the same position since the time of their dislocation.

Along the coasts of Cape Bon, we thus encountered numerous wave emplaced blocks and boulders on top of the elevated terrace platforms lying up to 5 m a.s.l. and up to 50 m distant from the sea. In both study areas, two rock pool generations were observed on the dislocated blocks. In general, rock pool generation I appears to be considerable deeper and wider than rock pool generation II. Regarding the size of the rock pools, it can be noticed that, at both locations, rock pool generation II has only about ¼ of the size of rock pool generation I. These findings indicate that, at both sites, a comparable period of time was needed for the formation of rock pool generation II. We thus conclude that the displacement of the blocks occurred during the same event.

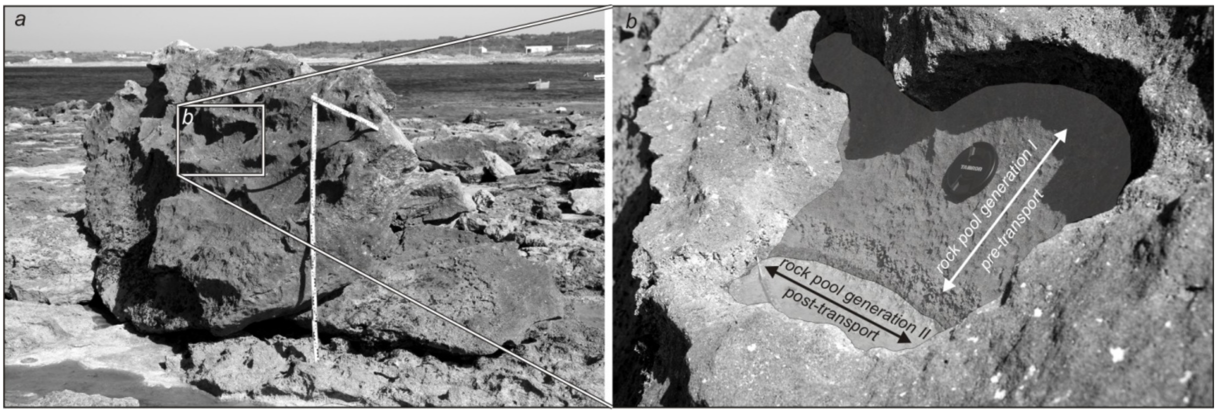

Figure 5: a) Imbricated block (~ 5.3 m³, ~ 11 t) with two rock pool generations. b) Rock pool generations I and II found on top of block shown in a).

As for the situation at El Haouaria site B shown in figure 5, due to the low lying terrace surface, it is assumed that the blocks are often flooded during usual winter storms. However, no more than two different rock pool generations were observed for all investigated blocks. These findings thus document a stable position of the blocks since their displacement and, in some cases, even since the related formation of imbrication trains. A recurrent transport, shifting or tilting of the investigated blocks during winter storms can thus be excluded.

During the last decades, several authors reported on cemented marine sediments of mid- to late Holocene age along the southern Tunisian coasts, found in elevations up to 1 m a.s.l. (for instance Jedoui et al. 1998, Morhange & Pirazzoli 2005). According to these authors, this marine sequence developed during a mid-Holocene sea level high stand. Vött et al. (2010) present findings of beachrock-type calcarenitic tsunamites from three different coastal areas in western Greece, partly associated to dislocated blocks. Within the context of the results presented in this paper, the deposition of fine-grained marine sediments above present mean sea level along the Tunisian coasts may possibly be explained by extreme wave events, rather than by a relative sea level high stand. However, further studies on these cemented marine deposits are needed to answer this question.

6 Conclusions

Block fields along rocky shorelines, consisting of rock-slabs, blocks and boulders, partly imbricated, are reported from all over the world. Their formation is linked to tsunami- or other extreme wave events, such as huge winter storm surges or hurricanes (for instance Goto et al. 2009, Kelletat & Schellmann 2001, Nott 2003a, Scheffers et al. 2005, Scicchitano et al. 2007, Switzer & Burston 2010, Williams & Hall 2007). However, it remains difficult to realize an appropriate determination of the event source, and the application of hydraulic equations dealing with the wave energy necessary for the wave induced transportation of blocks, which may be helpful to estimate the event source and intensity, still exhibits considerable uncertainties (see for instance Nott 2003a, 2003b, Switzer & Burston 2010).

This paper documents, for the first time, extreme wave emplaced blocks and boulders on the coast of northeastern Tunisia. Due to our findings, the following conclusions can be made considering the formation of the block fields:

1. At the north-western shore of Cap Bon peninsula, block dislocation and deposition occurred up to 5 m a.s.l. The emplaced blocks are assembled in fields on top of elevated marine terraces and have been transported up to 50 m inland.
2. Several blocks and slabs were overturned or tilted by wave activity. Numerous blocks exhibit two rock pool generations. At study site El Haouaria B, blocks show distinct imbrication and are arranged in imbrication trains of up to 6 tilted blocks.
3. The existence of two rock pool generations on top of numerous displaced blocks suggests one singular event responsible for displacement. Considering the dimensions of the rock pool generations, the period of time since dislocation of the blocks is considerably shorter than the period of time before their displacement when the blocks were lying in their original positions.
4. A stable position of the blocks before and since the time of movement can be assumed. Therefore annually recurring winter storm activities do not shift or move the blocks, although, due to the low lying cliff top platform, some of the blocks most likely are overflown by sea water during winter storms.
5. Due to these findings, a tsunami event rather than a storm has to be assumed for the deposition of the observed block fields. Also regarding the stable position of the blocks since their displacement, a storm-generated origin seems to be unlikely.

In general, the question of determining and localizing the event source and the ability to distinguish between tsunami and storm origin is important in palaeo-event research; further analytical studies are required to improve our understanding of the geomorphological and sedimentological fingerprints of the different kinds of extreme wave event deposits.

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