Boulder Deposits on the Southern Spanish Atlantic Coast: Possible Evidence for the 1755 AD Lisbon Tsunami?

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Abstract

Field evidence of visible tsunami impacts in Europe is scarce. This research focused on an analysis of large littoral debris and accompanying geomorphic features and their relationship to a tsunami event at Cabo de Trafalgar, located on the southern Spanish Atlantic coast. Relative dating of weathering features as well as minor bioconstructive forms in the littoral zone suggest the Lisbon tsunami of 1755 AD as the event responsible for the large deposits described. This tsunami had run up heights of more than 19 m and was generated at the Gorringe Bank, located 500 km west off the Cape. Tsunami deposits at Cabo de Trafalgar are the first boulder deposits identified on the southern Spanish Atlantic coast and are located approximately 250 km southeast of the Algarve coast (Portugal), where other geomorphic evidence for the Lisbon tsunami has been reported.

1. INTRODUCTION

Literature on tsunami deposits along European coastlines is scarce and mostly restricted to individual locations. The few publications on tsunami deposits include the findings of fine sediments in coastal marshes and lakes in Scotland and western Norway deposited by the Storegga tsunami approximately 7200 BP (Dawson *et al.*, 1988; Long *et al.*, 1989; Bondevik *et al.*, 1997; Dawson and Smith, 2000); reports on rounded gravel and sand on the coastlines of the Aegean Sea deposited by the Amorgos tsunami of 1956 (Dominey-Howes, 1996; Dominey-Howes *et al.*, 2000); documentations on sand and cobble deposits at the Algarve coast (Campos, 1991; Andrade, 1992; Dawson *et al.*, 1995; Hindson *et al.*, 1996); or Banerjee *et al.*'s (2001) publication on sand and cobble on the Scilly islands, most likely originating from the Lisbon tsunami in 1755 AD. Heck (1947) and Mastronuzzi and Sanso (2000) described tsunami deposited boulders at the southern Italian coast. Extended boulder ridges, boulder assemblages, and filled bays were observed in western and southwestern Cyprus (Kelletat and Schellmann, 2001, 2002; Whelan and Kelletat, 2002). From Bartel and Kelletat (2003) tsunami boulders from Mallorca island (Spain) have been reported and dated by AMS to about 460 BP and 1400 BP. Kelletat (2005) observed large tsunami boulders broken from beachrock at the southern coast of Turkey, and Scheffers and Kelletat (2005) described and dated tsunami deposits and associated landforms west of Lisbon. This study focuses on newly detected tsunami-deposited boulders at Cabo de Trafalgar, located on the southern Spanish Atlantic coast.

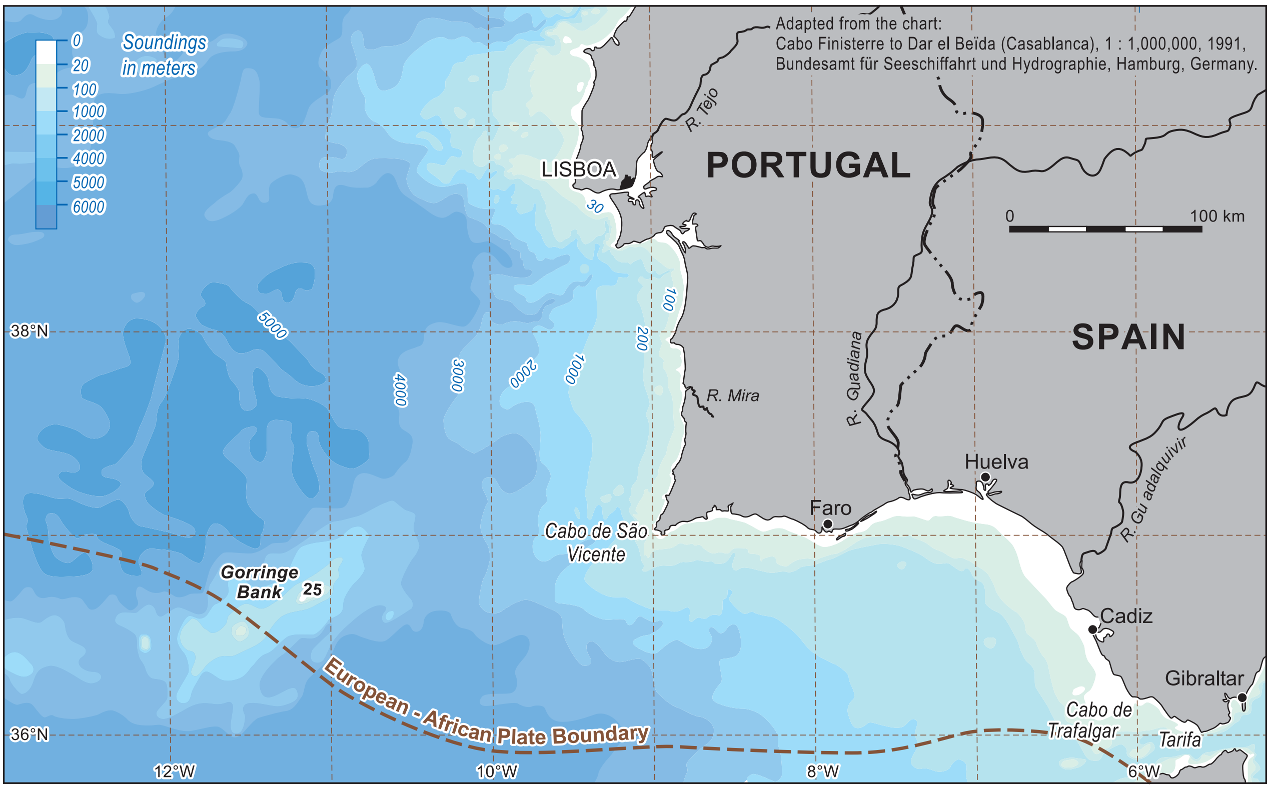

Fig. 1 The position of Cabo de Trafalgar in relation to the Gorringe Bank.

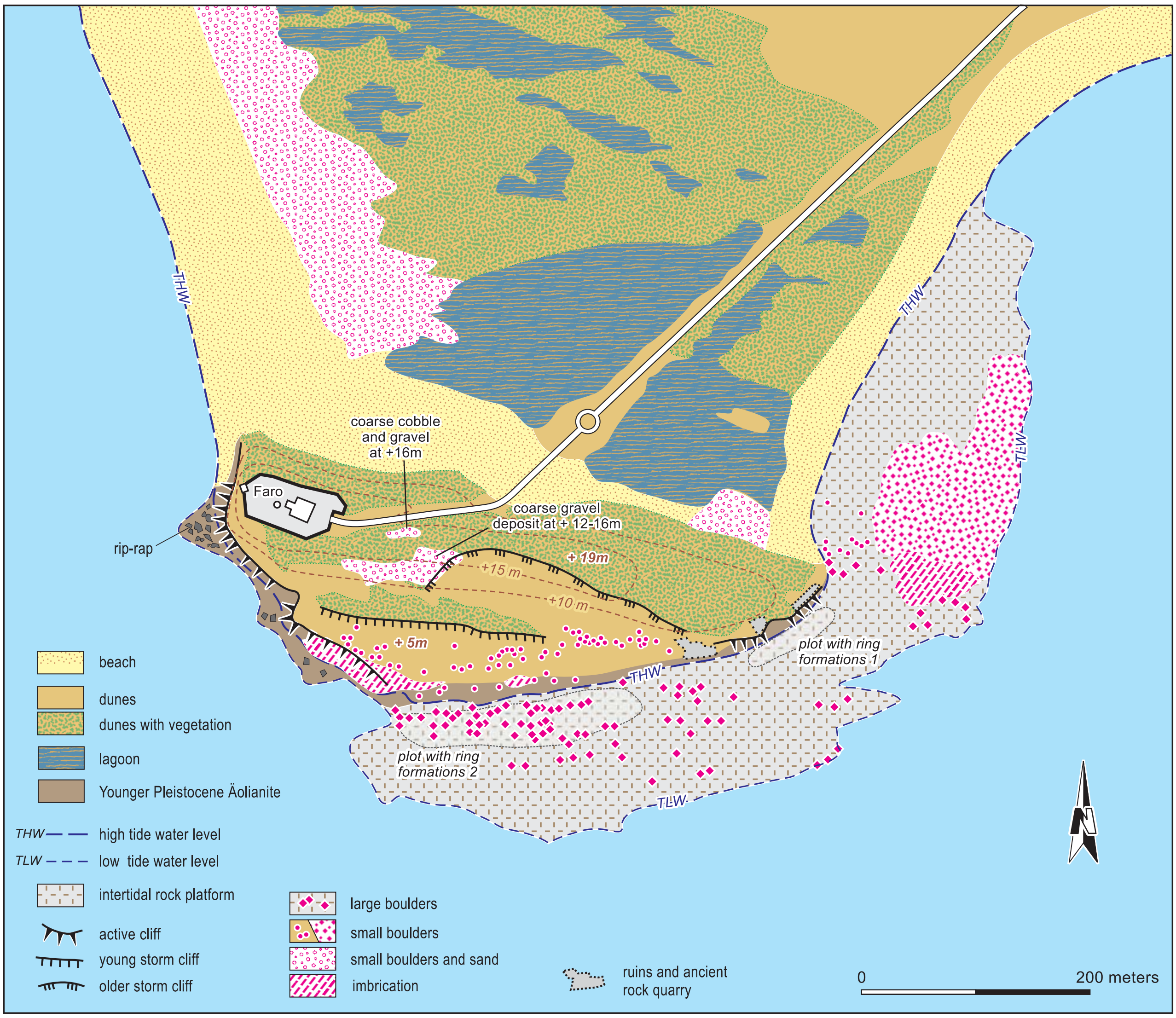

Fig. 2 Sketch of the geomorphologic units of Cabo de Trafalgar.

2. STUDY AREA

Cabo de Trafalgar (Figs. 1 and 2) is a small headland located 36°10´N and 6° W. The centre of Cabo de Trafalgar used to be an elongated (E to W) and isolated island in earlier Holocene times, later connected in the north (Playa de las Plumas) and east (Playa de Mari Sucia) by two beach tombolos, closing a wide and shallow lagoon. This former island was about 500 m long and 200 m wide and nearly 20 m high. Partly mobile dunes cover its relative flat top. The cape is exposed to Atlantic swell and storms, but shallow water extends seaward for several kilometers. Tidal range is about 2.1 m. The former island consists mostly of Young Pleistocene eolianite, resting on a conglomerate (older beach-) platform (Fig. 2). Rather steep cliffs surround the headland, in particular at its exposed western flank. Numerous smaller and very large boulders decorate the coastline in the south and are resting on the intertidal platform, which marks the area of interest.

3. PURPOSE AND METHODS

This study was conducted to analyze the unusually large boulder deposits at Cabo de Trafalgar, their distribution patterns, and the mechanisms likely to be responsible for their transport and deposition. Imbricated boulders with lengths greater than 1 m were analyzed for their kind of setting. All boulders larger than 2 m^3 were mapped using a Global Positioning System (GPS) and were surveyed using supplemental field methods. Measured parameters included length, width, and depth. The orientation of the longest axes, likely transport distances, degree of weathering and encrustations were also analyzed. Potential wave heights for storm or tsunami waves responsible for the boulder transport according to Nott (2003) were calculated. Additionally the spatial pattern of cobble deposits and their characteristic shapes were recorded. Vegetation and soil development as well as anthropogenic features at Cabo de Trafalgar were also observed. All mapping was based on use of a GPS, a 1:5,000 scale topographic map (Instituto de Cartografía de Andalucía, 1997), and a 1:20,000 scale true color aerial photograph (Instituto de Cartografía de Andalucía, 2001).

4. FIELD OBSERVATIONS: MARINE-DEPOSITED DEBRIS

4.1 Spatial patterns of deposits

The large boulders preserved at Cabo de Trafalgar are the only possible proofs for a tsunami event along an approximately 100 km stretch of coastline between the mouth of the Guadalquivir and Punta Camarinal halfway between Barbate and Tarifa. Reasons why geomorphic tsunami evidence or visible deposits have not been preserved along this coastline include extended active beaches and fore dune development, steep and high active cliffs, extended marsh areas, and artificially altered coastlines. Cabo de Trafalgar seems to be the only place susceptible to the preservation of any older geomorphic features along this 100 km long coastal section.

4.2 Large boulders located on the intertidal platform

More than half of the cape is surrounded by a rock platform located to the south and east. This platform is in an intertidal position, and represents the border between the Younger Pleistocene eolianite and a conglomeratic beach deposit at its base (Fig. 2). It is located approximately 1.1 m below mean high tide water level and slightly declines to the south (seaward). The platform extends approximately 80 to 100 m in this direction and ends with a vertical wall, which provides a breaking point for waves during low tide. There is no debris on this platform, with the exception of about 80 large boulders with weights exceeding 10 tons (Fig. 3). Apart from these boulders and some (artificial) ring formations, bioconstructive forms generated by barnacles and vermetids predominate the platform. The barnacles form elongated rims that surround flat water pools (Fig. 4).

Fig. 3 Overview of the boulders on the intertidal platform south of Cabo de Trafalgar during low tide. See person for scale.

Fig. 4 Barnacle rims on the intertidal platform of Cabo de Trafalgar.

Evidently the large boulders have not been moved for a long time. They are not rounded, relatively flat (deriving from the conglomeratic strata) and of irregular shape (Fig. 5). Recent movement can be excluded because of thick incrustations by barnacles and vermetids, which connect the boulders with their basement. No fresh boulders or those without thick barnacle coatings could be found on the platform, even if they do not weigh more than 5 tons. The boulders have been broken off the seaward border of the intertidal platform, which represents a Pleistocene beach layer of limited thickness. This layer is underlain by less resistant rock, which is visible at several notches. Boulder dimensions, volumes and weights (density calculated was 2.5) are listed in Table 1.

Fig. 5
One of the large boulders on the intertidal platform with a weight of approx. 50 tons

The origin of the large boulders from the border of the intertidal platform and their distance moved (20 to more than 200 meters) on this platform is evident. The boulders seem to be moved during the same event, because there is no difference in barnacle coating, bioerosion or other features. Astonishingly no smaller boulders have been thrown on this platform in recent times. Theoretically, they should be stopped in their movement across the platform by the barrier of the large boulders, but this did not occur. The main question is which kind of power has moved boulders of this size: storm waves or tsunami. Evidently during the last decades or even longer no movement has taken place, which excludes storms as an important factor for boulder movement at this site. We used the formulas of Nott (2003) for the physics of boulder movement, in particular equations for the joint bound scenario (because the boulders have been broken off a hard conglomerate stratum) to calculate wave heights. To move 20 ton boulders joint bounded, Nott (2003) has calculated storm wave heights from about 16 m for a cube to more than 40 m for a platy fragment, and to move a boulder of 67 tons (i.e. a cube of 3 m of edge length, with density 2.5) the cubic fragment will require a storm wave height of about 24 m and the platy one close to 50 m, which all can be excluded for any coastline of the world. In contrast, tsunami wave heights

Table 1 Dimensions of the 40 largest boulders from Cabo de Trafalgar.

Length of axes [cm]			Volume	Weight*
a	b	c	[m]	[t]
700	450	150	47.3	118.1
600	500	120	36	90
600	500	100	30	75
600	500	80	24	60
500	430	110	23.7	69.1
500	380	120	22.8	57
450	380	120	20.5	51.3
400	350	120	16.8	42
410	300	115	14.1	35.4
320	260	160	13.3	33.3
400	300	110	13.2	33
450	350	80	12.6	31.5
400	300	100	12	30
400	300	100	12	30
460	360	65	10.8	26.9
450	350	70	10.1	25.2
400	280	90	10.1	25.2
400	250	100	10	25
530	240	75	9.5	23.9
300	300	100	9	22.5
600	200	70	8.4	21
380	360	60	8.2	20.5
400	250	80	8	20
350	200	110	7.7	19.3
300	300	80	7.2	18
350	270	70	6.6	16.5
400	150	100	6	15
400	150	90	5.4	13.5
300	200	90	5.4	13.5
350	220	70	5.4	13.5
280	210	85	5	12.5
280	220	80	4.9	12.3
300	200	80	4.8	12.0
320	200	70	4.5	11.2
250	250	70	4.4	10.9
350	250	50	4.4	10.9
300	200	70	4.2	10.5
350	170	70	4.2	10.5
300	300	45	4.1	10.1
250	200	80	4	10

* density 2.5

values of 4 to 10 m for the 20 ton fragment and up to 12 m for the 67 ton fragment are required. These values, however, are calculated with respect to overturn a boulder, but the Trafalgar boulders have been dragged for 20 to more than 200 m over a rough surface, and some boulders seem to be transported by a swash of water and smashed down, breaking into several pieces. Because of the dense cover of algae and barnacles on the intertidal platform no scratch marks or other features could be found demonstrating a certain kind of boulder movement, but – of course – their existence cannot be excluded. All in all, tsunami run up or wave heights for the Cabo de Trafalgar boulders of 14-16 m are conservative values.

The majority of the long axes of the broken-off boulders (N-S) seem to be directed perpendicular to the direction of transport (W-E), however, deviations occur and could be explained by different waves, wave refraction along the platform edges, or transport in suspension rather than rolling over the ground.

4.3 Imbricated boulders

Approximately 280 imbricated boulders weighing between 1 and 10 tons were observed between high tide water level and 5 m above in a coastal stretch of 100 long directly south of the headland. Another approximately 100 imbricated boulders can be found more eastward. Most of these boulders are partially covered with sand (Fig. 6). About 90% are well rounded. Imbrication axes in both areas are determined using the Poser and Hövermann (1952) methodology, showing, that approximately 62% to 72% of all imbricated boulders were aligned perpendicular to the direction of transport (Fig. 7). Another site of well imbricated boulder can be seen on the eastern part of the intertidal platform between high and low water level.

Fig. 6
Imbricated boulders of 1 to 10 tons of weight south of the Trafalgar headland.

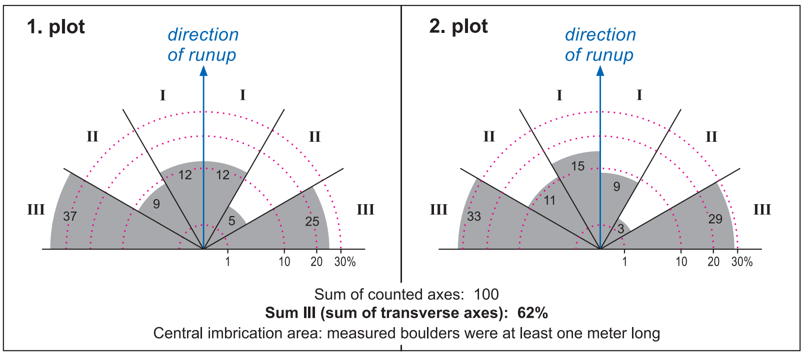

Fig. 7
Direction of axes of two sites with imbricated boulders.

4.4 Cobble deposits on top of the cape

An abundance of well rounded cobbles with diameters exceeding 15 cm were observed near the lighthouse road at ca.15 m asl and close to the roman ruins between 12 and 16 m asl (Fig. 8 and 9). These cobbles are made of Tertiary sandstone and harder strata of the eolianite. On a test plot of 1000 m² at the top of the headland, 51 of 108 cobbles were broken. The percentage of broken cobbles east of the headland at the leeward side of storm or tsunami waves from the west is around 12%. It is important to note that at heights of at least 16 m asl cobbles and even well rounded boulders up to several 100 kg are incorporated in the sand. This forms prove that on top of Cabo de Trafalgar not only dune sand has been deposited but also bimodal sediments with floating boulders and cobbles in the sand were found. As some of the largest floating boulders can be found at the northern (leeward) slope of Cabo Trafalgar, waves at least 19 m high (i.e. the maximum height of Cabo de Trafalgar) would be required for the transport of these boulders.

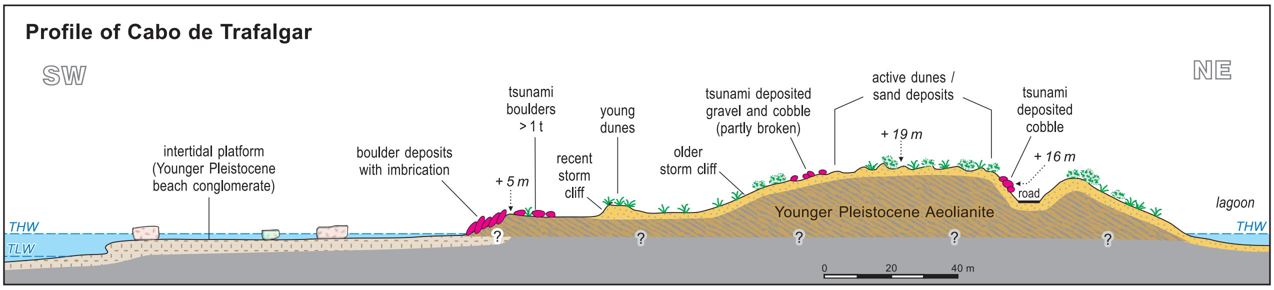

Fig. 8 Distribution of cobbles and large boulders on a profile across Cabo de Trafalgar.

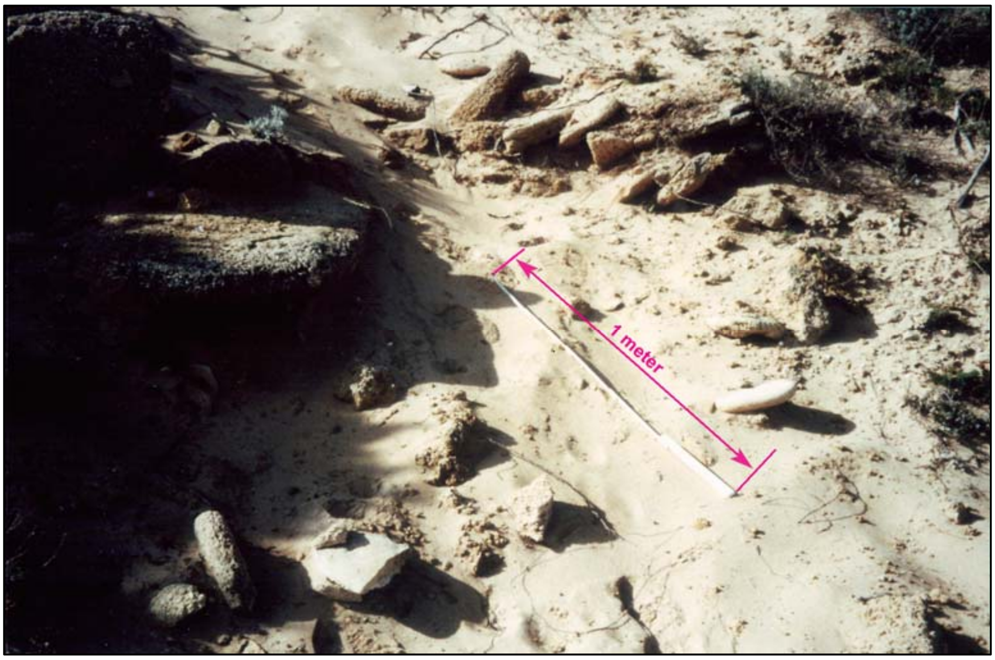

Fig. 9
Well rounded boulders floating in sand on top of Cabo de Trafalgar at 16 m asl.

4.5 Storm versus tsunami deposits

The lighthouse keeper's wife mentioned that a boulder of approximately 50 tons, which appears fresh compared to the intertidal boulders, was deposited in the west in 1989 and broke off a part of the old lighthouse structure. It has been mapped in the rip rap zone in Fig. 2. She was not sure whether extreme storms deposit fresh boulders on the intertidal platform, although waves cross the beaches and lagoonal area north of Cabo de Trafalgar, so that the lighthouse is isolated for some days during winter storms. On the platform, however, there is no evidence for younger boulder deposition or boulder movement: all boulders show the same intensity of barnacle incrustations, no small boulders are piled up against the very large ones, and the boulder assemblage seems to be deposited simultaneously. Fresh boulders with white calcareous algae or *Lithophaga* borings at the landward side of the platform at about high water level may reach weights of not more than 500 kg. These boulders verify that winter storms in this region only have limited capability to transport boulders, most probably because of the shallow water far out into the sea. Even boulders of less than 10 tons will not be moved by storms on the intertidal platform. There are, however, at least two storm marks at the southern slope of the Trafalgar headland (Fig. 2): the higher and older one may reach up to 10 m asl and has cut into older vegetation including some low bushes, and the younger one has only cut a narrow platform in the fore dune, which is scarcely vegetated, at approximately 5 to 5.5 m asl. Both have not rearranged any boulders significantly.

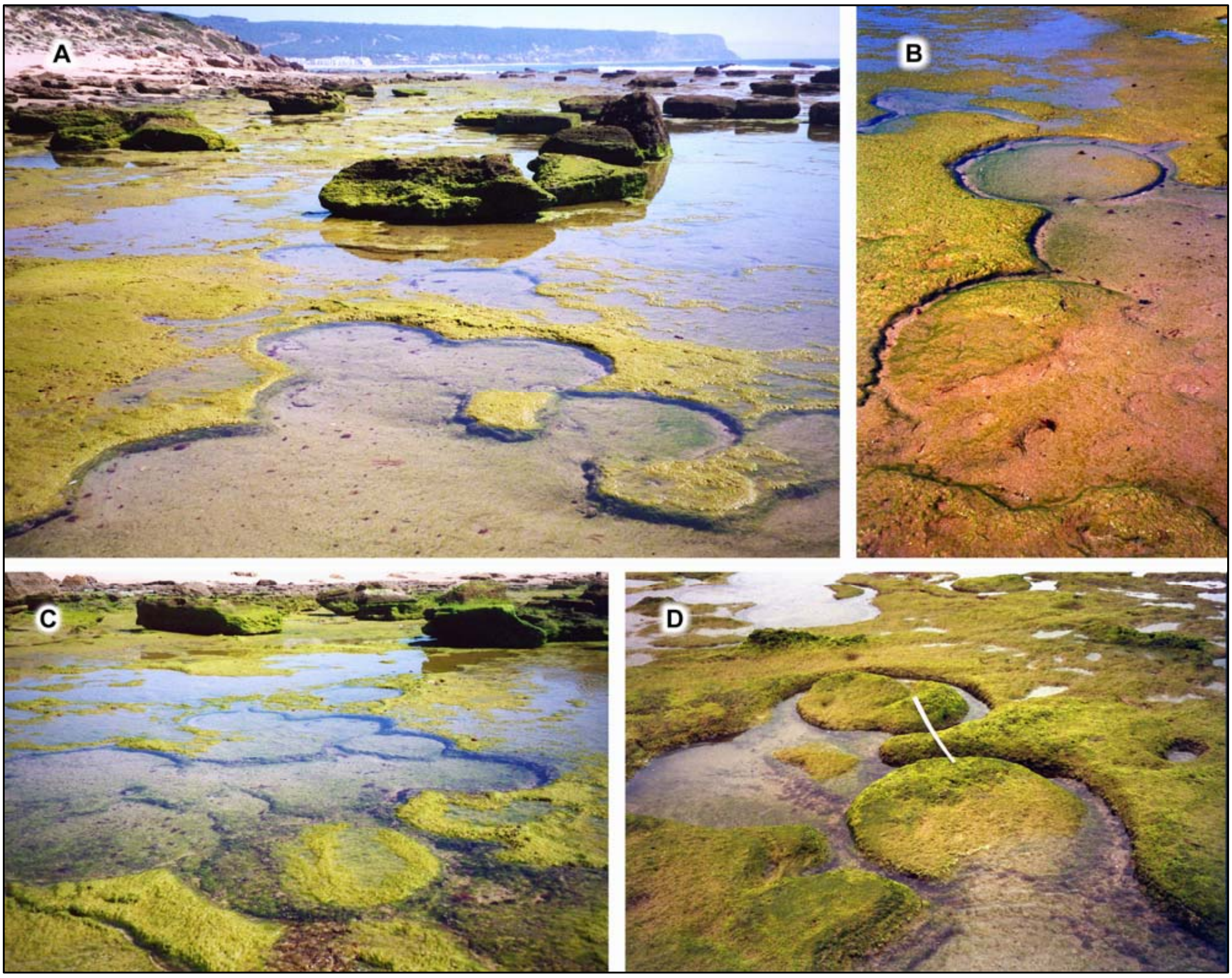

Fig. 10 Ringlike carvings in the conglomerates of the intertidal platform at Cabo de Trafalgar as signs for antique quarrying of column sections.

At the southeastern side of the headland, Roman ruins at about 10 m asl and some low lying quarries can be observed in the eolianite. Without a cross section at the ruined site it is difficult to predict how much this place has been affected by (tsunami) waves in former times. The intertidal platform gives some more evidence of a limited abrasive power of the waves in this region: hundreds of ringlike features (Fig. 10) document, that the hard conglomerate of the intertidal platform was used in antique times as a quarry for column sections, looking like millstones and with diameters of mostly 1.15 m, with a minority of diameters of 0.74 m. The abrasion – although sand, cobbles and boulders are present all along the landward section of the intertidal platform – evidently was not more than some centimeters since antique times.

5. CONCLUSIONS: RELATIVE DATING AND POSSIBLE LINKING WITH THE LISBON EARTHQUAKE AND TSUNAMI IN 1755 AD

Age indicators for the deposition of the boulders are barnacle incrustations (with some vermetids) of many centimeters of thickness, a few signs of bioerosion by gastropods on the limestone parts of the large boulders, a limited soil and vegetation cover on the bimodal sediments with floating boulders on top of the Trafalgar headland, and a deposition of a broad sandy beach in front of the cobble ridge along the beach north of Cabo de Trafalgar (see Fig. 2). At cliffs in eolianite only a few tafoni have been developed by salt weathering. Broken cobbles in the east of the headland as well as on its top show a slight smoothing of former sharp edges by wind abrasion. The well developed and extended barnacle rims on the intertidal platform (Fig. 4) may have developed within many decades or even centuries. These rims have not changed within the last 30 years (*pers. obs.*).

Due to these relative indicators, a correlation of the boulder deposits and the bimodal sediments with floating boulders on the headland as well as the deposition of the cobble ridge in the northern beach to the 1755 AD Lisbon tsunami is a possible conclusion. The epicenter of the earthquake that generated this tsunami was located near the Gorringe Bank, approximately 500 km west of Cabo de Trafalgar (Fig. 1). According to Johnson (1996), a crustal block of 180 to 280 km in length was displaced 10 to 14 m affecting a total area of 800,000 km^2 (Chester, 2001). Based on Moreira (1988), the strongest tectonically induced tsunami in Europe originated from the Gorringe Bank, which is located approximately 200 km to the west of Cabo Sao Vicente (southwestern corner of Portugal). The Gorringe Bank is situated at the Azores-Gibraltar fault zone (Fig. 1), which is the plate boundary between Europe and Africa. Multiple tsunami have been generated in this area, including those in 218/216 BC, 210 BC, 209 BC, 60 BC, 382 AD, 881 AD, 1731 AD, 1755 AD, 1769 AD, and 1969 AD (Moreira, 1988, 1993; Campos, 1991). The 1755 AD earthquake ranked 8.75 to 9.0 on the Richter scale (Campos, 1991; Mader, 2001) and was one of the strongest in human history. The earthquake was felt in Hamburg (Germany), southern England, and North Africa. It generated ripples in lakes all the way up to Finland (Reid, 1914).

Without doubt, the Lisbon earthquake triggered a tsunami of extreme height. However, different run ups have been reported in the literature (Table 2).

Sedimentologic and geomorphologic evidence of the 1755 AD Lisbon tsunami includes sand, pebbles, and cobbles on the Scilly islands and in southern England (Banerjee *et al.*, 2001), and on the Algarve coast in southern Portugal (Hindson *et al.*, 1996; Dawson *et al.*, 1991; Dawson *et al.*, 1995). Andrade (1992) reported the transformation of barrier islands on the Algarve coast, e.g. overwash and channels, generated by the 1755 AD tsunami.

However, there are no sources reporting boulder deposits (>1 t) along the southern Portuguese or Spanish coastline, whereas new investigations found a lot of them west of Lisbon, as well as signatures of run up up to 50 m asl in vegetation scars and datings of older tsunami there (about 2400 BP and 6000 BP(?), see Scheffers and Kelletat, 2005). At Cabo de Trafalgar we could not identify any field evidence of tsunami older than a few centuries. Comparing the run up heights reported for the south coast of the Iberian Peninsula in Table 2, the run up height of a minimum of 19 m asl (i.e. the maximum altitude of Cabo de Trafalgar, which was overrun by waves documented by the large floating boulders) for the Trafalgar area points to an extreme tsunami impact, which may well agree with the tsunami catastrophe of the Lisbon tsunami in 1755.

Table 2 Run up heights of the 1755 AD Lisbon tsunami as reported in the literature

Greater Area	Region	Run up [m]	Source
Portugal	Porto	2	Moreira, 1993
	Lisbon	20	Mader, 2001
		6	Baptista et al., 1999a Kozak &James, 2001 Moreira, 1993
		5-12	Reid, 1914
	Cabo Sao Vicente	30	Moreira, 1988 Kozak &James, 2001
		15	Baptista et al., 1999 a
	Boca do Rio	11-13	Dawson et al., 1995
	Ria de Formosa	12	Moreira, 1993
		9	Andrade, 1992
Spain	Cadiz	11-20	Andrade, 1992
		18-20	Campos, 1991
		>10	Baptista et al., 1999a
		4	Moreira, 1993
	Tarifa	11	Campos, 1991
	Gibraltar	2	Kozak & James, 2001
Morocco	Tanger	10	Baptista et al., 1999b
Madeira		5	Reid, 1914
S-England		3	Reid, 1914
Antillean Islands		>2	Lander & Whiteside, 1997

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