TSUNAMI RELICS ON THE COASTAL LANDSCAPE WEST OF LISBON, PORTUGAL

Anja Scheffers
Dieter Kelletat

Department of Geography – Geomorphology and Quaternary Research
University of Duisburg-Essen
Universitätsstr. 15
D-45141 Essen, Germany

e-mail: anja.scheffers@uni-essen.de

ABSTRACT

Lisbon and the mouth of the river Tagus (Tejo) are known to have suffered from the great earthquake and tsunami of November 1st, 1755. Whereas historical sources mention tsunami waves and describe inundation in Lisbon, field evidence from this event has been found only along the Algarve coast and the Spanish Atlantic coast in the south. Our observations in the Cabo da Roca-Cascais area west of Lisbon resulted in the discovery of several very significant tsunami relics in the form of single large boulders, boulder ridges, pebbles and shells high above the modern storm level. Deposition of large amounts of sand by the tsunami waves has intensified eolian rock sculpturing. Abrasion of soil and vegetation still visible in the landscape may point to the great Lisbon event of only some 250 years ago, but radiocarbon and ESR datings also yielded older data. Therefore, we have evidence that the Portuguese coastline has suffered more than one strong tsunami in the Younger Holocene.

1. INTRODUCTION

On November 1st, 1755, an earthquake with a magnitude of 8.5 to 8.9 on the Richter scale occurred several hundred kilometers southwest of Lisbon near the Gorringe Bank, where the European and African plates move along each other. It was one of the greatest disasters in human history.The number of casualties caused by the tsunami triggered by the earthquake has been estimated to be about 900, whereas the total number of fatalities was near 60,000. According to 130 historical sources, recently checked again by Baptista *et al.* (1998), run-up values were more than 15 m near Cabo Sao Vicente and at Cadiz, and in Lisbon itself inundation reached at least 250 m. Geomorphologic and sedimentologic proofs of a strong tsunami impact have been detected along the Algarve coast in southern Portugal by Andrade (1992), Dawson *et al.* (1995), and Hindson & Andrade (1999), mostly as washover fans in coastal barriers. Luque *et al.* (2001) were able to identify sand sheets and pebbles dislocated more than two thousand years ago along the barrier coastline of southern Spain, deriving from a tsunami with wave energies and run-up heights similar to or only a little less than those of the year 1755. Field surveys at Cabo de Trafalgar in southern Atlantic Spain by Whelan & Kelletat (2003) resulted in the mapping of large boulders of up to 100 tons in the intertidal area, and smaller boulders and shelly sands thrown over the cape with run-ups of at least +19 m asl. Astonishingly, to date no field inspection has been undertaken in the vicinity of Lisbon itself, although the coastal section north of the Tagus river mouth from Cascais to Cabo da Roca (see Fig. 1) has been extremely exposed to all tsunami waves from the Gorringe area in the SW. The reason may be that this coastline is a rocky one with medium to steep slopes from about +10 to +20 m asl extending into the sea, or even vertical cliffs of up to more than 30 m in height. Deposits of tsunami waves along this type of coastline are not to be expected; geologists and sedimentologists prefer to inspect accumulative geomorphologic units with a good stratigraphy for dating. Field research on Cyprus (Kelletat & Schellmann, 2001, 2002) and Mallorca (Bartel & Kelletat, 2003) has shown, however, that rocky shorelines may well preserve the imprints of tsunami waves.

2. FIELD OBSERVATIONS

In May 2004, the authors conducted field research in the Cascais-Cabo da Roca area west of Lisbon in order to study the fine sculpturing by shifting sands on the limestone rocks. Being aware of boulder deposits from Holocene tsunami in other regions (Mediterranean, Caribbean), we also looked for geomorphologic or sedimentologic evidence of a possible tsunami imprint from the 1755 Lisbon event in this area. As we will briefly describe below, there are several tsunami relics which may yield some good indication of run-up values and impact times.

Fig. 1 shows the study area in more detail: The broad promontory of Cabo Raso consists of gently folded limestone, forming a rocky shoreline with low cliffs and numerous deep and narrow incisions along fault lines or abraded mylonitic rocks. The rocks normally are bare of vegetation up to about 7-8 m asl because of the strong exposure to Atlantic storm waves and swell. The highest storm-moved boulders can be found at about +5.5 m asl with a maximum of +7 m weighing nearly 100 kg in fissures. On higher ground, soil and vegetation appear, mostly on a sandy stratum of up to several meters in

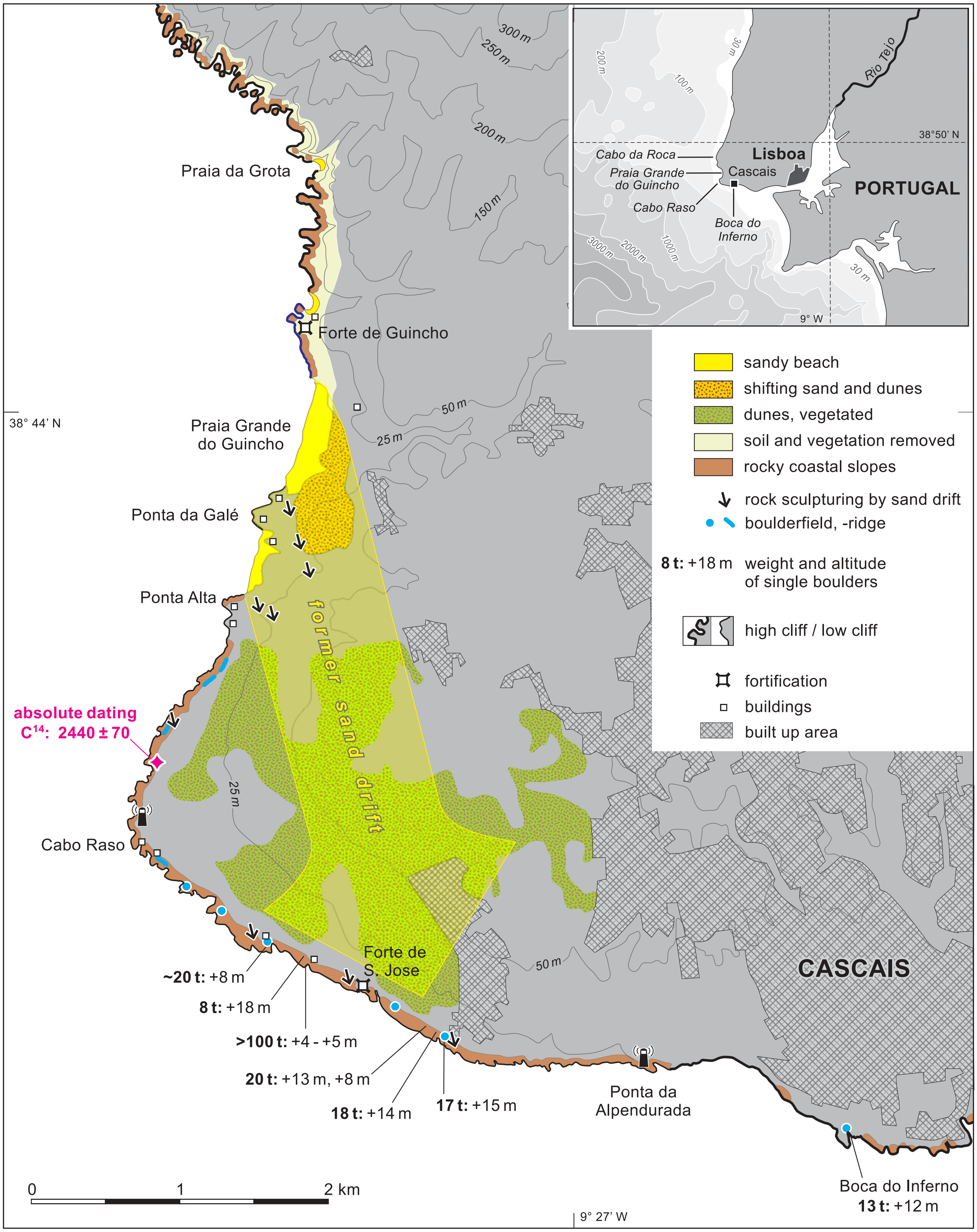

Fig. 1: Coastal features along the section Cascais-Cabo da Roca west of Lisbon.

thickness. To the east (i.e. direction of Lisbon, up the river Tagus), the coastal cliffs become higher and very steep and are strewn with huge cube-like boulders at their base, some of them exceeding 1000 tons. These giant boulders give the impression of a sudden collapse of the vertical cliffs.

More than 1 km north of Cabo Raso, sandy beaches occur with a width of about 1 km, interrupted by the small promontory of Ponte da Galé. Evidently sand supply to these beaches is very good, as can be seen by the development of a foredune belt as well as high and bare sand dunes which are shifting inland. During stronger northerly winds, shifting sand is a danger to road traffic in this area. The sand is rather fine (about 0.05 mm in diameter), highly polished and rounded and shows 3-5% percent carbonate particles from broken shells. North of Guincho beach, the deeply incised rocky shoreline becomes steeper and higher, containing some small pocket beaches on the west-facing section. Closer to Cabo da Roca, cliffs of far more than 100 m occur, cut into cristalline rocks and strongly folded and faulted sedimentary units, disturbed by dikes, the whole being a very complicated geologic situation.

As is normal along limestone coasts, a belt of bio-erosive rock pools with a characteristic sharp miniature relief has developed along the surf line on the limestone reaching a height of about +4 to 5 m asl. Higher up, the bare carbonate rocks exhibit smoother contours typical of karst solution under a soil cover. The intensity of the karstification can be seen from numerous perpendicular solution shafts many meters deep. From about +8 to 9 m asl, these hollows are more or less filled with relics of an old red soil with caliche, belonging to this phase of deep karstification in Pleistocene times. The red Pleistocene soil is mostly covered by a sandy stratum containing a dark brown soil from Holocene times (up to at least 2 m deep, B-horizons preserved), which itself may be covered by younger sands with only a very light brown colouring, thus showing a very young and short soil development (Fig. 2). Traffic and tourist impact have destroyed these soils in many areas of the coast. Further inland, dense shrubs and pine forests cover extended sand bodies, partly showing dune features now fixed by vegetation.

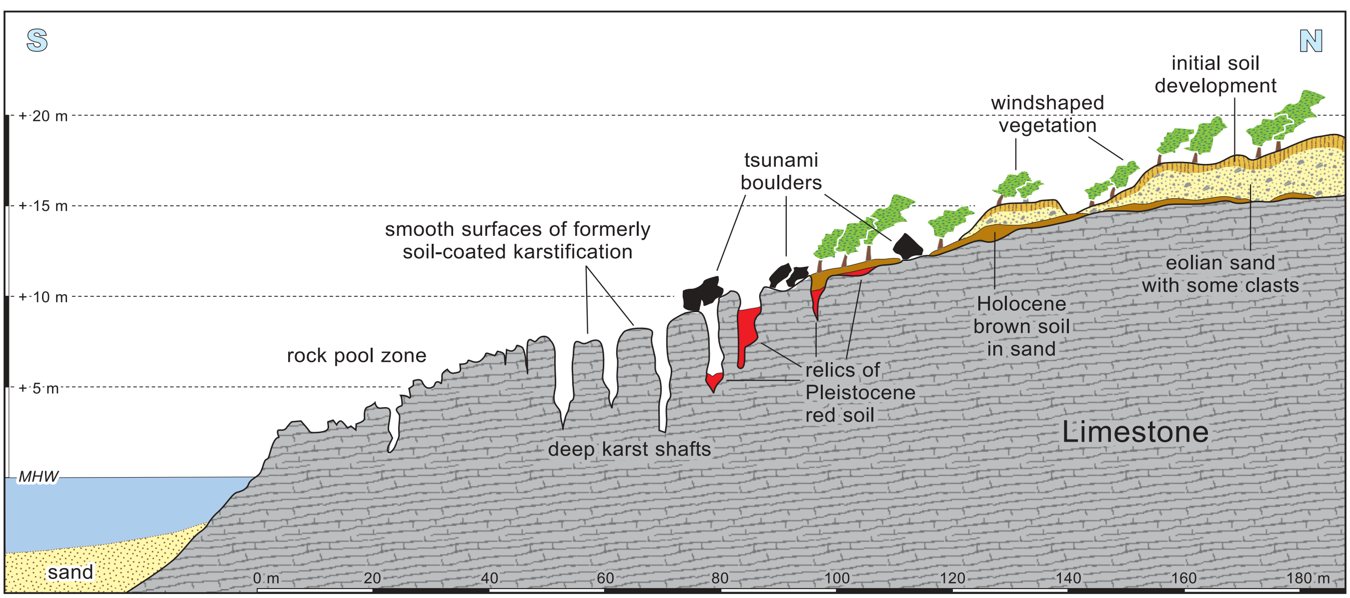

Fig. 2: Schematic cross-section of the rocky shoreline in the Cabo Raso area.

Outside the reach of even the strongest storm waves – as is visible from the soil and vegetation as well as the weathering on rocks –, single boulders have been deposited on the boundary of or even within the denser vegetation. Some distinctive boulders have been mapped in Fig.1. Weights ranging from more than 10 tons to about 20 tons can be found up to nearly +20 m asl (Figs. 3-5), and, 500 m west of the Forte de José, a boulder of more than 100 tons (longest axis 8 m) has been dislocated at +4 to 5 m asl (Fig. 6). On the south facing shoreline as well as on the westerly exposure north of Cabo Raso, smaller boulder fields (more than 50 fragments) or boulder ridges occur, again at around +10m or higher (Figs. 7 and 8).

Single boulders are not only dislocated for 50 m or more against gravity on a rough surface, but turned upside down, as can be seen from smooth karst forms at their bases. The status of their weathering, including karstification, soil development around them as well as pioneer vegetation on these boulders, points to the fact that over many decades or even centuries they have not been moved, which excludes strong storm impacts. Observations along stormy coastlines of the world as well as the state of the art of the knowledge of coastal boulder movement by waves (Nott, 1997, 2003; Scheffers, 2002, 2003, 2004) show that there is only one force which can move boulders of this size high above the surf line, namely tsunami waves. Therefore, we can take these boulders as being proof of one or more tsunami events along this coastal section of Portugal.

This conclusion is confirmed by the presence of well-rounded sand with pebbles (at some places enriched by deflation) and shells, both around the boulder deposits and higher and further inland. North of Praia Grande do Guincho, the size of the dislocated boulders is less than that of those in the south, reaching several tons landward of Forte de Guincho, which is located at +12 m asl. At around +30 m asl, the boulders weigh only 50-300 kg and are mixed with shelly sand and extremely well-rounded quartz pebbles of a smaller size (see also Fig. 9).The petrography of these boulders shows granite, quarzite, diabase, basalt, sandstone, limestone, and others. As

Fig. 3:

Tsunami boulder of about 20 tons, turned upside down at +10 m east of Cabo Raso.

Fig. 4:

Tsunami boulder of 25 tons near Forte de San José, moved inland for at least 30 m.

Fig. 5:

Tsunami boulder of more than 12 tons in a precarious setting at +13 m asl at Boca do Inferno, Cascais.

Fig. 6:

The largest tsunami boulder, broken by dislocationof several meters upwards into 4 pieces at +4-5 m asl about 400 m west of Forte de San José (Cascais). When first moved, the boulder had a weight of nearly 200 tons. The largest fragment with a longitudinal axis of about 8 m, still weighs more than 100 tons.

Fig. 7:
Tsunami boulder ridge with imbrication east of Cabo Raso at about +12 m asl.

Fig. 8:
Tsunami boulder field at about +14 m asl north of Cabo Raso.

Fig. 9:
Tsunami deposits (basaltic pebbles, coarse sand, shell fragments north of Guincho beach at +35 m asl.

mapped in Fig. 1, a rather sharp line separates dense shrubby vegetation from nearly bare land seaward of it, exhibiting an abrasive cutting of vegetation and soil in younger historical times. In some places, this line reaches +50 m asl, and beach pebbles and sand can be found even higher up. Some now vegetated dune-like sand bodies contain well-rounded floating boulders, and in total, these features are evidence of a tsunami with run-up heights of more than +50 m locally in this area.

What needs to be explained is the huge amount of sand and dune-like features which are bare or under vegetation from the town of Cascais to the Cabo Raso promontory. Two sources may be responsible for this: One is Guincho beach in the north, which in fact delivers shifting sands from direction NNW or 345° far inland, the other may be tsunami waves taking fine sediments from the open mouth of the Tagus with waves from SW. Evidence of the latter assertion are the large dislocated boulders close to the shoreline and the floating boulders and clasts within the sandy deposits inland. The sand directly east of Cabo Raso is much coarser than that of Guincho beach, with a diameter of around 1mm, bad sorting, less carbonate content and less polished grains than sand from the Tagus.

Shifting sands from Guincho beach have formed fine sculptures which are elongated and strictly parallel to 345° on bare rock (see arrows in Fig. 1 and Fig. 10). Through wind sculpting, the karst topography has been transformed into asymmetric rock outcrops (Fig. 11). Similar ones can be seen along the south-facing shorelines east of Cabo Raso (Figs. 12 and 13), evidently formed by wind from 345°, but now inactive with a slight destruction of the wind-polished surfaces by karstification in the range of several millimeters to 1 cm. These forms are evidence of a strong sand shift from the Guincho area across the broad promontory and from land to sea along its south shore. It is certainly not necessary to discuss climatic changes during more recent historical times to explain drifting sand in this landscape, because this might have also been caused by deforestation (cutting or burning). We are convinced, however, that the phase of sand sculpting on the south coast from direction 345° was triggered by sand from the Guincho area, where tsunami waves have picked up huge amounts of fine particles from the shallow foreshore.

Fig. 10:

Scuplturing of limestone rock shaped by modern sand drift south of the Guincho beach.

Fig. 11:
Rock outcrops of limestone have been sculpted asymmetrically by sand polishing south of Guincho beach.

Subsequently, the sand was shifted by strong northerly winds across the promontory to the south coast. By this process, some of the grains were broken and, after deposition, the carbonate content nearly disappeared, and a light brownish soil developed on the dune-like deposits. After the dislocation of this huge mass of sand to the south, the normal sand supply of today (which is still rather strong) has been overwhelmed by vegetation after several hundred meters of movement, and the southward sand transport into the Tagus ceased.

In sum, we found several evidences of tsunami in this area:

- boulders too large for transportation by storm waves dislocated high above the surf and far inland,
- boulder fields and boulder ridges with delicate setting and imbrication,
- floating boulders and clasts within chaotic sand deposits, i.e. typical bimodal tsunami sediments,
- beach sand and perfectly rounded beach pebbles and boulders far inland and up to more than +50 m asl,
- abrasion of soil and vegetation with a sharp scar, best identifiable on aerial photographs taken north of Guincho beach (for position compare Fig. 1),
- huge amounts of sand deposited in one short pulse, subsequently transported inland and seaward to the south,
- shells and molluscs of different species incorporated into the finer deposits high above sea level.

As concerns the boulder tracks, imbrication, the deposition of the largest boulders and vegetation scars, the direction of the tsunami undeniably came from SW to SSW. Run-up heights along the south-facing shorelines were at least +20 m, because large boulders can be found at up to +18 m and, north of Guincho beach, run-up was more than +50m in places, as can be identified by the vegetation scar crossing the 50 m isohyps in Fig. 1. As regards the number of tsunami waves, we were unable to find any definite evidence in the field.

Fig. 12:
Asymmetrical wind sculpted rock outcrops on the south coast of the Cabo Raso promontory, subsequently weathered.

Fig. 13:
Although transformed by karstification, inactive rock sculptures produced by wind polishing can still be identified east of Cabo Raso. Wind direction was from left in the picture.

3. RELATIVE AND ABSOLUTE DATING

From the field survey, we have derived some inductive and objective criteria for a relative dating of tsunami in the Cascais-Cabo da Roca area:

- *first*: the position of tsunami boulders in vegetated areas and those embedded in a soil on sand many decades to several hundred years old and far beyond the reach of the modern energetic surf;
- *second*: the weathering status, including the karstification of the boulder surfaces, again several hundred years or more in age;
- *third*: the slight destruction of sand-polished surfaces on limestone outcrops by karstification within the range of a few millimeters to about one centimeter, which again may need several hundred years to form;

- *fourth*: the good development of rock pools above the surf line without any traces of destruction by tsunami waves, demonstrating that the period after this event was long enough for good bio-erosive rock-pool formation;
- *fifth*: a still visible scar along the shrubby vegetation between about +20 to +50 m asl north of Guincho beach, evidence of a destructive impact more recent than the oldest juniper and mastix bushland on the coastal slopes;
- *sixth*: the existence of coastal fortifications (Forte de Guincho in the north, Forte de San Jose in the south from 1796), i.e. about 200 years old, founded in the tsunami-affected area but not harmed by a tsunami;
- *seventh*: the good preservation of molluscs in the finer tsunami deposits.

Whereas the founding period of the fortifications may yield only an absolute minimum date of a strong tsunami impact on the Cabo Raso area of more than 200 years ago, absolute dating by radiocarbon and ESR methods on marine carbonates (*Patella* sp., *Dolium* (Tonna) *galea*) are fairly reliable indicators of the time of the tsunami events occurring along this coastline of western Portugal. The most abundant molluscs dislocated and deposited high above the surf environment are limpets (*Patella* sp., see Fig. 14). The reason may be that these gastropods are widespread on rocky coasts with no beaches, where they resist even extreme surf beat. Evidently, the tsunami waves have pulled them from their original habitats, perhaps partly by abrading the highest parts of the shells and thus producing ringlike segments as shown in Fig. 14.

As with 1755 a rather young age for radiocarbon dating (regarding the reservoir problems) is given, Prof. Dr. U. Radtke (Cologne, Germany) tested some samples with ESR technique, which was sucessfull parallel to radiocarbon with coral samples from tsunami of the Caribbean (Radtke

Fig.14:

Patella sp., extracted from tsunami sediments at +14 m north of Cabo Raso. Ringlike fragments are typical, perhaps because of abrasion of the shells' tops by tsunami waves. Radiocarbon dating yielded a conventional age of 2440+-50 BP.

et al., 2002). A sample of well preserved *Dolium* (Tonna) *galea* gave an ESR signal of some hundred years as maximum, but older than modern. This would well fit into the 18th century as does the vegetation scar north of Guincho beach. A radiocarbon datum of 2440 +-50 BP from *Patella* sp. north of Cabo Raso at +12 m asl definitely hints at an older strong tsunami impact. It is highly likely that it was the same tsunami which was identified by Luque *et al.* (2001) in southern Spain, most probably from the years 218 or 216 BC, which were mentioned in older texts. The ESR signal from this sample was the same than that of another one from north of Guincho beach at +30 m asl. They certainly are of the same age, and by this we have two sites with older historical tsunami data. One sample of Patella from south of Guincho Beach at +14 m asl gave ESR signals about 2.5 times older than those from 2440 BP, pointing to ages of Middle Holocene around 6.000 to 7.000 BP, which will well fit into the geomorphology and soil stratigraphy of the region. As a result we carefully should say that the Lisbon event of 1755 left boulders and vegetations scars up to +50 m asl and shell in the Cabo Raso-Guincho area, and that it is highly likely, that at least one older tsunami (3rd century BC) has affected this area, maybe another one at the beginning of the Holocene high sea level. Regarding the distribution of dislocated boulders, they all may have had their origin near the Gorringe Bank southwest of Cabo Sao Vicente, SW Portugal.

4. DISCUSSION AND CONCLUSIONS

The different tsunami deposits preserved north of the mouth of the Tagus west of Lisbon evidently point to a strong event with run-up values of +20 to +50 m asl, depending on coastal configurations and exposure. We did not find clear evidence of the number of tsunami waves or backwash features but at least some hints as to the minimum age of the tsunami such as weathering intensity and vegetation and soil development. This was about 200-300 years ago, thus pointing to the well-known historical catastrophe of the year 1755. Uncertainties remain concerning the intensity of soil development and the degree of karstifikation on dislocated boulders, whereas the distinctive vegetation scar north of Guincho beach certainly must have been caused within a limited time frame in order to have been preserved. Absolute dating by ESR and radiocarbon methods, however, yielded the clear result that at least two major tsunami events have impacted this coastline in historical times (i.e. 18th century and 3rd century BC). Both were of a very similar strength and had similar run-ups as well as the same direction (from SW). There is no doubt of this because of the evidence of the vegetation scar that in 1755 – triggered by the open exposure to the tsunami wave from the southwest and the steep slopes in the embayment southeast of Cabo da Roca – tsunami run-up reached heights of at least +50 m asl in places. These values are much higher than those cited to date for the Lisbon event. On the basis of our observations and findings along the short coastal section between Cascais and Cabo da Roca, we are convinced that there are many more tsunami deposits from the 1755 Lisbon event and earlier impacts to be found along the coastlines of Portugal (and southern Spain, Morocco and other areas), and that the two historical tsunami events identified and dated so far cannot have been the only strong ones in the coastal regions of the Iberian peninsula.

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