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^{14}C-DATED CHARCOAL AND SEDIMENT DRILLING CORES AS FIRST EVIDENCE OF HOLOCENE TSUNAMIS AT THE SOUTHERN SPANISH COAST

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ABSTRACT. At 2 locations of the southern Spanish coast, we found indications for tsunamis induced by submarine earthquakes. Charcoal, which we sampled in 2 stratified, assumed tsunamigenic sediment (tsunamites) layers at the shore outside the ruins of the Roman city of Baelo Claudia, close to the Strait of Gibraltar (province of Cádiz), and radiocarbon dated, surprisingly turned out to be of identical age, about 465 BP. In the laguna of the Cabo de Gata (province of Almería), we found possible remnants of tsunamites in drilling cores deposited above organic sediments, ^{14}C dated as 680 ± 30 BP.

INTRODUCTION

Andalusia (Spain) belongs to the most seismically active regions of Europe due to convergence of the African and Eurasian plates. As the recurrence rate of earthquakes with high intensities is rather low, we have been searching for evidence of multiple events within buried paleosols at major faults (Becker-Heidmann and Reicherter 2003; Reicherter et al. 2003). Several epicenters are located in the seafloor of the Atlantic Ocean as well as the Mediterranean Sea, and at least 2 events with high impact to human settlements by tsunamis are historically documented (1 November 1755, Atlantic Ocean, destroying Lissabon [Portugal]; 22 September 1522, Gulf of Almería). The aim of our recent study is to find remnants of these known or earlier tsunami-associated earthquakes within sediments at the Atlantic and Mediterranean coasts of Andalusia.

LOCATIONS

Several major faults, which we investigated in a previous study (Reicherter et al. 2003), continue from land into the offshore seafloor. We chose 2 locations for further examination regarding tsunamites: the Cabo de Gracia fault in the axial zone of the Gibraltar Strait, near the ancient Roman city of Baelo Claudia, and the Carboneras fault ending at the natural reserve area of Cabo de Gata in the Gulf of Almería.

Baelo Claudia

The ancient Roman city of Baelo Claudia (36°05′22″N, 5°46′30″W) was destroyed abruptly in AD 40–60 and a second and final time in AD 350–395. Significant evidence was found pointing to natural hazards as the cause for the destruction, e.g. the fact that all columns of the forum fell to the same direction. Silva et al. (2005) found strong indications that the 2 recorded events can be reasonably related to recurrent earthquake occurrence in the Gibraltar Strait. Figure 1 shows a tectonic survey map of the bay of Baelo Claudia. At 10–15 m off the beach, some hundred meters in the western part of the ancient village, 4 m asl, we found sediments covered by layered (probably solifluction) material with developed soil. The striking characteristics of this soil are 2 distinct, straight, horizontal charcoal layers of about 2 cm depth with about 10–15 cm vertical distance from each other, pervading continuously the topsoil throughout more than 50 m of the coast line. The substrate (II) in

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between these layers differs from those above (I) and below (III) by a higher silt content. The well-distinguished annual rings of the coarse fragments are about 3–5 mm thick (see Figure 2). The actual vegetation nearby is pine.

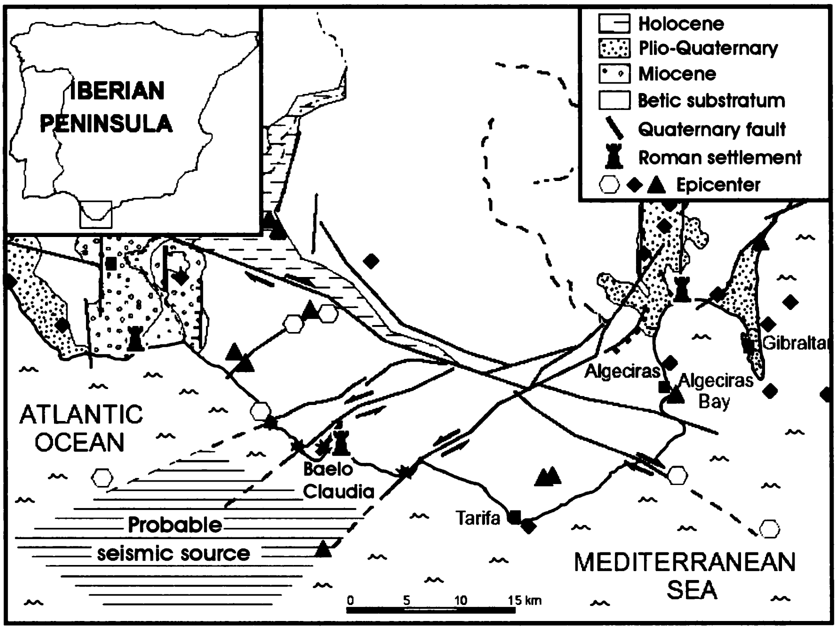

Figure 1 Tectonic survey map of the bay of Baelo Claudia with known seismic events (cf. Silva et al. 2005).

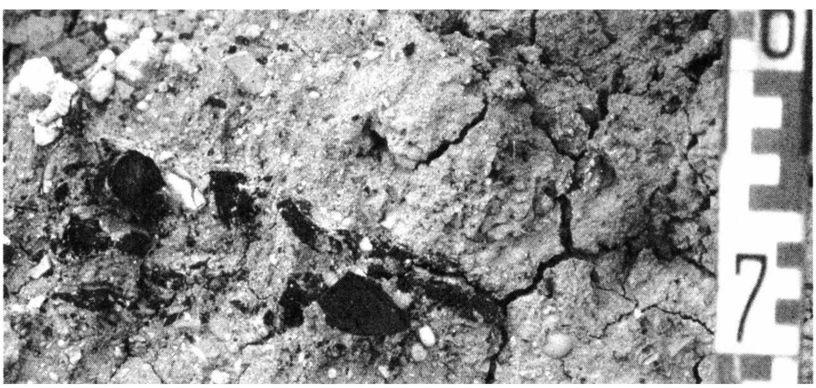

Figure 2 Lower coarse charcoal layer in a soil profile at Baelo Claudia beach

Cabo de Gata

Our second location is at Cabo de Gata at the Mediterranean Sea (36°45′44″N, 2°13′57″W) at the Gulf of Almería. The tectonic setting of the area is sketched in Figure 3. The Carboneras Fault Zone (CFZ) represents a major sinistral strike-slip fault in the Betic Cordilleras of southeastern Spain accompanied with pressure ridges and pull-apart basins. The onshore segment of the CFZ is striking approximately NE-SW and is anastomosing in E-W striking minor faults of about 50 km length.

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Soil profile description (Baelo Claudia)

Horizon	Depth (cm)	Description of characteristics
I A	0–10	10YR3/2 (moist), fine shrinkage cracks, worm tubes, many mussels and gastropods
I B1	10–35	10YR3/2 (moist), few mussels and gastropods
I B2	35–50	10YR3/2 (moist), gravel, single stones, few to no mussels and gastropods
	50	Absolutely plane thin layer of fine charcoal
II B3	50–65	10YR4/3, loamy sand
	65	Layer of coarse charcoal, 2 cm diameter, with identifiable branch structure
III B4	65–90	2.5YR4/4, clayey sand
III C1	90–135	7.5YR5/6, clayey sand, coarse gravel, micro-conglomerates, solitary sandstones, few land snails of 5 cm diameter, several pieces of terra cotta vessels
III C2	135+	10YR4/6, coarse sand, bone and shell fragments, larger pieces of pottery

Further details of the tectono-stratigraphic evolution are discussed by Sanz de Galdeano (1990) and Montenat and Ott D'Estevou (1996). Since the Tortonian, about 30 km of horizontal slip occurred along the individual faults, placing Neogene volcanics of the Sierra de Gata (Wilson and Bianchini 1999) against the metamorphic basement of the Betics. The northeastern termination branches into the sinistral NNE-SSW-trending Palomares Fault. The southwestern continuation of the CFZ prolongs offshore into the Gulf of Almería for at least 50 km (Reicherter and Hübscher 2007). More recent investigations were concerned with Quaternary tectonics and earthquake deformation; Bell et al. (1997) and Reicherter and Reiss (2001) found evidence for Quaternary deformation, but were not able to relate it to the 1522 Almería earthquake. Martín et al. (2003) studied the long-term uplift of the Cabo de Gata area from the Neogene to the Recent and found that most of the uplift took place well before the Pliocene. They claimed, as did Bell et al. (1997) before, that most of the activity of the CFZ during recent times results in vertical uplift, not in strike-slip movement. On the contrary, Reicherter and Reiss (2001) showed significant strike-slip-related deformation in Tyrrhenian terraces of the latest interglacial highstand (oxygen isotope stage 5e, approximately 123 kyr). Also, Silva et al. (2004) reported on deformed Pleistocene sediments along the Serrata pressure ridge. Vertical uplift of Tyrrhenian beach terraces after the Roman period in El Playazo (Cabo de Gata area) was thought to be related to co-seismic movements induced by the 1522 Almería or 1518 Vera earthquakes (Bell et al. 1997) but was never proven.

An aerial photograph (Figure 4) shows the Gulf of Almería framed by the Cabo de Gata consisting of Neogene volcanic and carbonate sediments to the east and by the Plio-Quaternary sediment complex of the Campo de Dalías to the west. Both developed coastal lowlands, the laguna of the Cabo de Gata, which is used as a saline since Phoenician times (Ruiz-Gálvez Priego 1993), and the Albuferas de Almería, a swampy area in the Campo de Dalías. These lagunas form a potential reservoir for marine ingressions, such as strong winter storms or tsunamis. However, the Cabo de Gata was never infiltrated by marine water during storms in the last 40 yr (personal communication, saline workers). The beach wall is up to 4 m high and very straight; no active washover fans or bypasses exist (Figure 5). The laguna has a deposit history of 6000 yr, commencing with a 2500-yr-old freshwater lake. After 3500 yr BP, a hypersaline environment typical for a laguna developed. The sedimentation rate is about 1 m per 1000 yr (1 mm/yr) and relatively stable; this means the sed-

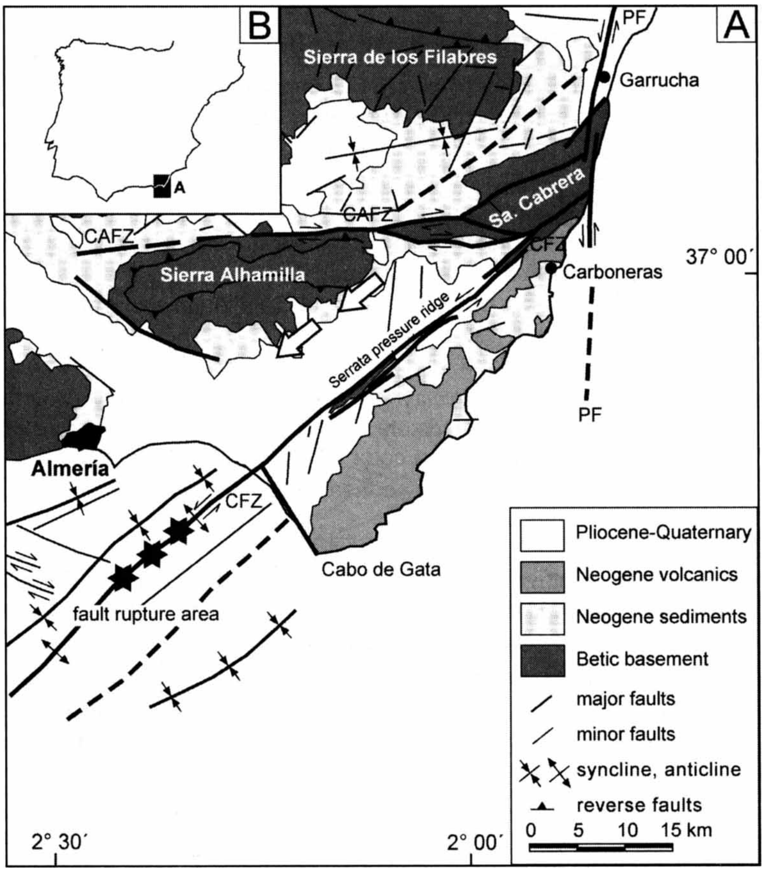

Figure 3 Tectonic survey map of the Carboneras Fault Zone (CFZ) between Carboneras and the Bay of Almería (after Reicherter and Hübscher [2007], simplified).

imentary filling is approximately 6 m thick. First, reddish conglomerates from the Cabo de Gata fan system were deposited, then organic-rich clayey and evaporitic layers follow upsection. In these well-bedded cyclic deposits of the laguna stage, several sandy and coarse-grained layers are intercalated; partly well-sorted sand layers are interpreted to be eolian dunes.

During the fieldwork in September 2004, we drilled in the lagunas and salinas of the Cabo de Gata at 5 localities (Figure 5). Several coarse-grained intervals with fining-up and thinning-up sequences contain rip-off clasts, shells of lamellibranchs, and foraminifera. The coarse-grained intervals have erosive bases and show up to 3 sequences divided from the next one by a small clayey layer. These intervals are interpreted as tsunamites and the sequence as "tsunami trail" deposits. We have also found multiple intercalations of those coarse-grained layers downhole, which are interpreted as either an expression of repeated earthquake activity or tsunami-like waves induced by submarine slides triggering seismic shaking in the Gulf of Almería. Several core segments have been ^{14}C dated; here, we present the results of core 3. After examination of these results, core 1 and 5 were dated too; the dates will be published elsewhere when analyses are completed.

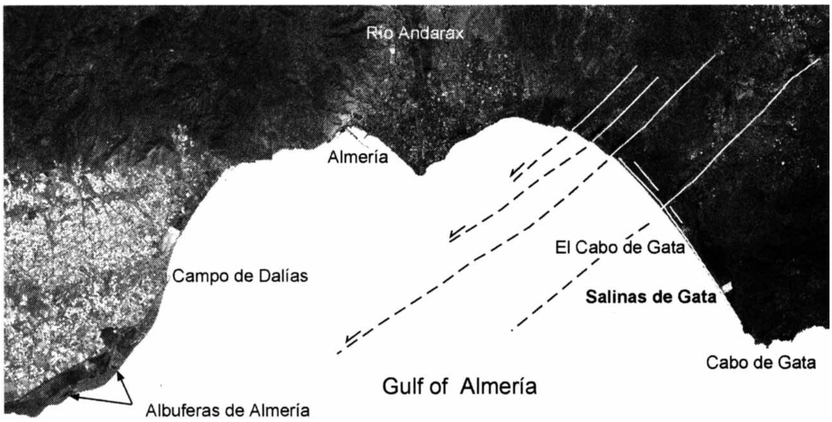

Figure 4 Aerial photo of the Gulf of Almería with marked minor faults near Cabo de Gata

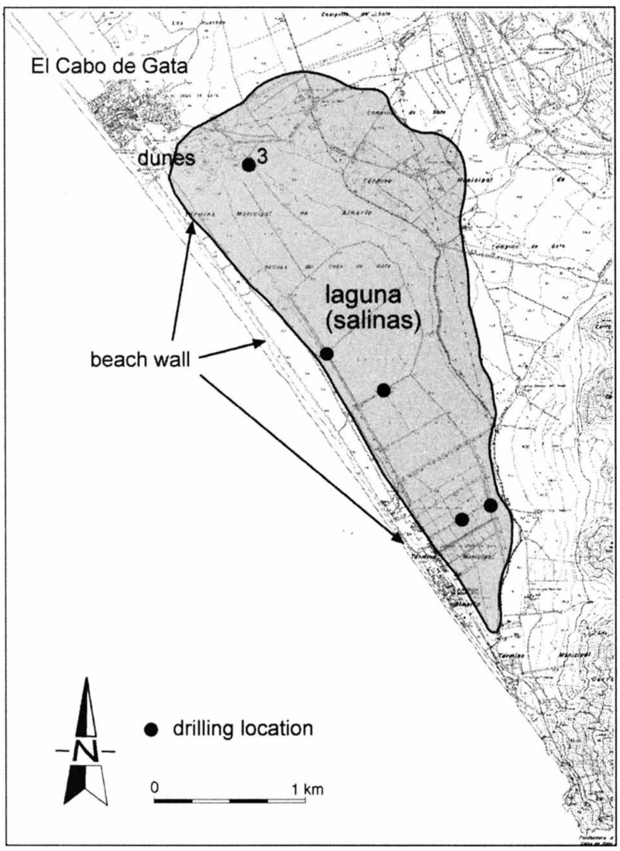

Figure 5 Topographic map of the Salinas de Cabo de Gata with drilling locations.

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METHODS

Sampling of the charcoal layers at the Baelo Claudia site was carried out in February 2001. The upper layer was finely distributed. The charcoal pieces of the lower layer appeared to be of only 1 species, so pieces from the layers were chosen randomly within 1.5 m width of the profile.

Drilling of 5 sediment cores with a slotted probe began at Cabo de Gata in September 2004. Core 3 was 5 m deep and contained a sediment layer that was classified as tsunamigenic. Subsamples from several stratified organic sediment layers from below this layer were taken for ^{14}C dating.

The charcoal samples (about 20 g each) were carefully cleaned and chemically pretreated by standard acid-alkali-acid succession. Benzene preparation from the sample carbon was conducted in 2 steps. First, the samples were combusted in an oxygen stream; the CO_2 was trapped in ammonium hydroxide; and, by reaction with $SrCl_2$, precipitated as $SrCO_3$. Then, the carbon was released from the $SrCO_3$ by hydrochloric acid in a vacuum line and converted to benzene using laboratory standard reaction conditions (Becker-Heidmann et al. 1995). Measurements of ^{14}C activity were carried out in our liquid scintillation (LS) spectrometer Packard 1050 TRLL.

The drilling core samples had a pH between 7.5 and 8.0 and thus were treated with HCl to destroy carbonates, washed with distilled water, and dried at 105 °C. The remaining total organic carbon was less than required for the LS method. Further preparation and ^{14}C measurement by accelerator mass spectrometry (AMS) was conducted at Poznań Radiocarbon laboratory.

RESULTS AND DISCUSSION

Baelo Claudia

The limited thickness of both charcoal layers in combination with their existence at the same depths above sea level, along more than 50 m of the coastline, contradicts an in situ fire as well as a fireplace. More probably, we can assume a nearby forest fire and transport of the resulting charcoal by water or hangsliding possibly connected with an earthquake and/or even a tsunami. According to the heartwood nature of the charcoal, the fire must have occurred only some decades after the obtained calibrated age of the charcoal, i.e. after AD 1450 (Table 1). As Baelo Claudia was definitely abandoned since before AD 711, the Arab conquest of the Iberian Peninsula, human activity as the reason for the charcoal distribution can be safely excluded. Also, the coast has been untouched by the archaeological excavations at the Roman village.

Table 1 ^{14}C ages Baelo Claudia.

Sample ID	Lab code	$\delta^{13}C$ (‰ PDB)	^{14}C age (BP)	Calibrated age
A	HAM-3747	–24.9	455 ± 35	cal AD 1425–1451
B	HAM-3748	–24.0	475 ± 35	cal AD 1421–1444

The ^{14}C dating results of the 2 clearly distinct charcoal layers surprisingly turn out to be identical within 1 statistical standard deviation, i.e. they are of the same origin. We strongly doubt that there were 2 fire events within 20 to 40 yr because of the 15 cm thickness of the soil layer between them, which corresponds to a normal sedimentation and soil development period of at least 150 yr documented for this region. It is not totally impossible, but very improbable, that the upper layer might originate in a successive fire of older trees that survived the first fire, because the observed wide tree rings imply a massive rejuvenation of the vegetation within 150 yr with a correspondingly considerably younger ^{14}C age. Therefore, a swap of soil material and charcoal from an elevated inland area, which is typical of an earthquake, with subsequent leveling by high tide waves seems more likely to us. To explain the high amount of swapped soil, the power of a tsunami would be necessary.

If this hypothesis holds true, the ^{14}C age of the charcoal would be the maximum age of this seismic event, which then happened later than the end of the 15th or beginning of the 16th century AD. The only known earthquake since this date causing a strong tsunami occurred in 1755 and destroyed Lissabon. Reasons why the 1755 tsunami was not the first and only tsunami that acted at this site were discussed by Silva et al. (2005); the high earthquake intensities (IX–X MSK) calculated from the observed level of destruction in Baelo Claudia could not sufficiently be explained by known far-away strong events as assumed before or by the more probable and recurrent moderate local seismicity on the offshore prolongation of the close NE–SW active strike-slip faults alone. Instead, a mechanism of amplification of the damage has to be identified. Besides ground shaking amplifying the ground site conditions, tsunamies induced by offshore quakes are possible, as the epicenters of the 2 events that led to the destruction of the Roman settlement are still unknown and could well lie below the nearby seafloor.

Cabo de Gata

The ^{14}C dates of all core segment samples we analyzed lie between the creation of the lagoon at about 6000 BP (Goy et al. 1996) and very recent years. Table 2 shows the results of the organic matter of the stratified clayey sediments directly below the tsunamites in core 3, dated by ^{14}C AMS as 680 ± 30 BP for the upper layer (0.49 m below surface) and 850 ± 35 BP for the lower layer (1.28 m below surface). The observed sedimentation rate of 1 mm/yr (Jalut et al. 2000) fits quite well to the results of drilling (however, we have to take compaction while drilling into account). During the tsunami event, deposition rates are significantly higher, which explains the 1.28-m drilling in the lower layers. The modern age of the third sample belonging to the "alluvial fan stage" with very coarsely granular, red, terrestrial conglomerations, and sands may be explained by hypersaline groundwater. The occurrence of layers containing modern carbon in greater depth of sediments and soils is not unusual and has been explained by rapid percolation and accumulation at abrupt texture steps (Becker-Heidmann and Scharpenseel 1986). Sivan et al. (2002) discuss downward flux of dissolved modern carbon in saline environment in detail. The other dated cores show the same depth sequence.

Table 2 ^{14}C ages Cabo de Gata.

Sample ID	Depth (cm)	Lab codes	^{14}C age (BP)	Equivalent cal age[a]
CDG3-1-1,48-49	48–49	HAM 3859/ Poz-13037	680 ± 30 BP	cal AD 1272–1314 cal AD 1357–1388
CDG3-2-3,27-28	127–128	HAM 3860/ Poz-12978	850 ± 35 BP	cal AD 1050–1083 cal AD 1125–1137 cal AD 1152–1262
CDG3-4-5,98-100	398–400	HAM 3861/ Poz-13097	106.18 ± 0.42 pMC	1955.50(Jul)–1957.32(Apr)

[a]See text below.

In the last column of Table 2, an equivalent calibrated age is given, which we would gain from an inert sample—like charcoal instead of the dated organic sediment carbon—with the obtained ^{14}C age, and representing the minimum age or earliest date of sedimentation. The tsunamites above the topmost dated sediment layer must have been deposited later than the 14th century, which may well correlate with the 1522 Almería earthquake. The 1522 Almería earthquake affected large areas in the western Mediterranean and caused about 2000 causalities. The earthquake of magnitude M 6.8 (Instituto Andaluz de Geofísica 2005) was followed by several aftershocks between 10 am and 10 pm. Major destruction was reported from Almería, where the castle, the cathedral, the convent, the Medina, and the harbor were completely destroyed (Martín de Salinas, in: Rodríguez Villa 1903). A contemporaneous woodcut from 1523, of an anonymous German artist first mentioned in Varela Hervías and von Waldheim (1948), displays drowning people, ships in distress, and inundations along the coastline (cf. Kozak 1996). The text in ancient German tells about earthquakes accompanied by flooding in the western Mediterranean. Reicherter and Hübscher (2007) interpreted the picture as follows: Almería and the harbor were destroyed by ground shaking, and tsunami wave action also took place. Therefore, arguments for an offshore epicenter for the 1522 Almería earthquake relatively close to the coast along the 50-km-long sinistral Carboneras Fault Zone (CFZ) are reasonable. Different epicentral areas have been suspected; however, no onshore surface ruptures and paleoseismological evidence for this event have been found. High-resolution sea-floor imaging yields evidence for an offshore rupture along a strand of the CFZ that is supported by evaluation of historic documents. Based on these data, they proposed the epicenter precisely at the observed sea floor rupture area at 36°42′N, 2°23′W in the Gulf of Almería.

CONCLUSION

Our first evidence of Holocene tsunamis found at 2 different locations at the coast of southern Spain suggests a non-negligible tsunami and hazard potential for offshore active and seismogenic faults in the western Mediterranean region. As the Costa de Sol is one of the touristic hot spots in Mediterranean Europe and is very densely populated, its vulnerability is of great concern. Therefore, further and more detailed investigations are reasonable.

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