

Tsunami deposits on the coastline of west Crete (Greece)

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Abstract

The eastern Mediterranean and the Aegean Sea in particular, are the most active seismic regions in Europe. Historically, numerous earthquakes have occurred in this part of the world and comprehensive tsunami recordings exist. Nevertheless, field evidence of tsunamis is rare, although many neotectonic movements certainly must have triggered very strong tsunami waves. Along the coastlines of western Crete, we found evidence for tsunami impacts, such as 1) bimodal deposits (large clasts floating in sands comprised of shell fragments); 2) dislocation of large boulders with tilting of biogenous notches; and 3) boulders (with *Lithophaga* or *Cliona* borings) weighing up to 75 tons thrown onshore and imbedded in strata of marine shells. This paper documents these deposits and discusses whether they originated from the sudden uplift that occurred in 365 AD. Moreover, numerical radiocarbon ages reveal the occurrence of two tsunamis dated to 5660 yrs BP and 500 yrs BP. Evidence for other tsunami impacts is discussed, but not supported by numerical dating due to the lack of suitable material.

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Keywords: Crete; neotectonics; tsunami; boulder dislocation; radiocarbon dating

1. Introduction

The last strong European tsunami, with a maximum run up of greater than 30 m, was the Amorgos event in 1956 in the Aegean Sea (Galanopoulos, 1957; Ambraseys, 1960; Stiros et al., 1994; Dominey-Howes, 1996a; Dominey-Howes, 1996b; Perissoratis and Papadopoulos, 1999; Dominey-Howes et al., 2000). This event was one in a long list of described tsunamis that occurred in the eastern Mediterranean over the past 4000 yrs (Ambraseys, 1962; Antonopoulos, 1979; Papadopoulos and Chalkis, 1984; Papazachos et al., 1986; Moreira,

1988; Soloviev, 1990; DiMaro and Maramai, 1992; Tinti and Maramai, 1996; Perissoratis and Papadopoulos, 1999; Soloviev et al., 2000; Scheffers and Kelletat, 2003). The historical sources provide much more information about these tsunamis than the coastal landscape, where either little evidence is preserved or little has been identified. For example, field evidence for tsunamis that followed the explosion of the Santorini volcano possibly in 1628 BC or from the early Byzantine tectonic paroxysm sensu Pirazzoli (1986) 365 AD that caused a sudden uplift of a vast area in the Aegean Sea (with a maximum at the southwestern cape of Crete of at least 9 m) has not been found (see also Dominey-Howes, 1996a). In contrast, field research in recent years has identified extraordinary tsunami relics in different parts of southern Europe and the Mediterranean, and several are not mentioned in any tsunami

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catalogue (Piatanesi and Tinti, 1998; Mastronuzzi and Sanso, 2000; Gianfreda et al., 2001; Kelletat and Schellmann, 2001, 2002; Scheffers, 2003; Kelletat and Scheffers, 2004; Mastronuzzi and Sanso, 2004; Scheffers and Kelletat, 2004; Whelan and Kelletat, 2005; Kelletat, 2006).

In this paper we concentrate on the western part of Crete, from which the most extreme neotectonic event in historical times has been reported, the co-seismic uplift of up to 9 m on during the 365 seismic sequence (Thommeret et al., 1981; Pirazzoli et al., 1996; Stiros, 2001; Stiros and Papageorgiou, 2001). First observations on elevated shorelines in the form of notches and algal rims derive. First observations on elevated shorelines in then form of notches and algal rims are published in the nineteenth century (Spratt, 1865; Raulin, 1869), and much more field work has been performed since (Hafemann, 1965; Dermitzakis, 1972; Kelletat, 1979; Thommeret et al., 1981; Jaques and

Bousquet, 1984; Pirazzoli, 1986; Kelletat, 1991, 1994, 1996; Stiros, 1996; Pirazzoli et al., 1996; Kelletat, 1998; Peterek et al., 2003; Stiros and Drakos, 2006). Most researchers now agree that after a series of smaller phases of subsidence interrupted by yo-yo effects, the last uplift in 365 AD reached at least 9 m in the southwesternmost part of Crete, diminishing to 0 m towards the east of Chania (see Fig. 1 for isobases of uplift). Due to a slight sea level rise in the eastern Mediterranean since antiquity, the uplift that can be measured at present day sea level was in fact greater (compare discussion in Pirazzoli, 1976, 2005). This means that the area affected by the uplift was more extended to the east than can be detected today. A sudden uplift of this extension, which would have pushed away a water mass of dozens of cubic kilometres, would certainly have instigated a strong tsunami. Many historical records from the fourth century AD describe destruction of coastal settlements,

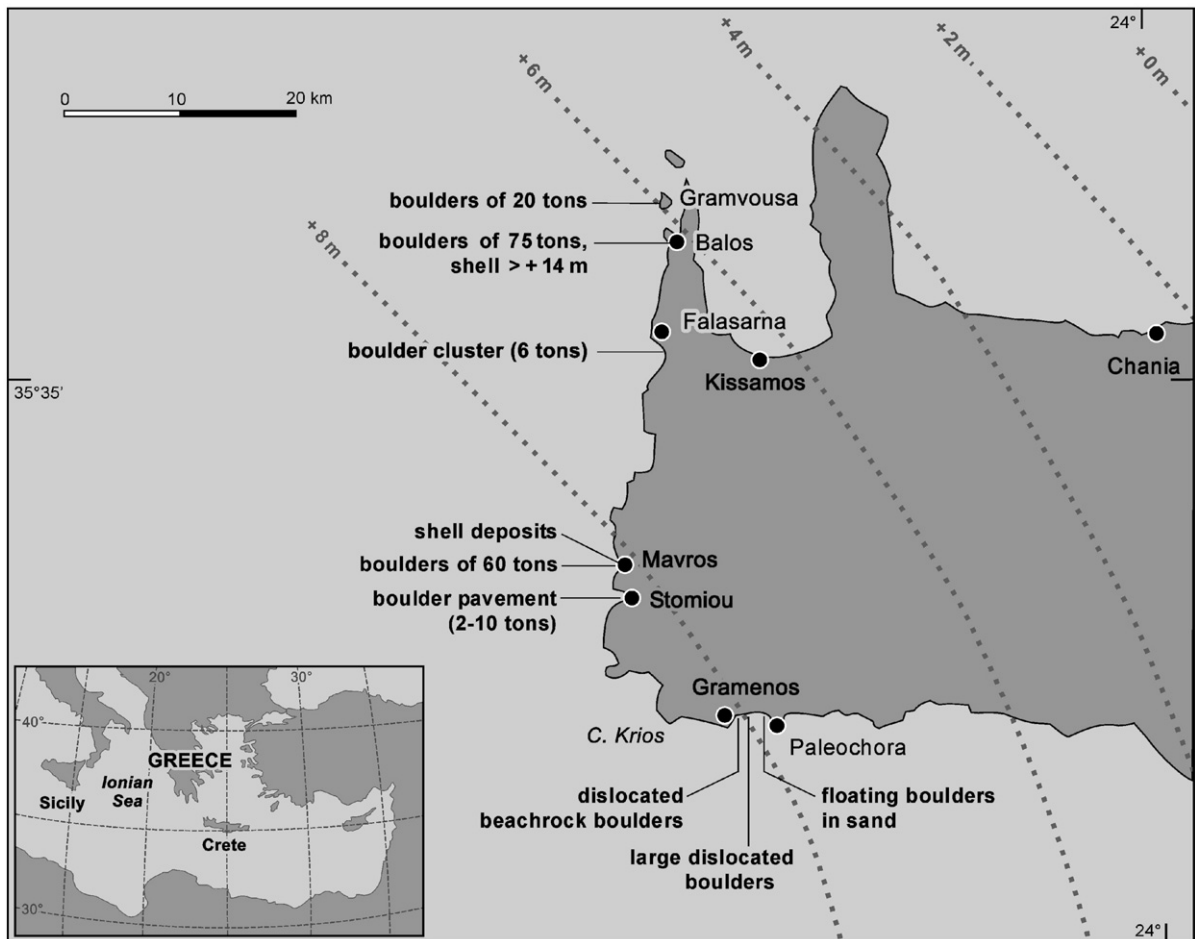


Fig. 1. Map showing the distribution of the tsunami evidence from the western part of Crete. Isobases for the uplift of this part of Crete that occurred in 365 AD are also included.

harbours, and ships by this event (Kelletat, 1998). However, except for some minor and debatable features from the ancient and uplifted area of Falasarna on the west coast of Crete (Hadjidaki, 1988; Frost, 1989; Pirazzoli et al., 1994; Dominey-Howes et al., 1998; Scheffers, 2006a,b), no significant field evidence from this tsunami has been published.

Our field work on the qualitative and quantitative geomorphological changes that have occurred since the uplift of 365 AD showed sedimentological and geomorphological proof of even younger tsunamis along the south coast of western Crete and the central and northern part of its west coast. The deposits moved by waves in the western Crete littoral environment are mostly much larger than those from well-dated historical tsunamis in western Greece (Vött et al., 2006) or the Lebanon coastline (Morhange et al., 2006). In the remainder of the paper, we describe this tsunami evidence in detail, and we discuss the issue of whether all of these sedimentological and geomorphological features derived from the Early Byzantine event (365 AD) or from a later tsunami affecting this part of the Mediterranean.

2. Methods

The amount of uplift that occurred in 365 AD already has been investigated in detail (e.g., Hafemann, 1965; Thommeret et al., 1981; Kelletat, 1994; Pirazzoli et al., 1996; Kelletat, 1998; Scheffers, 2006a,b). In this study, we focused our field work on the historical shoreline in the area of most extreme dislocation (~150 km of coastline in the south and west of Crete) in search of possible tsunami imprints related to this neotectonic event. In particular, we examined and thoroughly mapped sediments from the littoral or the foreshore that are now in an onshore position; sediment characteristics that disagree with normal wave or storm wave conditions in terms of emplacement, form, sorting, or size; and material for absolute dating.

As all Sea Pilots (e.g. DHI, 1971) of the area show, the spring tide range along the coastline of Western Crete is ~0.1 m and can be overridden by atmospheric pressure and wind surge. Although strong northern winds may occur in summer, the longer fetch south of Crete (>250 km) creates larger waves there that average ~1 m in winter (DHI, 1971). The longest fetch (>400 km), however, comes from the west, from which winter storms during a 7b cyclone form waves many meters high (>6 m) in the open ocean. However, these waves do not significantly affect the western coastline of Crete due to its wide and shallow foreshore.

To date, researchers do not agree on the most significant diagnostic criteria for tsunami versus storm deposits, although many teams have investigated the sediments affected by the most recent extreme events, such as the tsunami that hit Papua/New Guinea in 1998 or the Andaman–Sumatra tsunami of 2004 (e.g., Richmond et al., 2006; Scheffers and Kelletat, 2006; Wiegel, 2006). Currently, the debate about the characteristics of fine sediments deposited by tsunami- or storm waves continues. Herein, we consider the most important signature of a tsunami to be the dislocation of large boulders far away from the shoreline and far inland that bear undisputable signs of their littoral or foreshore origin in the form of *Lithophaga* borings, vermetid or calcareous algae cover, or *Cliona* borings, mostly accompanied by shell layers. As storm waves cannot cross a shallow foreshore without breaking and losing energy, the dislocation of large boulders (≥ 20 tons) into the terrestrial environment can be explained by a tsunami. Boulders may derive from a higher terrain, but the presence of littoral or marine organisms rules out this possibility. The biological criteria used to determine past sea levels, such as bioerosive notches and vermetid or algal benches and rims, are comprehensively discussed in Kelletat and Zimmermann (1991) and Kelletat (1997).

A new mapping of the emerged coastlines of Western Crete (Scheffers, 2006a,b) shows that before 365 AD, nearly all shorelines were rocky steep cliffs with bioerosive notches and bioconstruction of calcareous algae and vermetids. The present day distribution of coastal lowlands up to 500 m wide and all of the beaches (including the beachrocks) are part of the former foreshore; they did not exist 365 AD. These geomorphologic and sedimentologic facts provide an important temporal guideline for the interpretation of the coastal geomorphology of western Crete.

3. Results and discussion

3.1. Tsunami field evidence west of Paleochora, south coast of western Crete

The ~5 km long region from the large peninsula of Paleochora to the smaller Gramenos peninsula (also known as Akrotiri Trahili, near the small village of Koundoura) in the west has been mapped in detail. Here the coastal uplift from 365 AD is perfectly preserved as a horizontal bioerosive notch along steep limestone rocks and can be detected at a height of 7–8 m above sea level (asl) in the westward direction. The neotectonic uplift exposed an older rock platform of hard limestone

at 4–5 m asl (Peterek et al., 2003; Scheffers, 2006a,b), which in several places is decorated by well preserved Younger Holocene calcareous algal reefs (Kelletat and Zimmermann, 1991) that have been radiocarbon dated to 3430 ± 60 yrs BP, 3180 ± 70 yrs BP, and 3110 ± 50 yrs BP and by extended sand, pebble, and cobble beaches that have been partly transformed into beachrock. Some small dunes occur and slope debris and soil partly cover the former foreshore forms and sediments. The emerged part of the former foreshore is up to 500 m wide close to Paleochora, but the central part of this study site shows segments of plunging cliffs, where huge boulders are slowly descending the steep slopes by gliding processes over the course of thousands of years. This process is evident in the tilting of the historic coastal notch or breaking of coastal rock covered by young and living calcareous algae. Higher than the remnants of Holocene shorelines (i.e. from about 8 m asl upslope), three different geomorphological units are present: chaotic gliding of huge tilted and broken blocks (weighing tens of thousands of tons) of limestone rock on schists; Pleistocene slope debris in the form of breccia fans; or well-preserved Pleistocene marine terraces on bedrock, accompanied in places by abrasion tunnels, caves, or former sea arches and wide abrasion notches (Peterek et al., 2003). In this environment, several structures hinting on Younger Holocene tsunami impacts exist:

- The wide coastal plain west of Paleochora situated at 3–5 m asl is composed of unsorted coarse sands mixed with shell fragments, in which floating quartzite boulders of sizes up to 1 ton are present. This mixture, as well as the many broken shells and the lack of any stratification in the sands, together with the bimodal character of the sediment are evidence of a tsunami younger than 1600 yrs BP, i.e. after the neotectonic uplift.
- Throughout the whole area, well-rounded pebbles distributed among boulders of different size and rocky outcrops can be found. It is possible that these pebbles were washed down from higher marine terraces and that they were not transported from the sea during the last centuries. However, halfway between Paleochora and Koundoura, a small section with blown sand and a dune-like attachment to the higher slope, now mostly covered by old juniper bushes, exhibits the same bimodal character; yet floating boulders are much less common here. Several pebbles, although hard quartzite, seem to be freshly broken and have sharp contours. The deposit reaches at least 100 m inland and up to 7 m asl. At one place, fragments

of a young beachrock are incorporated into the sand and have been exhumed by the destruction of vegetation due to overgrazing. The beachrock is certainly younger than the neotectonic coastal uplift from 365 AD, as prior to the uplift no beach existed in this area (Scheffers, 2006a,b). The location of these fragments is far removed from the modern storm beach and separated from the sea by a belt of old vegetation and soil, so the fragments could not have been transported to their present position by storm waves.

- On the northeast corner of the Gramenos peninsula, up to 1 m asl and 20 m inland, a wide beachrock exists, which is covered by 2 m of water. Because this beach was formed as a tombolo after the 365 AD uplift, the beachrock there must be younger than this event. Nevertheless, it has been destroyed in two phases: 1) the oldest phase was the destruction and dislocation of boulders weighing up to 2 tons, which were later again cemented to the beachrock basement and 2) the younger phase, which left beachrock boulders weighing up to more than 10 tons under water and several smaller ones imbricated onshore. The sublittoral topography in this extremely protected environment, where only refracted swell reaches the beach, is chaotic, consisting of dislocated boulders of an older molasse and a younger beachrock. A younger tsunami impact is the only acceptable explanation for this setting of boulders.

3.2. Observations along the west coast of Crete

3.2.1. Boulders and shell deposits of Ormos Stomiou and Mavros Bay

The most accentuated embayment along the west coast of Crete, Ormos Stomiou, is situated in the southern section and is approximately 2 km wide and 2 km inland. It is decorated by a pebble beach with rocky outcrops and a >100 m wide plain just below 8 m asl, which is the approximate height of the uplifted historical notch in this region. This plain is characterized by large very well-rounded boulders of quartzite and very hard sandstone that are scattered in loose clusters or lie close together as a boulder carpet. The embayment is the coastal part of a broad valley and is filled with quartzite boulders up to 30 m asl. Most of these are derived from older and higher deposits, but the boulders on the lower level have been rearranged in new patterns by waves. Many of these boulders weigh >2 tons, with a maximum around 6 tons; even the smallest of them



Fig. 2. A boulder of at least 40 tons, decorated by calcareous algae, about 60 m apart from the shoreline at Mavros Bay.

weigh >100 kg. Only a few of these boulders are broken along hidden joints in the rock, but many show impact marks clearly originating from collision during the movement process. Although quartzite boulders are rather common features near the coastline of southwestern Crete, those from Ormos Stomiou are by far the largest, with axes up to 1.5 m. Their final movement and rearrangement can only be explained by extreme wave energy, which could not have been generated by storms because of the very shallow foreshore here. We have no way of determining the exact age of their last movement because organisms for dating do not exist. However, we can not exclude a tsunami originated by the uplift of 365 AD.

Towards the north, Akrotiri Mavros (Mavros Cape) separates Ormos Stomiou from the next bay. This

northern embayment has a sandy beach about 1 km long and has been transformed into a beachrock with a width up to 80 m over its entire length. This beachrock shows a total vertical cementation of >2 m and lies partly below and partly above modern sea level. Today it is in a phase of destruction due to abrasion and plucking or mechanical breakage along fine joints. This beachrock, which is not currently cementing, evidently was formed by beach cementation after its emergence about 1650 yrs ago, when the sea level was lower than it is today, documented by submerged ruins from antique times along most of the Crete shoreline. (Kelleat, 1979, 1994, 2006). About 60 m from the shoreline in the northern part of this bay, two large boulders (~15 and 40 tons; Fig. 2) are cemented in this beachrock. They were moved during or after the neotectonic emergence, as



Fig. 3. Boulders of eolianite weighing more than 50 tons, showing a tilting of the young bioerosive notch by boulder movement.

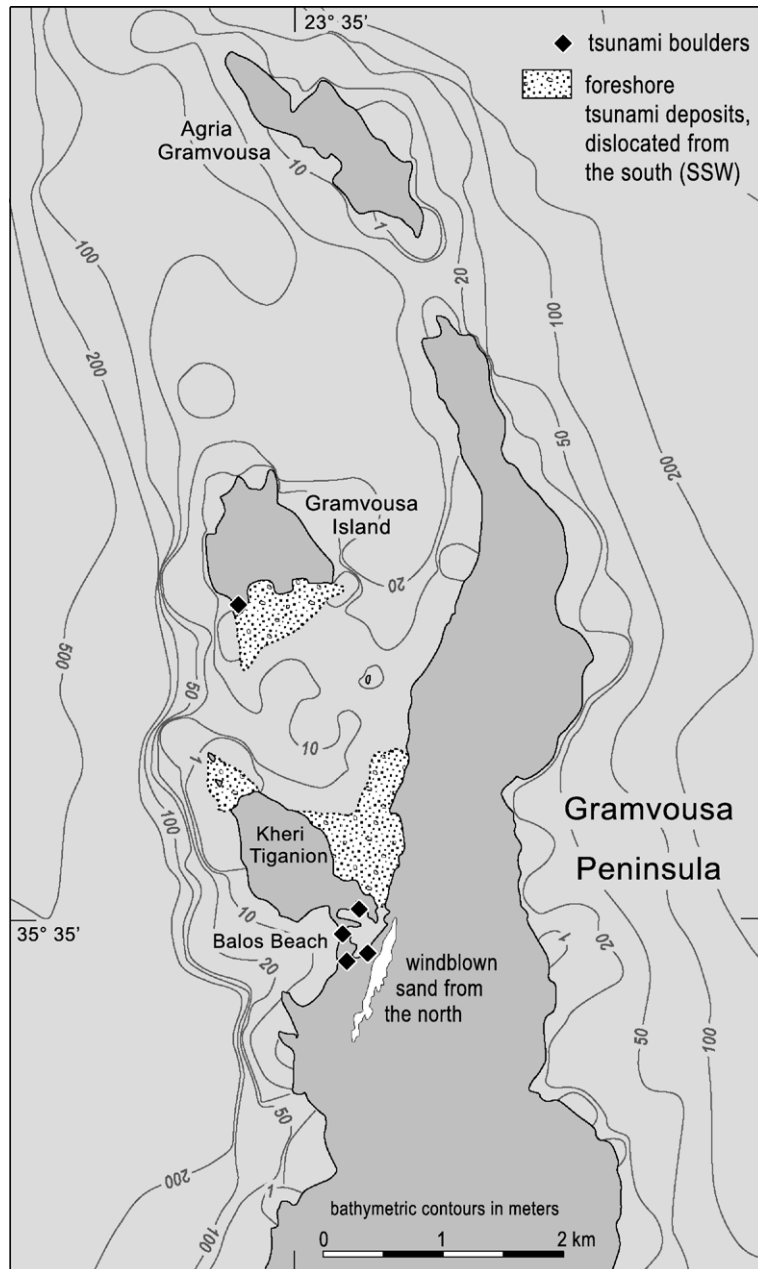


Fig. 4. Map of the northernmost part of the Gramvousa peninsula and the surrounding islands to the west.

indicated by attached tilted rims of calcareous algae. The tremendous weight of the boulders proves that they could only have been moved by extremely energetic waves, but the foreshore is covered only by shallow water several hundred meters seaward precluding large storm waves. In the central part of this bay, very large (up to 6 tons) quartzite boulders are present. In between these boulders and the broad beach are low and partly vegetated dunes that are of young age and covered by one to three different soil structures with a thickness of

10–30 cm. Below the dune sand and these soils and exposed in the dune cliffs at about +4 m asl sits a stratum of molluscs (95% is *Glycimeris glycimeris*) dated to 5660 ± 60 yrs BP (conventional radiocarbon age; Beta-209491). Most of these shells lie with the open side downwards and show signs of abrasion. Fine material is cemented to these only at the inner parts, which suggests that this side was covered with living tissue during deposition. The deposit shows characteristics of a single and sudden event during which huge

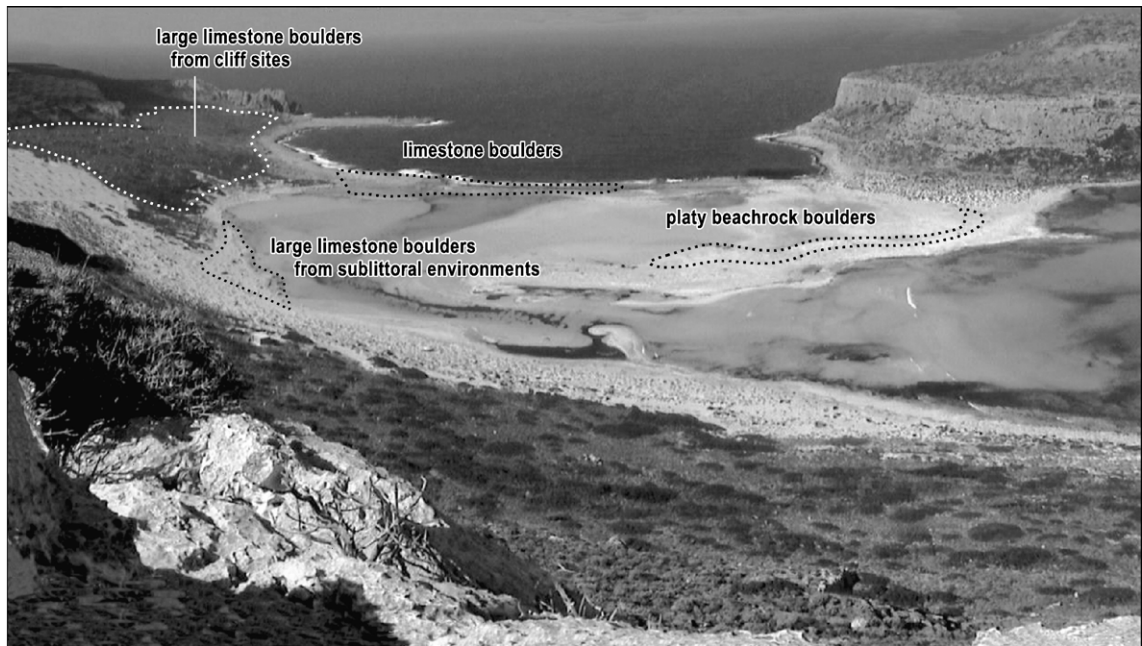


Fig. 5. Balos with its large lagoon, seen from the Gramvousa peninsula looking to the southwest. Areas with tsunami deposits are visualized.

numbers of living molluscs from the shallow foreshore were exhumed. The sandy inland platform is covered by smaller rock fragments that are not rounded.

3.2.2. Tsunami evidence from Falasarna Bay

In the northern part of the west coast of Crete, the ancient harbour of Falasarna dried up as a result of the 365 AD uplift. Excavations (Hadjidaki, 1988; Frost,

1989; Pirazzoli et al., 1994; Dominey-Howes et al., 1998) have identified walls partly destroyed or pushed aside by an earthquake as well as a layer of shells and foraminifera of deeper water origin in the harbour sediments. These were the only tentative historical tsunami hints of Crete up to our field survey.

Falasarna Bay (or Ormos Livadi, see Fig. 1), from the Nisakia islands in the south to Cape Koutri in the north, is



Fig. 6. The largest boulder in the southeast of Balos at about +14 m asl weighs 75 tons.



Fig. 7. Many marine mollusks and gastropods typical of Mediterranean rocky shore environments can be found around the largest boulders at +14 m and higher on the slopes.

about 3 km wide and is protected by Petalida Island and shallow rocky reefs for most of its length. Therefore, it is protected from strong waves or swells, although it is exposed to a long fetch (>400 km) from the west. The ancient uplifted notch (Scheffers, 2006a,b), here at heights between 6.8 and 7.2 m, is well preserved along an old perpendicular cliff cut in limestone, conglomerates, Neogene marine sandstone and marl, or eolianite. Seawards, the emerged foreshore plain reaches up to 500 m in width in the south but only a few meters in the north. Its shoreline shows schists, Neogene rocks, limestone, or eolianite in many outcrops, together with

a number of beachrocks as conglomerates or sandstones and pebbly beaches in the south as well as sandy beaches in the north. The last 800 m south of Cape Koutri are rocky (eolianite and limestone).

About 1 km north of the Nisakia islands at the innermost part of Livadi Bay sits a sandy beach decorated with beachrock. About 20 to 70 m from the beach in a sandy environment with some initial dunes, approximately 100 boulders are distributed in several clusters. These boulders are parts of the beachrock, which indicates that they are young enough not to have undergone cementation (a process that itself is younger

Table 1

Summary of sedimentological and geomorphological evidence, likelihood of tsunamigenic origin and age assessment of the event

Locality	Sedimentological and geomorphological evidence	Min. run up (based on setting of deposits) (m)	Likelihood of tsunami	Age assessment
Ormos Stomiou	Shell bed	>3	High	5660±60 yrs BP (Beta-209491)
Ormos Stomiou	Boulder (40 t)	>6	High	?
5 km S Ormos Stomiou	Boulder pavement	>5	High	?
Falasarua S	Tilted notches at boulder >50 t	>8	Moderate to high	365 AD or later
Balos	Dislocated boulders (10–40 t) with borings	>6	High	365 AD or later
Balos	Dislocated boulders (67 t, 75 t) at 15–25 m asl	>25	High	365 AD or later
W Paleochora	Dislocated boulders (>20–200 t)	>8	High	Post 365 AD
Gramenos Peninsula	Dislocated beachrock slabs	>3	Moderate	Post 365 AD
Balos	Shell bed at 15–25 m asl	>25	High	500±60 yrs BP (Beta-210649)

than the uplift of 365 AD), but some of them are encrusted by calcareous algae, which suggests a formerly foreshore position in the subtidal environment. The boulders weigh between 1 and 10 tons and are rounded due to sand drift after deposition and show well-developed tafoni up to 1 m deep and wide. The distribution along this stretch of coast of boulders with a similar weight, form, and degree of rounding suggests dislocation by a single event. Vegetation in the area and the degree of tafoning are indicators of the age of their last movement which may well be more than 1000 yrs. Based on the size of the boulders and the much protected setting in which they sit, movement could well have been caused by a tsunami.

In the central part of Livadi Bay, rocky promontories from a higher marine terrace come close to the shoreline and at some places have placed huge boulders into the surf. The material is partly molasse conglomerate and partly of eolianite origin. The first exhibits tafoning of several meters, and the latter has preserved bioerosive notches from the time of the 365 AD uplift. These notches occur in a lower position than along the fossil rocky cliff, and more significantly, they show a slight tilting in different directions (Fig. 3). These boulders certainly have been moved, some of them via undermining by surf, but several sit on strong boulders or rock, which excludes such effects of the surf. Because their weight reaches up to 50 tons at 5 m asl and they sit 60–70 m apart from the modern shoreline, only tsunami waves could have been responsible for their movement.

3.2.3. *Tsunami evidence from Gramvousa Island*

Gramvousa island is protected from the north by the island Agria Gramvousa, from the east by the Gramvousa peninsula, and from the south by the former island Kheri Tiganiou (now connected to the mainland of Crete by tomboli (Fig. 4). Thus, large waves can reach the southern shorelines of Gramvousa island only from the west to built the southernmost spit, which is the only area with low relief, small beaches, and a low lying rocky platform. This rocky southern platform of Gramvousa island emerged via the sudden uplift of 365 AD, and the ancient coastline (at 6 m asl) can clearly be seen along the now inactive cliff surrounding the higher parts of Gramvousa. The foreshore area in this region consists of sea-grass covered sand and patchy rock outcrops. Therefore, we expected the elevated rocky platform, several 100 m long and wide, to be similarly covered. Because the platform can not be reached by storm waves and wind can not remove all finer particles from the many rock pools, the platform's present-day sediment-free appearance may well be the

result of tsunami waves following the sudden uplift that occurred more than 1600 yrs ago. After the former sea floor was exposed, rock pools formed by bioerosion and karst features developed due to rain on the limestone. More than 50 boulders weighing up to 10 tons at 8 m asl and boulders of 20 tons at 4 m asl are scattered on the platform at 10 to ~100 m away from today's rocky shoreline. They are balanced on edges of rock pools and settled on karstic relief, which means that they were deposited long after the exposure of this platform. *Lithophaga* borings and other marine features on some of the boulders leave no doubt about their rocky intertidal or subtidal origin. Storm waves most likely could not have transported boulders of this size several meters against gravity, and therefore we conclude that they were moved by at least one tsunami that occurred later than 1600 yrs BP (to give enough time for the rock pools and karst forms to develop).

3.2.4. *Tsunami evidence from the Balos region*

Balos is the name for the area between the west coast of the Gramvousa peninsula and the former island of Kheri Tiganiou. Kheri Tiganiou is now connected to Gramvousa peninsula by a low lying coastal landscape built by Young Pleistocene cemented coastal deposits, beachrock, sandy beaches, and very shallow lagoons with silt deposits. In the southwest a small gap exists in a rocky barrier, whereas in the northeast a wider channel opens to the sea, varying in depth (0.5–1.2 m) and width (20 to 60 m) depending on surf conditions and time of the year. Only the southwest portion is open to strong wave impact, but modern storm events do not deposit clasts at this location. Fig. 5 provides a view of Balos from the Gramvousa peninsula (viewpoint about 120 m asl) in a SW direction.

The sea level in ancient times (until the 365 AD uplift) in this area was ca. 6 m higher than today, and all that remains from that time is a formerly sublittoral or foreshore environment. The western barrier was a tombolo in the last interglacial period. The material of the tombolo is shelly sandstone with limestone fragments very strongly cemented together. Karstification of the southern end of this former tombolo is extreme. The sandy beaches contain several beachrock outcrops that are partly buried in the sand. The protected beaches at the lagoonal side of the northern spit and the lagoon bottom itself are in most places silty. We conclude that after the uplift, a southwestern ridge and a northern spit from the west existed, with shallow water in between, and that along the east coast of the lagoon beaches may have developed.

After the sudden neotectonic uplift (i.e., during the last 1650 yrs), beach development, bioerosion, karstification,

and beachrock formation occurred in the Balos area along both sides of the old northern spit. The cementation that occurred can now be seen at up to 1.5 m asl and below sea level. This cementation clearly occurred after the uplift and began during a phase of slightly lower sea level than today (compare Kelletat, 2006). Currently the beachrock is being destroyed by bioerosion, abrasion with sands, and mechanical destruction by waves. The distribution of platy beachrock fragments up to 6 m² in area and weighing more than 6 tons along a shallow water coastline with transport distances (from the now protected northern side of the area) exceeding 100 m cannot be explained by normal storm waves. A tsunami is a highly likely candidate for this kind of destruction and transport. We conclude that such an event occurred after the 365 AD uplift because the beachrock had to be built with a vertical cementation up to 3 m, and only after this process took place was the beachrock broken. After deposition of the giant slabs of beachrock (length of axis >4 m), they were partly transformed by abrasion of wind-shifting sands or salt weathering, which suggests the effects of a tsunami event that occurred several hundred years ago.

Along the west-facing beach in the protected inner part of the lagoon, many large boulders have accumulated along the shoreline, situated in the water or up to approximately 4–5 m asl. These boulders weigh from 3 to >20 tons and, in one case, 40 tons. They originated from the southern tombolo and were moved horizontally 200–400 m inland. All of them contain *Lithophaga* and/or *Cliona* borings, which prove their sublittoral origin. Because of their weight and transport distance in a much protected environment, there is no doubt that these boulders were transported by a strong tsunami coming from southerly to southwesterly directions.

A widely scattered cluster of boulders sits on the lower slopes near the southern tombolo along the Gramvousa side (Fig. 5). These boulder fields cover the area between 8 m asl and the sand-blown white strip at 25 m asl or slightly higher. In contrast to the tsunami deposits in the Balos region, these boulders are surrounded by a dense thicket of thorny bushes and soil, which hints at an older age. The largest two boulders weigh 67 and 75 tons, respectively (Fig. 6); the latter sits at 14 m asl and about 150 m from the sea in an area with a dense cover of molluscs (limpets, littorinids, and other species typical of a rocky shore environment, Fig. 7), which have been dated to 500±60 BP (with a 13C/12C ratio of -0.2‰, contamination by soil development cannot be excluded; Beta-210649). Only some of the boulders have boring marks, but there is no

doubt that they originated from a shoreline to the south to southwest, likely broken from cliffs south of Balos. The transport distance ranges from 60 m to more than 300 m. Multiplying the weight of the boulders, their transport distance, and their height above their original placement leads to transport figures of up to 170,000 (a transport figure of 2000 or lower is the threshold for the strongest storms possible on earth; see Scheffers, 2003). Therefore, there is no doubt as to the tsunamigenic origin of these boulder clusters. If the dating of 500±60 yrs BP is contaminated and too young, they may well be the result of a tsunami wave that resulted from the sudden uplift of 365 AD, from which the centre should be in the southwesterly direction in the area of highest uplift of more than 9 m.

North of the Balos beaches and lagoon for at least 1 km, the bay is shallow with a lot of sand, rubble, and boulders on the sea floor, whereas immediately south and west of the southern spit the water is deep and lacks sediment. This finding gives the impression that huge waves transported nearly all sediments from south to north through the waterway between Kheri Tiganiou and Gramvousa peninsula. Kheri Tiganiou has a kind of “tail” of shallow water with deposits from its northernmost point to NNW as well, which can be interpreted as a deposit in the tsunami wave shadow of this former island.

4. Conclusions

Based on all of our field evidence, we conclude that southwestern Crete shows undisputable proof of tsunami impacts from the Late Holocene and historical times (see Fig. 1, see Table 1):

- from chaotic shelly sands with floating boulders to dislocated huge plates of conglomerates weighing up to more than 200 tons;
- shell beds from a single event now buried under soil and dunes;
- tilted notches in boulders of more than 100 tons;
- boulder ridges (60 m long, 1 m high at Balos);
- dislocated beachrock slabs of up to 15 tons;
- deposits of sands and shells at 14 m asl and higher;
- and boulders of more than 50 tons dislocated for several 100 m and up to more than 25 m asl.

The age of the events responsible at a given locale may be several thousand years ago (absolute date of 5660 yrs BP), but mostly they are younger than the neotectonic uplift that occurred in 365 AD. In particular, the latter is true for dislocated beachrock boulders from

beaches that did not exist (but were mere foreshore flats) before 365 AD. A question that remains is which of the evidence for extreme wave energy presented herein is the result of the tsunami generated by the AD 365 seismic activity, because so far no absolute data have been found in or at coastal deposits from the 4th century AD.

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References

- Ambraseys, N.N., 1960. The seismic sea wave of July 9, 1956, in the Greek Archipelago. *J. Geophys. Res.* 65, 1257–1265.
- Ambraseys, N.N., 1962. Data for the investigation of the seismic sea-waves in the Eastern Mediterranean. *Bull. Seismol. Soc. Am.* 52, 895–913.
- Antonopoulos, J., 1979. Catalogue of tsunamis in the eastern Mediterranean from antiquity to present times. *Ann. Geophys.* 39, 113–130.
- Dermitzakis, D.M., 1972. Pleistocene deposits and old strandlines in the Peninsula of Gramboussa, in relation to the recent tectonic movements of Crete Island. *Ann. Géol. Pays Hell.* 24, 205–240.
- Deutsches Hydrographisches Institut DHI, 1971. *Mittelmeer-Handbuch*. 4. Teil: Griechenland und Kreta. 5. Auflage.
- DiMaro, R., Maramai, A., 1992. Tsunami in the Mediterranean and Pacific Areas: an analysis. *Sci. Tsunami Hazards* 10, 35–49.
- Dominey-Howes, D.T.M., 1996a. Sedimentary deposits associated with the July 9th 1956 Aegean Sea tsunami. *Phys. Chem. Earth* 21, 51–55.
- Dominey-Howes, D.T.M., 1996b. The Geomorphology and Sedimentology of Five Tsunamis in the Aegean Sea Region, Greece. Unpublished thesis, University of Coventry, UK. 272 pp.
- Dominey-Howes, T.M., Dawson, A., Smith, D., 1998. Late Holocene coastal tectonics at Falasarna, western Crete: a sedimentary study. *Geol. Soc. London, Spec. Publ.* 146, 343–352.
- Dominey-Howes, D.T.M., Cundy, A., Croudace, I., 2000. High energy marine flood deposits on Astypalaea Island, Greece: possible evidence for the AD 1956 southern Aegean tsunami. *Mar. Geol.* 163, 303–315.
- Frost, F.J., 1989. The last days of Phalasarna. *Anc. Hist.* 3, 15–18.
- Galanopoulos, A.G., 1957. The seismic sea wave of July 9, 1956. *Prak. Akad. Athenon* 32, 90–101.
- Gianfreda, F., Mastronuzzi, G., Sanso, P., 2001. Impact of historical tsunamis on a sandy coastal barrier: an example from the northern Gargano coast, southern Italy. *Nat. Hazards Earth Syst. Sci.* 1, 213–219.
- Hadjidaki, E., 1988. Preliminary report of excavations at the harbour of Phalasarna in west Crete. *Am. J. Archaeol.* 92, 466–468.
- Hafemann, D., 1965. Die Niveauperänderungen an den Küsten Kretas seit dem Altertum nebst einigen Bemerkungen zu älteren Strandbildungen auf Westkreta. *Akademie der Wissenschaften Mainz, Abhandlungen der Mathematisch-Naturwissenschaftlichen Klasse*, vol. 12, pp. 609–688.
- Jaques, F., Bousquet, B., 1984. Le raz de marée du 21 juillet 365. *Mélanges Ec. Fr. Rome* 96, 423–461.
- Kelletat, D., 1979. Geomorphologische Studien an den Küsten Kretas — Beiträge zur regionalen Küstenmorphologie des Mittelmeerraumes. *Abh. Akad. Wiss. Gött., Math.-Phys. Kl., Dritte Folge* 32 (105 pp.).
- Kelletat, D., 1991. The 1550 BP tectonic event in the Eastern Mediterranean as a basis for assuring the intensity of shore processes. *Z. Geomorphol., NF Suppl.-Bd.* 81, 181–194.
- Kelletat, D., 1994. Holocene neotectonics and coastal features in Western Crete, Greece. *Field Guide. Field Methods and Models to Quantify Rapid Coastal Changes. Crete Field Symposium*, April 9–15, 1994, International Geographical Union, Commission on Coastal Systems, Program, Abstracts and Field Guide. Essen, pp. 40–78.
- Kelletat, D., 1996. Perspectives in coastal geomorphology of Western Crete, Greece. *Z. Geomorphol., NF Suppl.-Bd.* 102, 1–19.
- Kelletat, D., 1997. Mediterranean coastal biogeomorphology: processes, forms, and sea-level indicators. In: Briand, F., Maldonado, A. (Eds.), *Transformations and Evolution of the Mediterranean coastline*, CIESM Science Series No. 3. *Bulletin de l'Institut Océanographique*, Monaco, numéro special, vol. 18, pp. 209–226.
- Kelletat, D., 1998. Geologische Belege katastrophaler Erdkrustenbewegungen 365 AD im Raum von Kreta. *Geogr. Hist.* 10, 156–161.
- Kelletat, D., 2006. Beachrock as sea-level indicator — remarks from a geomorphological point of view. *J. Coast. Res.* 22, 1558–1564.
- Kelletat, D., Scheffers, A., 2004. Tsunami in Atlantischen Ozean? *Geogr. Rundsch.* 56, 4–12.
- Kelletat, D., Schellmann, G., 2001. Sedimentologische und geomorphologische Belege starker Tsunami-Ereignisse jung-historischer Zeitstellung im Westen und Südosten Zyperns. *Essen. Geogr. Arb.* 32, 1–74.
- Kelletat, D., Schellmann, G., 2002. Tsunamis on Cyprus — field evidences and ¹⁴C dating results. *Z. Geomorphol., NF* 46, 19–34.
- Kelletat, D., Zimmermann, L., 1991. Verbreitung und Formtypen rezenter und subrezenter organischer Gesteinsbildungen an den Küsten Kretas. *Essen. Geogr. Arb.* 23 (168 pp.).
- Mastronuzzi, G., Sanso, P., 2000. Boulder transport by catastrophic waves along the Ionian coast of Apulia, southern Italy. *Mar. Geol.* 170, 93–103.
- Mastronuzzi, G., Sanso, P., 2004. Large boulder accumulations by extreme waves along the Adriatic coast of southern Apulia (Italy). *Quat. Int.* 120, 173–184.
- Moreira, V.S., 1988. Historical and recent tsunamis in the European Area. *Sci. Tsunami Hazards* 6, 37–42.
- Morhange, C., Marriner, N., Pirazzoli, P.A., 2006. Evidence of Late-Holocene tsunami events from Lebanon. *Z. Geomorphol., NF Suppl.-Bd.* 146, 81–95.
- Papadopoulos, G.A., Chalkis, B.J., 1984. Tsunami observed in Greece and the surrounding area from antiquity up to present times. *Mar. Geol.* 56, 309–317.
- Papazachos, B.C., Kontitas, C., Hatzidimitriou, P.M., Karacostas, B.G., Papaioannou, C.A., 1986. Tsunami hazard in Greece and the surrounding area. *Ann. Geophys.* 4 (B1), 79–90.
- Perissoratis, C., Papadopoulos, G., 1999. Sediment instability and slumping in the southern Aegean Sea and the case history of the 1956 tsunami. *Mar. Geol.* 161, 287–305.
- Petek, A., Beneke, K., Schwarze, J., Spinn, A., 2003. Küste und Küstenformung in Westkreta als Spiegelbild eustatischer, tektonischer und gravitativ-tektonischer Prozesse. *Essen. Geogr. Arb.* 35, 39–56.
- Piatanesi, A., Tinti, S., 1998. A revision of the 1683 eastern Sicily earthquake and tsunami. *J. Geophys. Res., [Solid Earth]* 103, 2749–2758.
- Pirazzoli, P.A., 1976. Sea level variations in the Northwest Mediterranean during Roman times. *Science* 194, 519–521.
- Pirazzoli, P.A., 1986. The Early Byzantine tectonic paroxysm. *Z. Geomorphol., NF Suppl.* 62, 31–49.

- Pirazzoli, P.A., 2005. A review of possible eustatic, isostatic and tectonic contributions in eight Late Holocene relative sea-level histories from the Mediterranean area. *Quat. Sci. Rev.* 24, 1989–2001.
- Pirazzoli, P.A., Ausseil-Badie, J., Giresse, P., Hadjidaki, E., Arnold, M., 1994. Historical environmental changes at Phalasarna Harbor, West Crete. *Geoarchaeology* 7, 371–392.
- Pirazzoli, P.A., Laborel, J., Stiros, S.C., 1996. Coastal indicators of rapid uplift and subsidence: examples from Crete and other Mediterranean sites. *Z. Geomorphol., NF Suppl.-Bd.* 102, 21–35.
- Raulin, V., 1869. *Description Physique et Naturelle de l'Île de Crète*. 3ième Vol., A. Bertrand, Paris.
- Richmond, B.M., Jaffe, B.E., Gelfenbaum, G., Morton, R.A., 2006. Geologic impacts of the 2004 Indian Ocean tsunami on Indonesia, Sri Lanka, and the Maldives. *Z. Geomorphol., NF Suppl.-Bd.* 146, 235–251.
- Scheffers, A., 2003. Boulders on the move: Beobachtungen aus der Karibik und dem westlichen Mittelmeergebiet. *Essen. Geogr. Arb.* 35, 2–10.
- Scheffers, A., 2006a. Argumente und Methoden zur Unterscheidung von Sturm- und Tsunamischutt und das Problem der Datierung von Paläo-Tsunami. *Die Erde* 136, 413–430.
- Scheffers, A., 2006b. Coastal transformation during and after a sudden Neotectonic uplift in Western Crete (Greece). *Z. Geomorphol., NF Suppl.* 146, 97–124.
- Scheffers, A., Kelletat, D., 2003. Sedimentologic and geomorphologic tsunami imprints worldwide — a review. *Earth Sci. Rev.* 63, 83–92.
- Scheffers, A., Kelletat, D., 2004. Tsunami relics in the coastal landscape west of Lisbon, Portugal. *Sci. Tsunami Hazards* 23, 3–16.
- Scheffers, A., Kelletat, D., 2006. Tsunami- and paleo-tsunami research: where are we now and where do we go. *Z. Geomorphol., NF Suppl.-Bd.* 146, 1–5.
- Soloviev, S.L., 1990. Tsunamigenic zones in the Mediterranean Sea. *Nat. Hazards* 3, 183–202.
- Soloviev, S.L., Solovieva, O.N., Go, C.N., Kim, C.S., Shchetnikov, N.A., 2000. Tsunamis in the Mediterranean Sea 2000 B.C.–2000 A.D. Kluwer, Dordrecht.
- Spratt, T.A.B., 1865. *Travels and Researches in Crete*. 2nd Vol. J. van Voorst, London.
- Stiros, S.C., 1996. Late Holocene relative sea level changes in SW Crete: evidence of an unusual earthquake cycle. *Ann. Geophys.* 39, 677–687.
- Stiros, S.C., 2001. The AD365 Crete earthquake and possible seismic clustering during the 4–6th centuries AD in the Eastern Mediterranean: a review of historical and archaeological data. *J. Struct. Geol.* 23, 545–562.
- Stiros, S.C., Drakos, A., 2006. A fault-model for the tsunami-associated, magnitude ≥ 8.5 Eastern Mediterranean, AD 365 earthquake. *Z. Geomorphol., NF Suppl.* 146, 125–137.
- Stiros, S.C., Papageorgiou, S., 2001. Seismicity of Western Crete and the destruction of the town of Kisamos at AD365: archaeological evidence. *J. Seismol.* 5, 381–397.
- Stiros, S., Marangou, L., Arnold, M., 1994. Quaternary uplift and tilting of Amorgos Island (South Aegean) and the 1956 earthquake. *Earth Planet. Sci. Lett.* 128, 65–76.
- Thommeret, Y., Thommeret, J., Laborel, J., Montaggioni, L.F., Pirazzoli, P.A., 1981. Late Holocene shoreline changes and seismo-tectonic displacements in western Crete (Greece). *Z. Geomorphol., NF Suppl.-Bd.* 40, 127–149.
- Tinti, S., Maramai, A., 1996. Catalogue of tsunami generated in Italy and in Cote d'Azur, France, a step towards a unified catalogue of tsunami in Europe. *Ann. Geophys.* 39, 1253–1300.
- Vött, A., May, M., Brückner, H., Brockmüller, S., 2006. Sedimentary evidence of Late Holocene Tsunami Events near Lefkada Island (NW Greece). *Z. Geomorphol., NF Suppl.-Bd.* 146, 139–172.
- Whelan, F., Kelletat, D., 2005. Boulder deposits on the Southern Spanish Atlantic Coast: possible evidence for the 1755 AD Lisbon tsunami. *Sci. Tsunami Hazards* 23, 25–38.
- Wiegel, R.I., 2006. Tsunami information sources. *Sci. Tsunami Hazards* 24, 58–171.