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# Geological identification of historical tsunamis in the Gulf of Corinth, Central Greece

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**Abstract.** Geological identification of tsunami deposits is important for tsunami hazard studies, especially in areas where the historical data set is limited or absent. Evidence left by historical tsunamis in the coastal sedimentary record of the Gulf of Corinth was investigated by trenching and coring in Kirra on the north coast and Aliki on the south coast. The Gulf of Corinth has a documented tsunami history dating back to the 4th century BC. Comparison of the historical records and the results of stratigraphical, sedimentological and foraminiferal analyses show that extreme coastal flooding events are detectable in the coastal sequences. The geological record from Kirra shows four sand layers deposited by high-energy marine flooding events. The deposits identified show many similarities with tsunami deposits described elsewhere. The lower sand deposit (layer 4) was radiocarbon dated to 3020–2820 BC. Assuming an average sedimentation rate of 2.6 cm $(100\,\mathrm{yr})^{-1}$, the ages of the other three sand layers were estimated by extrapolation to the time windows 1200–1000 BC, AD 500–600 and AD 1400–1500. There are no historical tsunamis which correlate with layers 2 and 3. However, layer 1 may represent the major AD 1402 tsunami. Sand dykes penetrating from layer 1 into the overlying silts suggest soil liquefaction during an earthquake event, possibly the 1 August 1870 one. At Aliki, no clear stratigraphical evidence of tsunami flooding was found, but results from foraminiferal and dating analyses show that a sand layer was deposited about 180 years ago from a marine flooding event. This layer may be associated with the historical tsunami of 23 August 1817, which caused widespread destruction in the Aegion area. The work presented here supports the idea that geological methods can be used to extend tsunami history far beyond the historical record. Although the tsunami database obtained will be incomplete and biased towards larger events, it will still be useful for extreme event statistical approaches.

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## 1 Introduction

Tsunami hazard assessment is often hindered by insufficient information on the frequency and size of past events, as well as of their inundation distance. In many cases the only information available consists of historical and rarely instrumental records, typically covering a short period of time and, therefore, limiting a quantitative assessment of tsunami hazard. For this reason, these studies may be greatly assisted by the geological identification of past events. The dating of palaeotsunamis provides information about recurrence intervals, while the thickness and extent of deposits may give information about possible impacts (Sugawara et al., 2008).

It has been widely recognized that a range of sediments may be deposited by tsunamis and that these deposits may be distinctive in the coastal stratigraphy (Goff et al., 1998; Kortekaas, 2002; Dawson and Stewart, 2007). The identification of tsunami deposits is of great value in tsunami-prone regions where written records are relatively short or non-existent, but even in areas with a well-documented tsunami history, such as Central Greece, the geological record can be used to obtain a data set of past tsunamis extending far beyond instrumental and historical records.

An important problem in the identification of tsunami deposits is to distinguish them from storm deposits (Nanayama et al., 2000; Goff et al., 2004, Tuttle et al., 2004; Kortekaas and Dawson 2007; Morton et al., 2007). Both tsunamis and storms are high-energy events that may leave marine deposits in coastal sediment sequences. There are a number of characteristic features that have been found in tsunami deposits

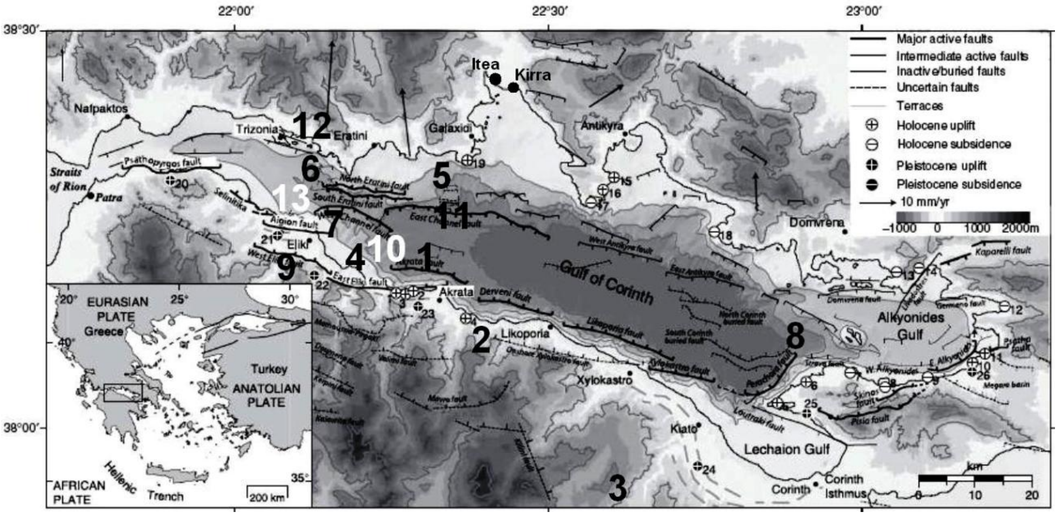


**Fig. 1.** Map of the Corinth Rift showing topography, bathymetry and faults (after Bell et al., 2009 and references therein). Inset box shows the location of the rift inside the Aegean region. The large figures from 1 to 13 indicate the locations of the tsunami sources discussed in the text and arranged according to their year of occurrence of the tsunamis as: 373 BC (1), AD 1402 (2), 1742 (3), 1748 (4), 1794 (5), 1817 (6), 1861 (7), 1887 (8), 1888 (9), 1963 (10), 1965 (11), 1995 (12), 1996 (13). Detailed references for each one of the 13 tsunami sources can be found in Papadopoulos (2003). Black figures show seismic sources, white show aseismic earth slump sources. The test-site of Kirra is shown at the north coast. The test-site of Aliki is situated very close to source n. 7. Figures attached to uplift and subsidence are in cm.

from all over the world that can be used as diagnostic criteria (e.g. Goff et al., 1998). However, many of these characteristics only indicate the high-energy conditions or marine source of the event and have also been reported for storm deposits (Kortekaas 2002, Morton et al., 2007).

The study of the deposits from recent tsunamis, including the 2004 Indian Ocean event, has improved the understanding of processes of tsunami sedimentation and erosion (Shi et al., 1995; Sato et al., 1995; Dawson et al., 1996; Minoura et al., 1997; Nishimura and Miyaji, 1995; McSaveney et al., 2000; Gelfenbaum and Jaffe, 2003; Hori et al., 2007; Srinivasalu et al., 2007; Pantosti et al., 2008). This may potentially improve the identification of palaeotsunami deposits, thus allowing a more accurate reconstruction of past tsunami events from the geological record.

The Gulf of Corinth, Central Greece, is characterized by frequent earthquake and tsunami activity. Many tsunamis that occurred in this area have been historically documented (see review in Papadopoulos, 2003). In addition, Kontopoulos and Avramidis (2003) identified six possible tsunami events from the geological record at the site of Aliki, on the southwestern Gulf of Corinth. In this paper, two areas in the Gulf of Corinth reported to have been flooded by past tsunamis were selected to compare the historical accounts of tsunami inundation with the geological evidence left in coastal stratigraphical sequences. This approach allowed stratigraphic, microfossil and sedimentological evidence of extreme flooding events in the recent geological record to be directly compared with detailed historical documentation on the time, location, and size/extent of tsunami-induced flooding. It allowed also the assessment of the extent to which the geological record may be used to enrich the database of past tsunamis.

## 2 Field sites

### 2.1 Geological setting

The Gulf of Corinth (Fig. 1) is an asymmetric half-graben with an uplifted footwall in the South and a subsiding hangingwall with antithetic faulting in the North (Jackson et al., 1982, Armijo et al., 1996). On the uplifting south coast, a thick sequence of graben-fill sediments is exposed (e.g. McNeill and Collier, 2004). In contrast, the north coast of the Gulf mainly consists of recent deltaic and coastal deposits (Lekkas et al., 1996). The north-south extension of this rift structure is controlled by normal faults (Avallone et al., 2004). These faults cut through folded Mesozoic and Tertiary phyllites, ophiolites, flysh and platform carbonates as well as younger unfolded sediments of Plio-Pleistocene age, which indicates that the rifting started mainly in the Quaternary (Armijo et al., 1996). Regional geodetic extension rates up to about 15 mm yr$^{-1}$ have been reported (Briole et al., 2000; Avallone et al., 2004).

The Gulf of Corinth was selected for this study because of its high seismicity and its rich historical tsunami documentation (e.g. Antonopoulos, 1980; Papadopoulos, 2003). It is one of the most tsunamigenic areas in the Mediterranean


**Fig. 2.** Google image of the Kirra field site, left in the photo, situated on the fluvial plain east of Itea. The local river is shown on the right in the photograph.

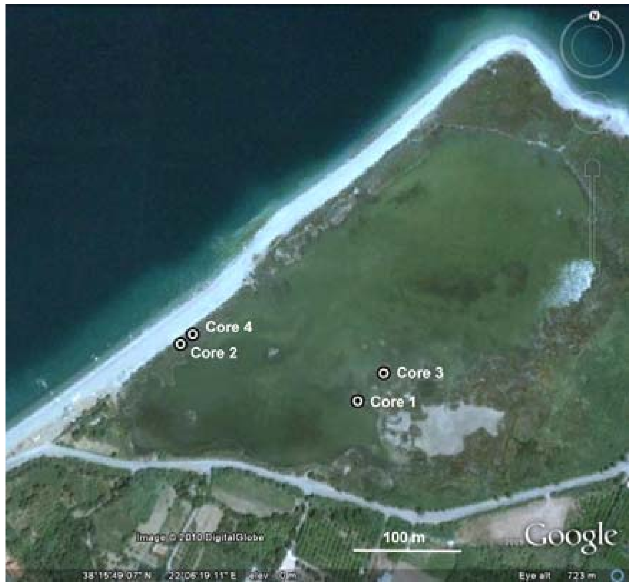


**Fig. 3.** The field site of Aliki lagoon from a Google image.

Sea region (Papadopoulos and Fokaefs, 2005; Papadopoulos, 2009), mainly due to its high seismicity. Strong earthquakes of $M_s \geq 6.0$ are frequent, having a mean recurrence interval of about 10 yr (Papadopoulos and Kijko, 1991). In addition, the high sedimentation rate combined with the steep bathymetry, especially along the south coast, create favourable conditions for submarine and coastal landslide generation. Both seismic and aseismic-induced landslides have triggered tsunamis in the Gulf of Corinth in the past, e.g. in 1963 and 1996 (Galanopoulos et al., 1964; Papadopoulos, 2003). The seismicity as well as the tsunamicity clearly decreases from west to east within the Corinth Gulf (Papadopoulos, 2003), which is compatible with the decrease of measured geodetic deformation from west to east (Avallone et al., 2004).

### 2.2 Site selection and setting

The historical documentary record of tsunamis in the Gulf of Corinth is one of the richest in the world and extends back to the 4th century BC (Papadopoulos, 2001, 2003). For the geological identification of historical tsunamis, sites were selected that are reported to have been flooded by tsunamis and that are potentially suitable for the deposition and preservation of tsunami-derived sediment. Areas particularly favourable for tsunami sedimentation, preservation and identification are typically low-energy, depositional environments such as coastal wetlands and lagoons, protected from the sea by a sandy barrier providing material for redeposition by the tsunami (Kortekaas, 2002). Moreover, the low-energy conditions of the environment protect the deposits from post-depositional erosion. In addition, the presence of organic material and shells in these environments make age dating using $^{14}$C possible.

Although many coastal wetlands in the Gulf of Corinth have been reclaimed and built over in recent years, two areas were selected for field investigation of paleotsunamis: Kirra, near Galaxidi and Itea on the north coast and Aliki, situated east of Aegion city on the south coast (Fig. 1). Both sites are situated in flat and low-lying coastal plains exposed to tsunami flooding. For both sites, reports exist that describe tsunami flooding in the historical past (Galanopoulos, 1960; Ambraseys, 1962; Antonopoulos, 1980; Papadopoulos and Chalkis, 1984).

The Kirra test-site (38°25.68′ N, 2°27.15′ E) is situated east of Itea on the north coast of the Gulf of Corinth. This area consists of a flat, low-lying coastal plain formed by two rivers and separated from the sea by a modern coastal road and a beach composed of sand and pebbles (Fig. 2). On its eastern side, the lowland is bounded by a small river that flows directly along a steep fault scarp, forming the boundary between the fluvial plain and the mountains of Jurassic and Cretaceous limestone to the east (Papastamatiou et al., 1962). The second river flows down the centre of the valley and reaches the sea just east of the town of Itea.

The Aliki test-site (38°15.73′ N, 22°06.42′ E), consists of a lagoon surrounded by salt marshes on a coastal plain formed by the Selinous River (Fig. 3). The lagoon is protected from the sea by a narrow gravel beach barrier.

### 2.3 Tsunami history

Catalogues, material compilations, and reviews for tsunami study in the Corinth Gulf have been published by several authors including Galanopoulos (1960), Ambraseys (1962), Antonopoulos (1980), Papadopoulos and Chalkis (1984),

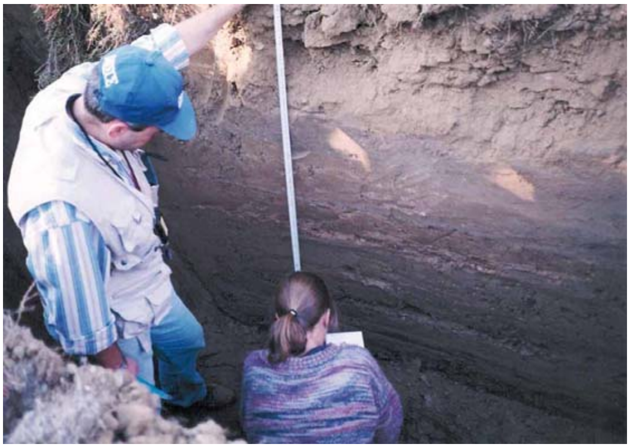

**Fig. 4.** One of trenches opened in Kirra.

**Fig. 5.** The very thin (0.5–4 cm) upper sand layer in Kirra, marked by an arrow showing upwards and four sand dykes, which penetrate into the overlying silts suggesting soil liquefaction during an earthquake event, very possibly the 1 August 1870 one.

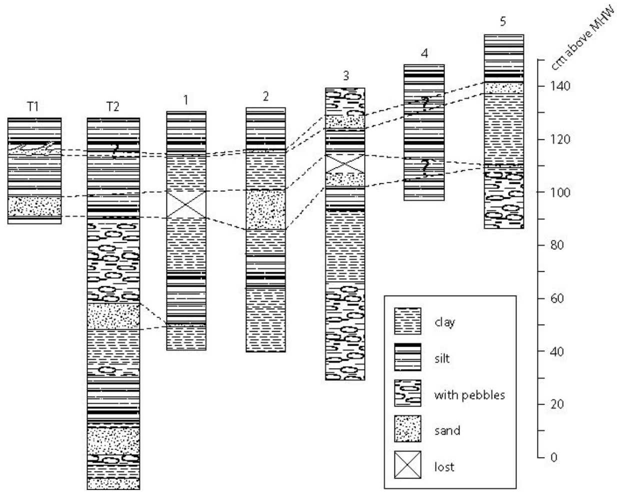


**Fig. 6.** Lithostratigraphy of Kirra in two trenches (T1 and T2) and five cores.

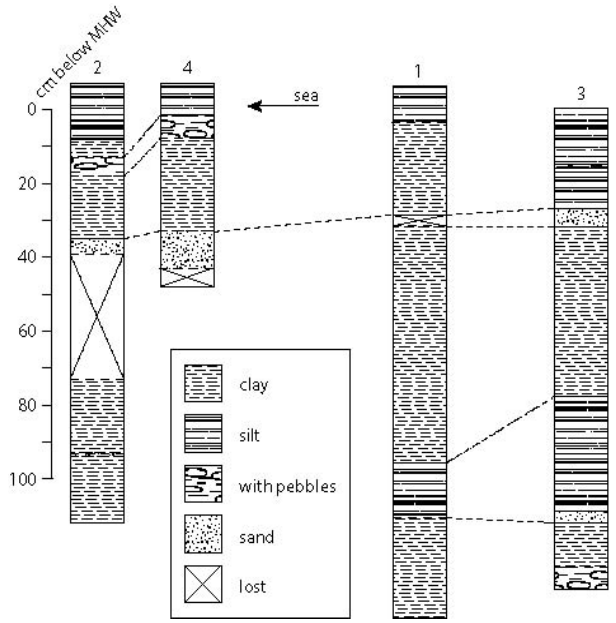


**Fig. 7.** Lithostratigraphy of Aliki. Cores 2 and 4 are located at the seaward side of the lagoon just behind the barrier and cores 1 and 3 at the landward side.

Evagelatou-Notara (1986), Guidoboni et al. (1994), Papazachos and Papazachou (1997), Guidoboni and Comastri (2005), Soloviev (1990), Soloviev et al. (2000) and Papadopoulos (2000, 2001, 2003, 2009). From a detailed review of tsunami phenomena in the Corinth Gulf, it can be seen that at least 17 tsunami events, regardless of size, are known to have occurred in the Gulf of Corinth from the 4th century BC to the present day (Papadopoulos, 2003). 13 of these 17 tsunami events are reported to have affected coastal zones around the test sites of Kirra and Aliki. In the South, the coastal segment around Aliki was inundated by the tsunamis of 373 BC, AD 1742, 1748, 1817, 1861, 1963, 1995 and 1996. The northern coastal segment around Kirra was inundated by the tsunami waves of 1402, 1794, 1861, 1887, 1888 and 1965. Figure 1 illustrates the locations of the 13 tsunami sources. Four historical earthquakes macroseismic epicenters were inserted. In order to understand the tsunami history of the two test sites, the following section (based on the detailed review of Papadopoulos (2003); for further references see therein) summarizes background information on these 13 tsunami events in chronological order.

The 373 BC tsunami was caused by a strong earthquake, that could be associated with the Eliki fault. A reconstruction based on the existing classical descriptions showed (Papadopoulos, 1998) that a sequence of three geophysical events may have taken place: (1) a large earthquake ($M_s \geq 6.6$), (2) co-seismic lateral spread and liquefaction of the coastal zone associated with subsidence, (3) a tsunami. The ancient city of Eliki, situated at distance of $\sim$7 km east of modern Aegion, was destroyed by the strong shaking, submerged because of the ground subsidence and inundated by the tsunami wave a few kilometers to the east of the Aliki test-site.

On an unidentified day in June 1402, a large catastrophic earthquake ruptured the area between Aegion and Xylokastro (Fig. 1). A large tsunami penetrated inland to a distance of ~1200 m along the southern Corinth Gulf coast. Fish were found after the retreat of the sea. In Salona (north Gulf coast), the wave killed animals and destroyed cultivated land. It is noteworthy that Salona, today Amfissa, is a town located inland and that "Salona coast", which is reported in a Venetian documentary source published by Kordosis (1981; see also in Papadopoulos, 2000) certainly includes Galaxidi, Itea and the test-site of Kirra.

A large damaging, tsunamigenic earthquake struck the north Peloponnese on 21 February 1742: *"At the time of the earthquake the sea rose 150 cubits [ca. 75 m, which is rather an exaggeration], flooding the coast of Vostiza…"*(Ambraseys and Jackson, 1997). Vostiza, today Aegion, was located about 2 km west from Aliki. Seismic activity recurred in Vostiza with the large, destructive earthquake of 25 May 1748. The tsunamis triggered by these events may have affected the areas of both test-sites. In fact, after the earthquake the sea retreated and then inundated (violently) the Aegion coast causing a number of human and animal victims and great damage to feluccas and other vessels, to engineering structures, port facilities and to cultivated land. At least three large waves struck the area. Fish and shells were found on land after the sea became calm. Significant damage was also reported from the north coast.

According to an anonymous but reliable manuscript, the area of Galaxidi (Fig. 1), close to Kirra, was hit by a strong earthquake on 11 June 1794 (Papadopoulos, 2000, 2003). A tsunami was generated due to coastal slumping immediately after the earthquake. The wave height was ca. 3 m and the wave period of about 10 min. The disturbance of the sea lasted for ca. 12 h.

The large, lethal earthquake of 23 August 1817 caused the sea to retreat a significant distance, causing boats to beach on the sea floor off the shore of Aegion. Then, the sea rose to a high wave inundating the coastal zone of Aegion. A number of human victims and significant destruction were noted. Large waves were observed along the northern coast also (Ambraseys and Jackson, 1997). On 26 December 1861 an earthquake of an estimated magnitude of 6.6 or more (Papadopoulos, 1998) triggered tsunamis which caused extensive flooding of the Aegion coast. At the same time the waves propagated to the north coast: "*…In Itea, the port of the Krissaic area, there were 5 waves. Because the coast is very flat in this area, all the houses near the beach were flooded up to 5–6 feet high. The first wave inundated only 3–4 paces inland, the second wave 6–8 paces, but the third wave 75 paces…*" (Schmidt 1879, our translation from the German text). "*…At Itea […], the sea advanced 35 m inland flooding the port a number of times, causing little damage. However, at nearby Kirra the sea advanced a long distance inland, up to Agorasia, submerging a large area of low-lying cultivated land, including Angali…*" (Ambraseys and Jackson, 1997).

A further damaging earthquake in the east Corinth Gulf occurred on 3 October 1887. A small tsunami was reported between Xilokastro and Sikia on the south coast, as well as at Galaxidi on the north coast, where the sea advanced 20 m inland. On 9 September 1888 a moderate tsunami was observed in Galaxidi after a destructive earthquake in the area of Aegion (Galanopoulos, 1955, Ambraseys and Jackson, 1997). The submarine slides that occurred offshore of Aegion caused a break in telegraph cables (Heezen et al., 1966) and possibly the small tsunami.

On 7 February 1963 a locally strong, 6-m high, destructive tsunami affected both coasts of the west Corinth Gulf. The wave was caused by a massive aseismic coastal and submarine sediment slump at the mouth of the Salmenikos river west of Aegion city (Galanopoulos et al., 1964; Koutitas and Papadopoulos, 1998; Papadopoulos et al., 2007). On 6 July 1965 a strong ($M_s = 6.3$), damaging earthquake in the west Corinth Gulf caused a coastal landslide at Eratini, some kilometres to the west of Kirra, following which a local tsunami as high as 3 m inundated the coast (Ambraseys, 1967).

The strong ($M_s = 6.1$), destructive shock that hit Aegion on 15 June 1995 caused a local tsunami as high as 1 m and 0.5 m in Aegion and Eratini, respectively (Papadopoulos, 1996a, 2003). During the very early hours of 1 January 1996 strong but local, aseismic tsunamis struck the coastal segment of Digeliotika village about 2–4 km to the east of Aegion, very possibly due to submarine and coastal slumps (Papadopoulos, 1996a, b).

## 3 Methodology

### 3.1 Sampling

During field surveys conducted in November 2001, February 2002 and May 2003, cores were taken and trenches excavated to study the local stratigraphy and collect samples for palaeo-environmental analysis. The cores were taken with Eijkelkamp hand coring equipment. The elevation of each core and trench was levelled using a Zeiss autoset level. In the absence of a local benchmark, the elevation of the cores was measured relative to Mean High Water (MHW). At Kirra, two N-S oriented trenches were opened and five cores (Figs. 4, 5) were taken at distance of ~150 m from the coast. The dimensions of the two trenches were approximately 1 m × 1 m and 40 cm deep for trench 1 and 1 m × 3 m and 1.40 m deep for trench 2. In Aliki, four cores were taken, reaching depths of up to 1.45 m (Fig. 7). It was not possible to excavate any trenches at Aliki due to the marshy nature of the site.

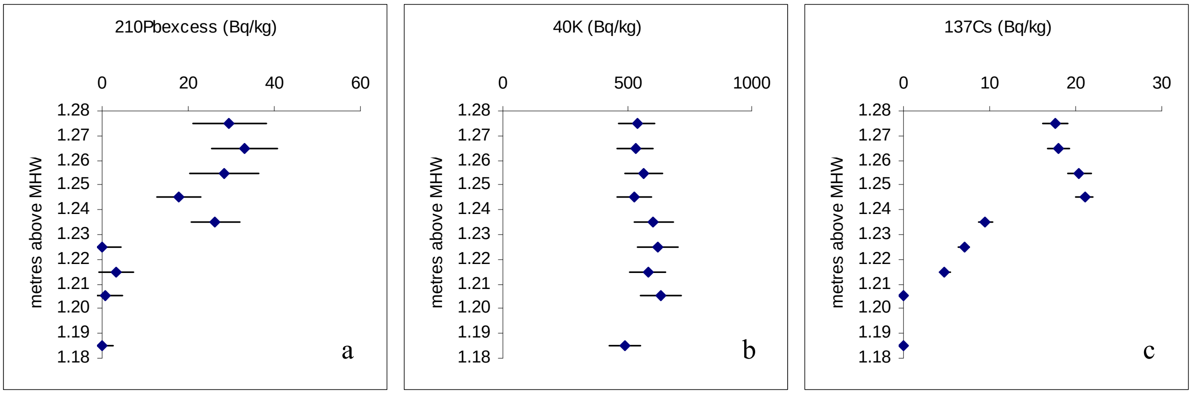


**Fig. 8.** Results of radiometric dating in trench 1, Kirra: variation in $^{210}$Pb **(a)**, $^{40}$K **(b)** and $^{137}$Cs **(c)** with depth.

### 3.2 Dating

A shell collected from one of the trenches in Kirra was radiocarbon dated while a combination of $^{210}$Pb and $^{137}$Cs dating was carried out on selected core samples from both field sites. $^{210}$Pb is a naturally-produced radionuclide, with a half-life of 22.3 yr, which has been extensively used in the dating of recent sediments. Dating is based on determination of the vertical distribution of $^{210}$Pb derived from atmospheric fallout (termed unsupported $^{210}$Pb, or $^{210}$Pb$_{excess}$), and the known decay rate of $^{210}$Pb (see Appleby and Oldfield, 1992 for further details of the $^{210}$Pb method). $^{137}$Cs (half-life = 30 yr) is an artificially-produced radionuclide, introduced to the study area by atmospheric fallout from nuclear weapon testing and nuclear reactor accidents. Global dispersion of $^{137}$Cs began in AD 1954, with marked maxima in the deposition of $^{137}$Cs occurring in the northern hemisphere in 1958 and 1963 from nuclear weapon testing and 1986 from the Chernobyl accident. In favourable conditions, periods of peak fallout/discharge provide subsurface activity maxima in accumulating sediments, which can be used to derive rates of sediment accumulation (e.g. Ritchie et al., 1990; Cundy and Croudace, 1996).

Core sub-samples were counted for at least 8 h on a Canberra well-type ultra-low background HPGe gamma ray spectrometer to determine the activities of $^{137}$Cs, $^{210}$Pb and other gamma emitters. Detection limits depended on sample size, countng time and radionuclide gamma energy, but were typically $<1$ Bq kg$^{-1}$ at 661 keV for a 5 g sample, counted for 60 000 s. The $^{210}$Pb$_{excess}$ activity was estimated by subtraction of the average value of $^{210}$Pb activity in deeper core samples (ca. 0.017 Bq g$^{-1}$), where $^{210}$Pb had reached near-constant activities with depth (e.g. Cundy and Croudace, 1996).

### 3.3 Foraminifera analysis

Sediment samples were examined for inclusion of foraminiferal tests. Samples for foraminiferal analysis were washed over a 63 µm sieve. Organic-rich samples were counted wet because these sediments tend to form a solid organic crust when dried. These samples were stored in water and divided into subsamples with a wet splitter prior to counting. The other samples were oven-dried at 40 °C and counted using a dry sample splitter. At least 300 foraminifera were counted for each sample, wherever possible. Samples from Kirra in particular had very low concentrations of foraminifera. Fragments of broken foraminiferal test were only counted if they were large enough to be identified and only if the fragment contained the umbilicus, with the aim of preventing counting the same broken specimen twice. Foraminiferal species identification was made with reference to Cimerman and Langer (1991) and the Challenger Foraminifera Atlas (Jones, 1994).

## 4 Results and interpretation: Kirra site

### 4.1 Results

#### 4.1.1 Stratigraphy

Five cores were taken and two trenches excavated in the plain of Kirra along a profile perpendicular to the coastline. The overall stratigraphy at this site consists dominantly of silt and clay, although four distinct sand layers of varying thickness are present (Fig. 5):

1. The upper sand layer has a thickness of 0.5–4 cm and consists of fine to medium sand with small pebbles grading into sandy silt in the most landward core. In trench 1 this layer shows sand dykes, which penetrate into the overlying silts, suggesting soil liquefaction during an earthquake event (Fig. 6).

2. The second sand layer has a thickness varying from 0.5 to 15 cm. It comprises fine sand with shell fragments, with large angular pebbles at its base.

3. The third sand layer is 10 cm thick in trench 2 and can possibly be correlated with a 0.5 cm thin sand layer in core

1. It consists of grey fine sand and silt with an abrupt upper and lower contact.

4. The lower sand layer is only recovered in trench 2, where it is 10 cm thick and consists of medium to coarse sand. It exhibits a sharp lower contact, fines upwards and contains abundant shell fragments.

Sand layers 1 and 2 were not found in trench 2 and core 4.

#### 4.1.2 Microfossils

Throughout the shallow stratigraphy, fossil planktonic foraminifera are found, which originate from the limestone in the hinterland. Fragments of bivalves, gastropods, sponges, bryozoa, echinoids, pteropods and ostracods of the lower Pleistocene, probably Calabrian, age (0.9–2 Ma) are present in most of the fine-grained samples. These fossils most likely originate from the Calabrian rocks that outcrop to the east of the plain (Papastamatiou et al., 1962).

Benthic foraminifera are found in the lower three sand layers, but not in the top layer. The assemblages of all three sand layers consist of a majority of marine foraminifera (see Table S1 in Supplement) together with the species *Ammonia beccarii* and *Haynesina germanica*, which are both characteristic of intertidal and/or estuarine environments (Scott et al., 1979; Kortekaas, 2002). Sand layer 4 contains a high percentage of the saltmarsh species *Jadammina macrescens* and *Discorinopsis aguayoi*, as well as marine and brackish species.

#### 4.1.3 Dating

A shell from the bottom sand layer 4, at 0.05 m above MHW, yielded a conventional radiocarbon age of $4670 \pm 40$ BP (lab no: Beta-172750). With $\Delta R = 143 \pm 41$ (Reimer and McCormac, 2002) this gives a $2\sigma$ calibrated age of 3020–2870 BC. This date is an indication of the maximum age for the oldest sand layer recovered. Unfortunately, no other material was available for dating. Therefore, the age of the other sand layers was estimated by extrapolation of the age of sand layer 4, assuming a constant average sedimentation rate of 2.6 cm $(100^{-1})$ yr (Table 1). In a fluvial, coastal environment a constant sedimentation rate is highly unlikely. Episodes of erosion will have occurred, possibly caused by river incision, marine or fluvial flooding events or during episodes of no deposition. Unfortunately however, insufficient data are available to calculate a more reliable age for the sand layers.

The near-surface sediments in trench 1 were dated using $^{210}$Pb and $^{137}$Cs dating. The $^{210}\mathrm{Pb}_{\mathrm{excess}}$ activity in the Kirra stratigraphy shows a slight decline with depth over the upper 5 cm, followed by a rapid decline to negligible activities below $-5$ cm (Fig. 8a). There are two possible explanations for this trend. The first is the presence of a recently deposited surface layer overlying an older unit, with a possible erosional surface at $-5$ cm. The unit below 5 cm depth is older than 1880 that is the limit of $^{210}$Pb dating. The second is the presence of a well-mixed surface layer between 0 and 5 cm depth overlying older sediments, whereby bioturbation or other mixing has caused the development of a surface layer of near-uniform activity. The relatively constant activity of $^{40}$K down the sediment sequence indicates that there are unlikely to be any major compositional changes in the top 10 cm of the sediments that could cause the rapid decline observed in $^{210}\mathrm{Pb}_{\mathrm{excess}}$ (Fig. 8b).

$^{137}$Cs shows a slight increase in activity with depth between the sediment surface and $-4$ cm, where a maximum activity of 21 Bq kg$^{-1}$ is observed (Fig. 8c). Below this depth, the activity rapidly declines with depth to negligible values at 7 cm depth. The sharp decline in $^{137}$Cs activity occurs at $-4$ cm, just above the observed rapid decline in $^{210}\mathrm{Pb}_{\mathrm{excess}}$ activity at $-5$ cm. This indicates that the upper 5 cm of the sequence are not completely mixed and, therefore, it seems more likely that a recently deposited surface layer overlies an older unit below $-5$ cm (scenario 1 as outlined above). The presence of low $^{137}$Cs activities in the sediments below $-5$ cm is most likely due to slight downward migration of $^{137}$Cs in the sediment column, as observed elsewhere (e.g. Cundy and Croudace 1996, Spencer et al., 2003). Attributing the subsurface $^{137}$Cs activity maximum at 3–4 cm depth to 1963, the peak fallout from atmospheric weapons testing (e.g. Cundy et al., 2000), gives a sediment accumulation rate of 0.8–1 mm yr$^{-1}$. However, the lack of either a clear decline in $^{210}$Pb activity with depth in the surface layers, or a well-defined subsurface activity maximum for $^{137}$Cs, means that accurate sediment accumulation rates cannot be determined for this sequence. However, the top part of the upper silt unit (less than 4 cm depth) is apparently younger than 1963, while its base at $-11$ cm clearly pre-dates 1880, that is the limit of 210Pb dating.

### 4.2 Interpretation

The stratigraphy at Kirra consisted of fine-grained material containing sand and gravels (Fig. 5). The fossils found within this sequence were of the lower Pleistocene, probably Calabrian age, which suggests that they originate from the conglomerate, limestone, and marls of the same age that outcrop east of Kirra (Papastamatiou et al., 1962). This indicates a fluvial origin for the fine sediment and thus conditions similar to those of today. However, this fluvial dominated deposition was interrupted four times when distinct sand layers were deposited. Sand layers 2, 3 and 4 contain foraminifera, indicating marine origin.

The oldest sand layer 4 contained a mixed foraminiferal assemblage with marine, estuarine and salt marsh species. The estuarine and marine foraminifera, as well as the abundant shell fragments, indicate that the sand was deposited inland from a marine source rather than downstream as a fluvial deposit. The presence of saltmarsh species shows that the water eroded a saltmarsh it swept across. This, in combination with the erosional base and the coarse grained nature of

**Table 1.** Extrapolated age for the sand layers at Kirra. Extrapolation is based on the radiocarbon date of a shell from sand layer 4 and assuming a constant sedimentation rate of 2.6 cm $(100\,\text{yr})^{-1}$.

| Sand layer(depth in trench) | Level above MHW | Extrapolated age |
|---|---|---|
| 1. 12–13 cm | 1.16–1.15 m | 500 BP∼AD 1400–1500 |
| 2. 30–37 cm | 0.98–0.91 m | 1400 BP∼AD 500–600 |
| 3. 70–80 cm | 0.58–0.48 m | 3100 BP∼BC 1200–1000 |
| 4. 117–127 cm | 0.11–0.01 m | 4860 BP∼BC 3020–2870 ($2\sigma$) |

the deposit, suggests a high-energy marine flooding event. At the present time, saltmarshes are not found in the Kirra-Itea area. It is however possible that at the time, sand layer 4 was deposited saltmarshes occurred along the coast in this area. Another possibility is that the flooding event transported the saltmarsh foraminifera from a more distal marsh.

The sharp basal contact of sand layer 3 indicates erosion or a rapid change in depositional environment. Its foraminiferal assemblage of marine and estuarine species suggests a marine origin. This layer was better sorted and overall finer than sand layer 4 and thinned rapidly inland. Unfortunately, the spatial extent of each deposit cannot be compared, as only trench 2 was deep enough to reveal sand layer 4. The difference in grain size, however, suggests that the oldest marine event was of higher energy than the flooding event that laid down sand layer 3.

Sand layer 2 contained abundant pebbles at its base, suggesting high-energy conditions. It thinned and fined inland, indicating marine origin, confirmed by its foraminiferal assemblage which showed a mixture of marine and estuarine species. This sand layer can be traced until core 5, situated ca. 200 m inland.

The upper sand layer did not contain any foraminifera. It is possible that fossils have not been preserved or possibly this layer has a non-marine origin.

## 5 Results and interpretation: Aliki site

### 5.1 Results

#### 5.1.1 Stratigraphy

Four shallow cores with a maximum depth of 1.45 m were taken at the edge of the Aliki lagoon. Two cores were situated on the landward side of the lagoon. The other two were situated on the seaward side, behind the barrier.

The stratigraphy in the seaward cores consists of a black organic rich saltmarsh soil, which overlies a brown compact clay containing pebbles (Fig. 7). At ca. 34 cm below MHW a sharp boundary separates the clays from more sandy material containing many pebbles. This material was difficult to core and was lost in both cores. Below a depth of ca. 74 cm below MHW, brown to grey clay is present containing small gastropods and a sandy horizon with pebbles at ca. 94 cm below MHW. The cores at the landward site of the lagoon consist almost entirely of clay and silt with two sandy horizons at ca. 30 cm below MHW and at ca. 110 cm below MHW. A pebble-rich horizon prevented core 1 from penetrating any deeper.

#### 5.1.2 Foraminifera analysis

The landward cores contain very few foraminifera. Only the sandy horizon at 30 cm below MHW shows a low concentration of saltmarsh and brackish species. The seaward stratigraphy contains abundant foraminifera in the top 15 cm, below which numbers decrease rapidly (see Table A2 in Supplement). The dominant species is *Trochamina inflata*, indicative of a high marsh environment. In most samples this species made up more than 90 % of the total assemblage, except at ca. MHW level depth, where its relative abundance decreased to 52 % and a relatively high percentage of intertidal and marine species was present (see Fig. S1 in Supplement).

#### 5.1.3 Dating

$^{210}Pb_{excess}$ activity in the Aliki core 4 showed a broadly exponential decline with depth, with activities rapidly decreasing to undetectable values at 7–8 cm depth (Fig. 9a). Sediment accumulation rates were determined using the simple model of $^{210}$Pb dating (e.g. Robbins, 1978), where the sedimentation rate is given by the slope of the least-squares fit for the natural log of the $^{210}Pb_{excess}$ activity versus depth. Based on this model, the $^{210}$Pb-derived sediment accumulation rate is $0.4\,\text{mm}\,\text{y}^{-1}$ ($2\sigma$ range = $0.3$–$0.8\,\text{mm}\,\text{y}^{-1}$) (Fig. 9c). This rate is a maximum due to the potential effects of bioturbation and mixing.

$^{137}$Cs shows a maximum in activity at or near the sediment surface, with an approximately exponential decline to undetectable activities below 10 cm depth (Fig. 9b). The relatively deep penetration of $^{137}$Cs into the core sequence below this near-surface maximum indicates that some downwards mixing or diffusion has occurred, as was also observed in the Kirra trench. The lack of a clear subsurface maximum in $^{137}$Cs activity means that it is not possible to accurately

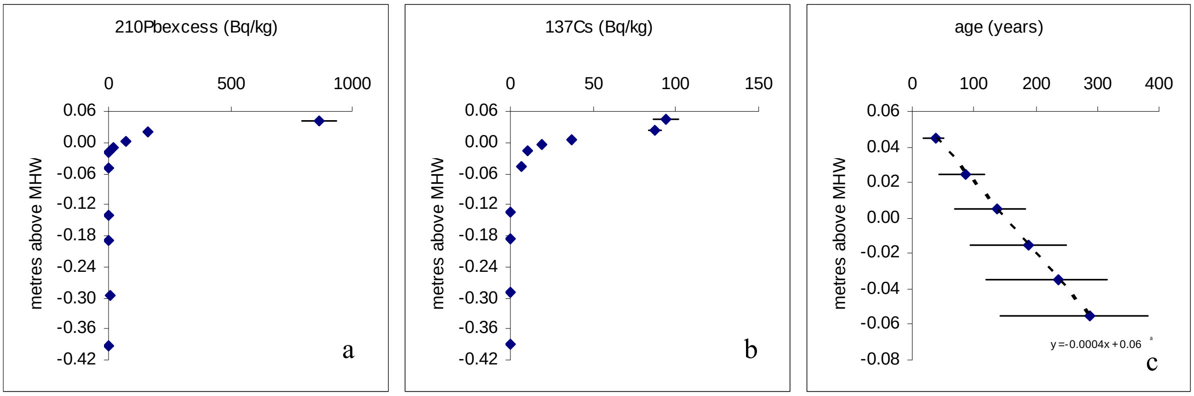


**Fig. 9.** Results of radiometric dating in core 4, Aliki: variation of $^{210}$ Pb **(a)** and $^{137}$Cs **(b)** with depth and the sediment accumulation rate (age-depth curve) based on the simple model of $^{210}$Pb dating **(c)**.

date this sediment sequence by $^{137}$Cs dating. The presence of maximum activity values at or within 4 cm of, the sediment surface indicates a sediment accumulation rate of less than 1mm/y, in broad agreement with the $^{210}$Pb data, assuming that the maximum in $^{137}$Cs activity corresponds to 1963, the period of peak fallout from nuclear weapons testing (e.g. Cundy et al., 2000).

### 5.2 Interpretation

The Aliki stratigraphy consists mainly of silt and clay reflecting a depositional environment similar to that of today. The pebbles found in the seaward cores originate from the nearby beach barrier. No clear stratigraphic evidence of marine flooding is found. However, results of the foraminiferal analysis show an increase in marine foraminifera at 6–7 cm depth (∼MHW level), suggesting marine inundation.

## 6 Discussion

### 6.1 Identifying tsunami deposits

The marine flooding deposits at Kirra and Aliki exhibit a number of the characteristics described from tsunami deposits in the literature (e.g. Dawson 1996; Goff et al., 1998; Kortekaas and Dawson, 2007) including: large inland extent, thinning inland, fining inland, fining upward, poor sorting, mixture of marine and marsh foraminifera, the presence of shell fragments and an erosional basal contact.

Sand layer 2 at Kirra was found in all cores at this site and has a minimum inland extent of ca. 200 m. The inland extent of the other marine flooding deposits identified at Kirra and Aliki cannot be estimated because of insufficient data. All sand layers at Kirra become thinner and finer inland indicating the marine origin of these deposits. Sand layer 4 also shows a fining upward trend, which may be associated with decreasing energy of the flooding event. Sand layer 2 has large pebbles at its base and all sand layers at Kirra show an erosional basal contact. Sand layer 2, 3, and 4 contain shell fragments and marine foraminifera. In Aliki, only the microfossil assemblage indicates a marine flooding event. No sedimentological characteristics of marine flooding were found at this site.

However, most of these characteristics merely reflect the marine origin of the deposit and the high energy of the event and, therefore, do not exclude a storm origin. Nevertheless, a tsunami origin is suggested here for sand layer 2, 3 and 4 at Kirra and the marine flooding layer at Aliki because storms are not capable of generating waves of sufficient height to reach the areas where these deposits occur. The Gulf of Corinth is an enclosed basin, which means that there is a limited fetch and storm waves have no opportunity to grow as large as they may do in the open ocean. Analysis of tide-gauge records from Posidonia and Patras, at the eastern and western ends of the Gulf, respectively, has shown extreme sea level values with a recurrence interval of 500 yr of 0.66 m and 0.52 m, respectively (Tsimplis and Blackman, 1997). A storm surge of 66 cm would not have been able to top the barrier at Aliki or deposit a sand layer at an elevation of 110 cm above MHW more than 200 m inland at Kirra.

Sand layers 3 and 4 at Kirra were found at elevations of 48 cm and 1 cm above MHW, respectively. These layers were deposited about 4860 and 3100 yr BP and it is important to consider the position of the local sea level at that time. Flemming and Webb (1986) derived a best estimate of the eustatic sea level curve for the Mediterranean corrected for local tectonic movements. This curve suggests a rapid rise of the sea level up to about 5–6 ka BP, followed by a slow rise of sea level of about 1 m from 4 ka BP onwards. According to the model of Lambeck (1996), the sea level was about 3 m lower at Kirra, ca. 6000 yr BP. According to palaeoshorline and archaeological data synthesized by Palyvos et al. (2008), a mean sea level rise of about 1.5 m has occurred in the Mediterranean Sea over the last 4000 yr. This means that at the time of deposition of the older two sand layers, the sea level at Kirra may have been one to a few meters lower than today.

### 6.2 Dating and correlation with the historical record

Several marine flooding events were identified in the coastal stratigraphy at the Kirra site. A shell from the oldest deposit was radiocarbon dated to a $2\sigma$ calibrated age of 4970–4820 BP (3020–2820 BC). This pre-historic age makes correlation with historical documentation impossible. However, the age corresponds to the age obtained for a tsunami deposit identified in cores taken from the Aliki lagoon on the opposite side of the Gulf of Corinth, which has been dated to ca. 4700 yr BP (Kontopoulos and Avramidis, 2003). Those authors suggested that a large tsunami triggered by the movement of the Aegion fault may have flooded the low-lying parts of the coast on both sides of the Gulf. The possible movement of the Aegion fault, however, is not documented. Sediment layer unconformities observed in a palaeoseismological trench opened in a segment of the Aegion fault system indicated an earthquake event dated to "sometime after 2058 BC" (Palyvos et al., 2005).

Because no other datable material was available, the age of the other sand layers was estimated, assuming a constant sedimentation rate. As constant sedimentation is unlikely in a fluvial-coastal environment where erosional events are expected, the ages calculated should be taken as broad estimates.

The age of sand layer 3 was estimated to ca. 1000–1200 BC. Therefore, similarly, this event layer cannot be compared with the historical record. Kontopoulos and Avramidis (2003) reported the identification of three possible tsunami events in the Aliki lagoon dated to ca. 3000, 2500 and 2350 yr BP; they suggest that the first two events may have been associated with movement along the Aegion faults and the latter with movement along the Heliki fault. The age estimated for sand layer 3, however, has such a large error that it is difficult to correlate it reliably with any of these events.

The age of sand layer 2 was estimated as around AD 500–600. Documentary sources indicate that several large earthquakes of a magnitude larger than 6 were recorded in the 6th century AD, but no tsunamis were reported (Papazachos and Papazachou, 1997; Papadopoulos, 2000). However, most of the documentary sources were written after the events had taken place and by people who were not at the location. Therefore, the occurrence of a tsunami event cannot be ruled out. In addition, as noted above, it is difficult to correlate stratigraphic units with the historical record due to lack of datable material in these units and subsequent limited chronological control.

The results of the radiometric dating of the near-surface sediments indicate that sand layer 1 pre-dates 1880, which is the limit of $^{210}$Pb dating. Age control of sand layer 1 is problematic, due to a lack of datable material. Based on sedimentation rates, this layer was roughly dated to about AD 1400–1500. Accounts exist of an historical strong tsunami that caused extensive flooding of the area around Kirra in June 1402 (Evagelatou-Notara, 1986). This event may have deposited sand layer 1. However, the absence of any benthic foraminifera may indicate a non-marine and possibly fluvial origin for this sand layer. Alternatively, the microfossils may not have been preserved.

The sand dykes extending from layer 1 up into the overlying silts suggest soil liquefaction during an earthquake. Ambraseys and Pantelopoulos (1989) described extensive liquefaction features occurring in the Kirra plain in association with the large ($M_s = 6.7$) earthquake that struck the area on 1 August 1870. An assessment of liquefaction potential has shown that the area of Itea is, indeed, highly susceptible to liquefaction (Novikova et al., 2007).

It is notable that no geological evidence of the 1861 tsunami, known to have flooded the Kirra area, was recovered. A possible reason may be that this event was smaller in size than the marine flooding events that have been preserved. Smaller events may leave no or very subtle evidence, which is impossible to detect or distinguish in the sedimentary record. Alternatively, and more probably, deposits may have been partly eroded by fluvial action or removed due to subsequent human activities in the coastal zone over the last 150 yr. Another possibility is that the inland penetration of the 1861 tsunami was insufficient to reach the area trenched. The last explanation would indicate that the sand layer 1 liquefied by the 1870 earthquake was not associated with the 1861 earthquake, but instead relates to an earlier flooding event (such as AD 1402).

At the Aliki test site a marine flooding event was identified at 6–7 cm depth. The age-depth curve derived using the simple model of $^{210}$Pb dating (Fig. 9b) indicates that this event occurred prior to AD 1900, ca. 170 yr ago. While the error bars on this age estimate are extremely large, it is possible that this flooding event is linked to the earthquake-induced tsunami of 23 August 1817. This was a strong tsunami with a vertical run-up locally reaching at least 5 m (Papadopoulos, 2003). At Aegion, the tsunami wave run-up reached over 5–6 m and caused many deaths and much damage along the coast (Xinopoulos, 1912; Stavropoulos, 1954).

## 7 Conclusions

Studying the geological evidence of tsunamis in the Gulf of Corinth is hindered by the fact that the coastline is highly developed, and there are consequently only a few remaining coastal wetlands or lagoons suitable for preservation of sedimentary deposits and coring. Two sites were investigated and the results show that in Kirra, on the north coast, at least three events of marine high-energy flooding have occurred since ca. 4860 BP, while in Aliki, on the south coast, one marine flooding event was identified.

In Kirra, a shell from the oldest sand layer (layer 4) was radiocarbon dated to 3020–2820 BC. Assuming a constant long-term deposition rate of 2.6 cm $(100\,\text{yr})^{-1}$, the ages of sand layers 3 and 2 were estimated in the time windows of 1000–1200 BC and AD 500–600, respectively. The marine flooding deposits at Kirra and Aliki exhibit many of the characteristics of tsunami deposits as described in the literature. However, most of these characteristics merely reflect the marine origin of the deposits and the high energy of the event and, therefore, do not exclude a storm origin. Nevertheless, a tsunami origin is suggested for the sand layers at Kirra and the marine flooding layer at Aliki because storms are not capable of generating waves of sufficient height to reach the areas where these deposits occur. In addition, for the sand layers 3 and 4 at Kirra, eustatic sea level changes indicate that at the time of deposition the sea level may have been one to a few meters lower than today, which again favours tsunami inundation over storm deposit origin.

Sand layer 4 may correlate with a tsunami deposit identified in the Aliki lagoon and dated to ca. 4700 yr BP by Kontopoulos and Avramidis (2003). Kontopoulos and Avramidis (2003) also identified three possible tsunami events in the Aliki lagoon dated to ca. 3000, 2500 and 2350 yr BP. The age estimated for sand layer 3, however, suffers from large errors which make it difficult to correlate with any of these three events.

No historical or other evidence is available for correlation with the sand layer 2 at Kirra. However, the occurrence of a non-documented tsunami event should not be ruled out. Radiometric dating of near-surface sediments indicate that sand layer 1 in Kirra pre-dates 1880, which is the limit of $^{210}$Pb dating. Based on extrapolation of sedimentation rates, this layer was approximately dated to AD 1400–1500. The closest (temporally) historical tsunami was that of June 1402, which caused significant inundation along the coastline around Kirra. Therefore, it is possible that sand layer 1 represents the 1402 tsunami. Sand dykes extending from layer 1 up into the overlying silts suggested soil liquefaction attributable to the 1 August 1870 ($M_s = 6.7$) earthquake, which is historically documented to have caused liquefaction at Kirra.

It is notable that no evidence of the 1861 tsunami, known to have flooded the Kirra area, was recovered. It is likely that either deposits from the 1861 event may have been eroded, or the tsunami did not penetrated inland sufficiently to reach the area trenched. Indeed, the very low sediment accumulation rates observed at this site may be related to erosion of part of the sediment sequence by the nearby river.

No clear stratigraphic evidence of marine flooding was found at Aliki. However, the results of foraminiferal analysis show evidence of marine flooding at 6–7 cm below the sediment surface. Based on the simple model of $^{210}$Pb dating, we conclude that this event occurred prior to AD 1900, possibly 170 yr ago. Given the large error on this latter age, it is possible that this in-wash event is linked to the tsunamigenic earthquake of 23 August 1817 ($M_s = 6.7$).

More generally, the work presented here supports the idea that geological methods can be used to extend tsunami history far beyond the historical record. Although the tsunami database obtained will be incomplete and biased towards larger events, it will still be useful for extreme event statistical approaches.

**Supplementary material related to this article is available online at: http://www.nat-hazards-earth-syst-sci.net/11/2029/2011/nhess-11-2029-2011-supplement.pdf**.

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