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Palaeoenvironmental evolution of the ancient harbor of Lechaion (Corinth Gulf, Greece): Were changes driven by human impacts and gradual coastal processes or catastrophic tsunamis?

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ABSTRACT

The Corinth Gulf, Central Greece, is one of the most rapidly widening tectonic rifts on Earth, where large earthquakes with magnitudes of up ~7.0 have been documented not only by instrumental records but also assessed from historical reports extending back to the 5th century BCE. Several of these earthquakes were associated with tsunamis, particularly in the western part of the Gulf. Of particular interest is the ancient harbor of Lechaion in the eastern side of Corinth Gulf. We reexamine the hypothesis that Lechaion was hit by high-energy tsunami waves in the 8th–6th century BCE, 1st–2nd century CE, and during the 6th century CE. On the basis of sedimentological, seismotectonic, archaeological and historical data, completed with field observations, we support that there is no evidence for tsunami impact in Lechaion. Local stratigraphy and environmental changes are rather interpreted by human impacts and gradual coastal processes. Such interpretations confirm that the tsunami potential in the east Corinth Gulf is relatively low.

1. Introduction

The Corinth Gulf, Central Greece, is a seismically very active tectonic rift with a E-W length of about 120 km and a maximum N-S width of ca. 30 km. Large earthquakes with magnitudes up to ~7.0 are not only documented by instrumental records in the last century or so, but also by a great number of historical reports extending back to the 5th century BCE (e.g. Galanopoulos, 1955; Papazachos and Papazachou, 1989, 2003; Guidoboni et al., 1994; Ambraseys and Jackson, 1990, 1997; Papadopoulos et al., 2000; Guidoboni and Comastri, 2005; Ambraseys, 2009). Several of these earthquakes were associated with strong tsunamis, particularly in the western part of the gulf (e.g. Galanopoulos, 1960; Papadopoulos, 2003). The seismicity of the area is controlled by active faults striking in a roughly E-W direction (e.g. Armijo et al., 1996). Of particular interest is the eastern side of the Corinth Gulf which was hit by very strong earthquakes, such as in 1981 when a series of three events, occurring on 24th and 25th February and on 4th March with magnitudes 6.7, 6.4 and 6.3, respectively, caused many human victims, extensive destruction and ground failures, including surface-fault traces (e.g. Papazachos and Papazachou, 1989, 2003). The high seismicity rate recorded in the Corinth Gulf is explained by that it is one of the most rapidly extending tectonic rifts on the Earth, with reported regional geodetic extension rates being up to about 15 mm/yr (Briole et al., 2000; Avallone et al., 2004).

In the eastern Corinth Gulf, the ancient harbor of Lechaion is one of the areas attracting special interest since it preserves a unique record of the geomorphological, palaeogeographical and geoarchaeological evolution of the area. One of the points of interest focuses on the palaeotsunamis that supposedly hit Lechaion. At least three distinct tsunami episodes have been considered as occurring in various historical time periods ranging from 8th century BCE up to 6th century CE (e.g. Brown, 2008; Hadler et al., 2011, 2013; Koster et al., 2011). However, the historical tsunami record in the particular area is extremely low (e.g. Papadopoulos, 2003), which contradicts claims for repeated tsunami occurrences in Lechaion. From this point of view Lechaion becomes an important test-site to control methods leading to the identification of palaeotsunamis. On the other hand, since the level of tsunami hazard is directly dependent on the tsunami frequency, Lechaion again is a suitable area for testing methods of tsunami hazard assessment.

In this paper the tsunami occurrence in Lechaion is re-examined on the basis of various, independent approaches including the historical

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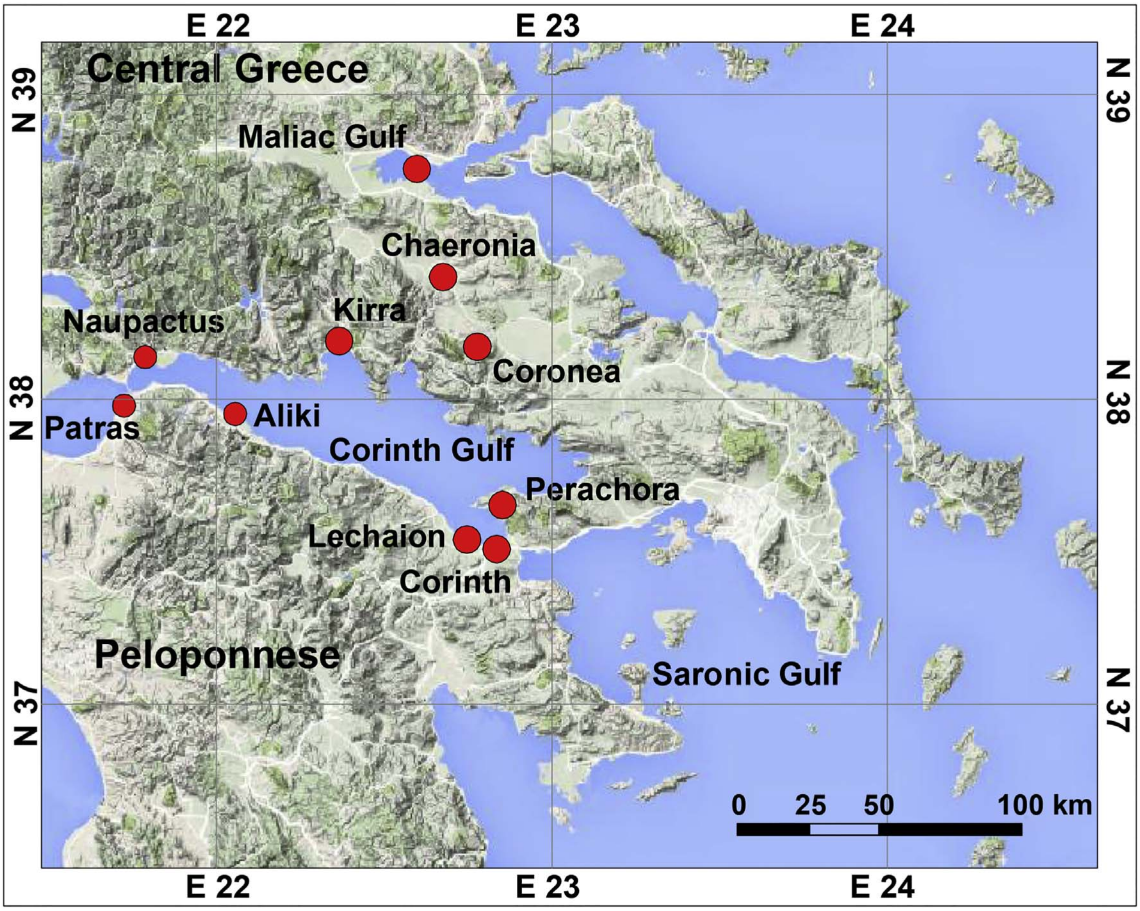

Fig. 1. Map of the locations mentioned in the text.

record and archaeological findings of the area, geomorphological observations and sedimentary analysis as well as the geoarchaeological and palaeogeographical evolution of the harbor. In addition, the important role of human intervention versus catastrophic scenarios in the historical evolution of Lechaion has been included in our analysis.

2. Tectonic setting and tsunami evidence in the Gulf of Lechaion

2.1. Late Holocene tectonic setting

The Gulf of Lechaion, which is an active rift structure with a high deformation rate, consists of a steep fault margin in the north and a smooth coastal morphology in the south and the east. The Late Holocene tectonic history of the Perachora peninsula, which is the northern margin of Lechaion Gulf (Fig. 1), is characterized by four uplifted tectonic movements with a cumulative amplitude of up to 3.20 ± 0.20 m occurring between 4380 ± 60 BCE and 315 ± 125 CE (Pirazzoli et al., 1994). In Lechaion, major neotectonic structures were associated with vertical tectonic movements during the Late Holocene (Mourtzas and Marinos, 1994; Maroukian et al., 1994; Stiros et al., 1996; Hadler et al., 2011; Koster et al., 2011; Morhange et al., 2012; Hadler et al., 2013; Mourtzas et al., 2014).

Mourtzas and Marinos (1994) described the recent tectonic evolution after the abandonment of the ancient harbor, which likely caused an uplift of at least 1.70 m and a partially emersion of the ancient harbor installations. The subsequent subsidence did not exceed 0.70 m, and resulted in the partial submersion of the fore-harbor installations. This may have happened by the end of the Hellenistic and Roman period (see also Maroukian et al., 1994). Stiros et al. (1996) dated marine fossils (calibrated age between 600 BCE and 50 BCE) and concluded that the tectonic uplift probably occurred between 500 and 200 BCE, most likely around 340 BCE.

Morhange et al. (2012) assessed apparent sedimentation rates in the basins of the inner harbor and suggested radiocarbon calibrated ages ranging from 493 BCE to 54 CE, thus placing the *terminus post quem* for the reconstruction of the harbor installations to the Roman period (see also Stiros et al., 1996). Moreover, Morhange et al. (2012) collected emerged *Balanus perforatus* fossils in growth position from a rectangular structure in the middle of the main Lechaion basin, called ‘nisaki’, indicating a biological sea level 1.20 m above msl. Radiocarbon analyses constrained the date of the uplift to 375 ± 120 cal BCE. However, the radiocarbon age of barnacles found on the structure, is in contradiction with the archaeological chronology which indicates that ‘nisaki’ is dated to between the second half of the 1st century BCE and 68 CE (Shaw, 1969).

Between the 4th and 6th centuries CE, a series of vertical co-seismic tectonic events repeatedly modified the sea-land relationship on the NE coast of the Peloponnese (Fig. 1). The west (Poseidonia) and south (Lechaion harbor) coast of Lechaion Gulf (Fig. 2) initially submerged by 2.0 m, likely 1.60 m between 365 CE and 375 CE and 0.40 m between 518 CE and 521 CE, and then emerged by 1.10 m probably during strong earthquakes of the 17th and 18th centuries CE (Mourtzas et al., 2014). At the same time, the north coast of Lechaion Gulf along the Loutraki fault zone (Fig. 2) was uplifted by 0.80 m to 1.10 m (Pirazzoli et al., 1994). In the same period, the Peloponnese coast of the Saronic Gulf to the east suffered a significant abrupt submersion by −3.30 m ± 0.15 m (Kolaiti and Mourtzas, 2016).

This recent tectonic history of the NE edge of the Peloponnese (Fig. 1), refers to a complex tectonic setting. The vertical tectonic movements in the Gulf of Lechaion are partly dependent on the position

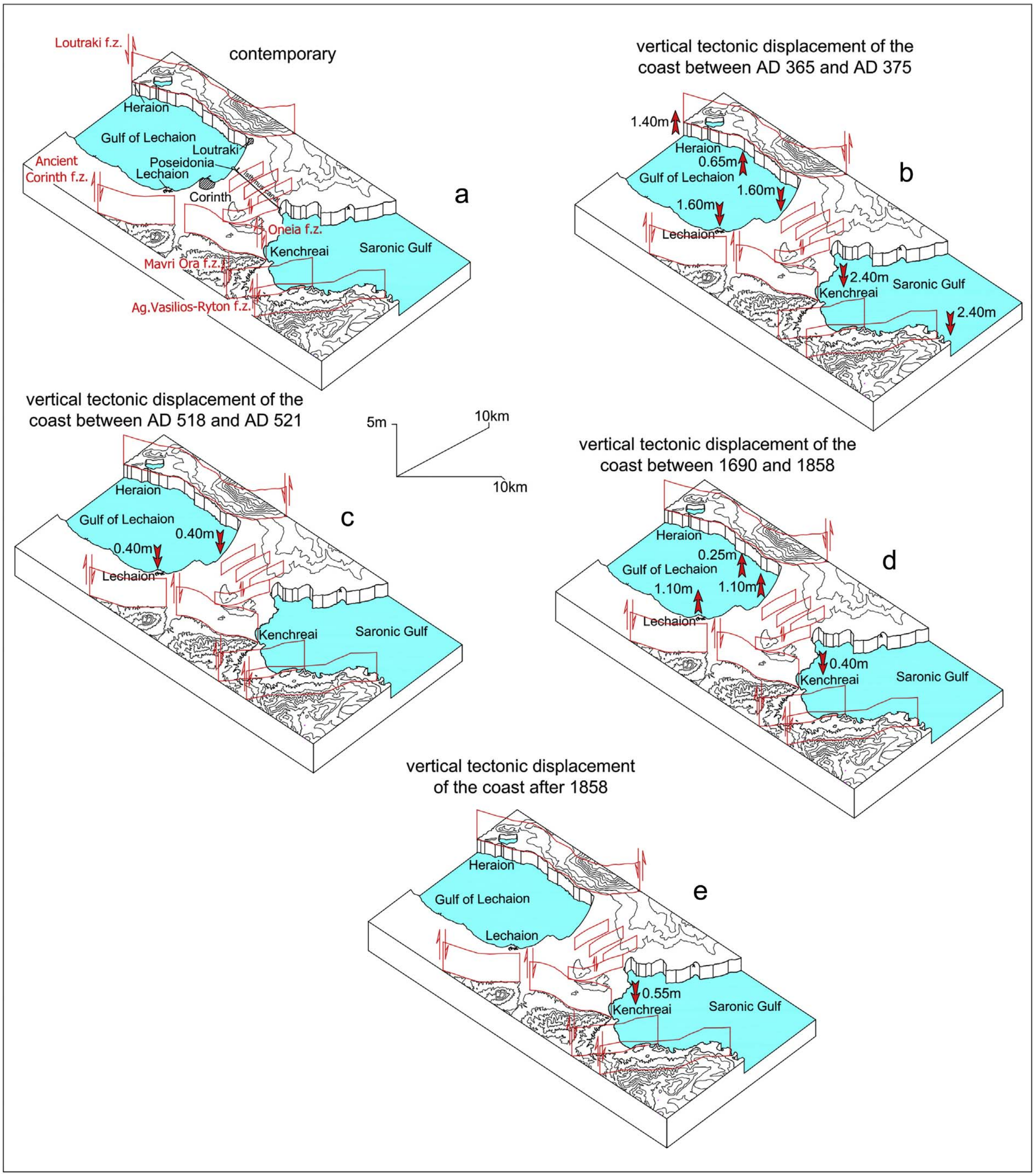

Fig. 2. Schematic diagram of vertical co-seismic tectonic events on the NE coast of the Peloponnese, based on data of Pirazzoli et al. (1994), Mourtzas (2004), Mourtzas et al. (2014), and Kolaiti and Mourtzas (2016).
(a) Simplified contemporary tectonic framework with stereographic projection (lower hemisphere) and palaeo-stress analysis of 43 individual fault planes of the Corinth Canal, (b, c, d, e) simplified tectonic evolution after 350 CE. Arrows and numbers show the direction and magnitude of vertical tectonic movements in each deformation phase.

of the coast in the footwall or the hangingwall blocks of active seismic faults and partly on the regional isostatic uplift of the eastern end of the Corinth rift.

On the north and south coast of Perachora peninsula (Fig. 2), the uplifted tidal notches up to the elevation of + 3.50 m at Mylokopi and + 3.20 m at Heraion (Pirazzoli et al., 1994), reflect a general uplift trend with intermediate subsidence intervals. Typical examples of the reversal of the general uplift trend of the coast is the most recent tidal notch at Mylokopi (1640 ± 190 CE) which is situated at a higher elevation (+ 1.10 ± 0.30 m) than the earliest (470 ± 70 CE) and lower notches (+ 0.80 m) (Pirazzoli et al., 1994), as well as the recent subsidence of the north coast by 0.60 m to 0.80 m (Andronopoulos et al., 1982; Jackson et al., 1982; Mariolakos et al., 1982; Hubert et al., 1996). The differential tectonic behavior of the western basin system, demarcated by the fault zones of Loutraki to the north and Onia and Ancient Corinth to the south, and the eastern basin system of the Western Saronic Gulf with offshore mainly N-S and E-W faults (Fig. 2), cannot be interpreted by the extremely low slip rates of the secondarily activated faults of Isthmus, or even by the 1981 seismic source of Alkyonides and its fault zones. The Onia fault, in the south margin of the east Corinth basin with slip rates 0.15 mm/yr (Koukouvelas et al., 2016), does not seem to affect the south coast of the Corinth Gulf. With the subsidence of the hangingwall of the Ancient Corinth fault could be linked the two initial subsidence episodes that submerged the harbor installations of Lechaion and Poseidonia. However, this cannot explain the subsequent uplift of the coast. The migration towards the west of the ever-higher uplift rates accompanied by subsidence intervals of the south coast of Corinth Gulf during the Late Holocene, which from 1 mm/yr in the eastern part exceeds 3 mm/yr in the central and western parts, may refer to a broader regional differential uplift on both sides of a significant tectonic boundary. However, the examination of this issue is beyond the scope of the present paper.

2.2. The tsunami hypothesis in Lechaion

The hypothesis that Lechaion was inundated by a tsunami in around mid-6th century CE can be found in Brown (2008). He referred to a catastrophic earthquake and tsunami episode, which according to the contemporary Byzantine historian Procopius Caesareus occurred during the 6th century CE. Brown (2008) speculated that the tsunami "…may have flooded Lechaion, but it is unlikely to have destroyed the city, which is, again, not mentioned specifically by name". The 6th century tectonic episode is a key event to our examination, and therefore, it is analyzed further in Section 4.

Hadler et al. (2011) and Koster et al. (2011) determined multiple tsunami impact for the Lechaion harbor site and the adjacent coastal areas. Using chronostratigraphy, they suggested that at least three distinct event layers can be identified, the youngest and most destructive event dated to the 6th century CE. Based on historical accounts as well as on geomorphological, sedimentological, geophysical and geoarchaeological data they concluded that the ancient harbor of Lechaion, though influenced by earlier tsunamis, was finally destroyed by tsunami impact which most likely occurred during the strong 521 or 551 CE earthquakes.

Later, Hadler et al. (2013) based on three vibracores drilled in the inner harbor of Lechaion, in-situ X-ray fluorescence analyses and microfossil analysis of sediment samples, electrical resistivity tomographies, and ground penetrating radar measurements, concluded that in the inner Lechaion harbor basin there is evidence of three high-energy impacts, although the geophysical methods showed only one upper unit reaching a maximum seaward thickness of 4 m and thinning inland. The chronostratigraphy was established by ^{14}C-AMS dates indicating that the three layers, attributed to tsunami action, occurred in the centuries 8th–6th BCE, 1st–2nd CE and 6th CE, claiming that the youngest event dated between 500 and 600 CE is responsible for the final destruction of the harbor and the nearby Christian Basilica. Hadler et al. (2013) also argued that beachrocks encountered along the Lechaion coast are extensive units of beachrock-type calcarenitic tsunamites.

In summary, the hypothesis that Lechaion was hit by tsunamis consists of two main suggestions. The first is that multiple tsunami events occurred in at least three different time periods extending from the 8th–7th century BCE up to the 6th century CE, while the second focuses on that the last event was powerful enough to cause destruction to both the Lechaion harbor and the nearby Basilica.

3. Materials and methods

We have re-examined the tsunami hypothesis by investigating alternative interpretations for the destruction of the harbor and the basilica. In view of such a methodological approach a variety of data sets and of observational materials have been collected and analyzed.

The historical documentation of earthquakes and tsunamis occurring in Corinth Gulf has been compiled from various sources and critically evaluated. The correlation of historical evidence with onshore geological tsunami signatures is of great value since no unique, standard criteria are in place for the identification of palaeotsunamis from geological evidence. This has been extensively discussed by Papadopoulos et al. (2014) as regards Mediterranean tsunamis, while good correlation examples come from Augusta Bay in eastern Sicily (De Martini et al., 2010), Corinth Gulf (Kortekaas et al., 2011) and Dalaman in SW Turkey (Papadopoulos et al., 2012).

Rapid changes in the Lechaion coastal geomorphology have been controlled by meteorological factors, such as wind, swell and sea currents as well as by human intervention. In this regard, we collected and analyzed wind data and performed field surveys to better understand mainly the erosional processes affecting coastal geomorphology. In addition, human intervention in Lechaion was examined on the basis of archaeological findings and historical documentary sources.

Various features of beachrocks were used as evidence to support the tsunami hypothesis by previous authors. We contributed in this issue by performing field observations on beachrocks not only in the Lechaion site but also in the eastern Corinth Gulf area. In addition, further laboratory analysis was performed for the Lechaion beachrocks.

4. Earthquake and tsunami history of Lechaion

The Gulf of Corinth is characterized by frequent occurrence of local but powerful tsunamis that do not propagate outside the gulf (Papadopoulos, 2003). Regardless the tsunami size, the highest rate of tsunami generation in the Mediterranean and adjacent seas has been reported in Corinth Gulf (Papadopoulos et al., 2014). This is not only due to the high seismicity of the area but also because of the high sedimentation rate along the coastal zones combined with the steep bathymetry, especially along the south coast, which yields favorable conditions for not only co-seismic but also for aseismic submarine and coastal landslides triggering tsunamis (e.g. Galanopoulos et al., 1964).

According to the most up-to-date data compilation by Papadopoulos (2003), 17 historical tsunami events are known in the Corinth Gulf from the 4th century BCE up to the present. However, it is noteworthy that there is a pattern of decreasing tsunami activity from west to east in the Corinth Gulf, which is consistent with similar decrease noted for both the seismic activity (Papadopoulos, 2003) and tectonic deformation (Avallone et al., 2004). As a matter of fact, 12 out of 17 events that is a ratio of 0.71, as well as the most powerful ones were observed in the western Corinth Gulf. In the central part, only three tsunamis were reported, while the eastern part is much less tsunamigenic with only two weak events being reported. The first was observed after the large (M = 7.0), damaging intermediate-depth shock of 2 June 1898 that caused weak tsunami inundation on the south coast of Corinth Gulf (Ambraseys and Jackson, 1990), although the earthquake epicenter has been placed onshore in Peloponnese, well outside of the Corinth Gulf (e.g. Papazachos and Papazachou, 1997). The triggering of unstable submarine sediments due to strong earth-shaking could provide a realistic interpretation for this local tsunami generation. The second event was also a weak tsunami recorded with an amplitude of 20–30 cm at the Posidonia tide-gauge station, near Corinth (Perissoratis et al., 1984) and observed by local people in the south coast of Alkyonides Bay (Jackson et al., 1982) after the very strong earthquake (M = 6.7) of 24 February 1981.

The earthquake and tsunami historical record of the Corinth Gulf goes back to the 6th and 4th centuries BCE, respectively (e.g. Papadopoulos et al., 2000). As a consequence, no historical tsunami records are available for the time period from 8th to 6th centuries BCE. By contrast, the sedimentary layers found at Aliki and Kirra (Fig. 1), situated in the SW and the North Corinth Gulf, respectively, and interpreted as tsunami deposits (Kortekaas, 2002; Kontopoulos and Avramidis, 2003; Kortekaas et al., 2011), were clearly dated outside of this time window, namely either in Late Holocene well before the 8th century BCE or in historical times during the 15th and 19th centuries. No earthquakes were reported from geological evidence or historical sources for the period from the 8th to 6th centuries BCE.

During the 1st century CE, no historical evidence for tsunami occurrence was found. The Corinth area was supposedly damaged by a doubtful strong earthquake, with chronological estimates varying from 69 CE to 79 CE (Guidoboni et al., 1994; Papazachos and Papazachou, 1997; Papadopoulos et al., 2000). During the 6th century CE several earthquake episodes hit Corinth Gulf. The main documentary sources are the books *History of the Wars*, *Anekdota* or *Secret History* and *On Buildings* of the Byzantine historian Procopius. He was born around 500 CE and died in 561 or 562 CE, while during the reign of the emperor Justinian he served in higher administrative positions. In *Anekdota*, Procopius mentioned that Corinth was among one of several cities affected by earthquakes and that this happened before the plague, which occurred on 542 CE (e.g. Downey, 1935/2004). According to the evaluation of the historian Evagelatou-Notara (1987/88), based on Byzantine chroniclers, this earthquake occurred between 524 and 528 CE, very likely in 524 or 525 CE.

The area around Corinth Gulf was also hit by lethal earthquakes during the mid-6th century, dated to 551 or 552 CE (Evagelatou-Notara, 1987/88; Guidoboni et al., 1994). *History of the Wars* by Procopius is the only first-hand documentary source available for this earthquake activity. This author narrated that great damage, human victims and various ground failures were caused by the earthquakes in countless towns and in eight cities. However, he named only Chaeronea and Coronea, both situated in Boeotia to the NE of Corinth Gulf, Naupactus on the NW side of Corinth Gulf, Patras in Achaia (Fig. 1), and the area around the Crissaean (Corinth) Gulf situated between the cities mentioned before. Although it is generally believed that the 551/552 CE earthquake activity caused severe damage in Corinth, this was neither reported by Procopius nor supported by other evidence. Procopius also reported that a powerful tsunami was generated in Maliac Gulf, NW Euboean Gulf (Fig. 1), but not in the Corinth Gulf. Based on historiography, Papaioannou et al. (2004) suggested that Procopius's description of a strong tsunami occurring in the Maliac Gulf in mid-6th century CE was an erroneous interpretation of classical sources referring to the 426 BCE tsunami, which may actually have occurred during the 3rd century BCE.

It is likely, however, that another earthquake affected Corinth after the 524/525 CE event but before those of 551/552 CE. In relation to Emperor Justinian's project for the construction of protective walls in various Greek cities, Procopius reported in *On Buildings* that the cities had fallen into ruin long before, at Corinth because of terrible earthquakes that hit the city. This may refer to the 524/525 CE earthquake but also to a later event probably occurring in 543 CE (Evagelatou-Notara, 1987/88; Guidoboni et al., 1994).

The estimates for maximum intensity of the earthquakes of 524/525, 543 and 551/552 CE range from 7 to 9 in MM scale while the estimated Richter magnitudes range between 6.5 and 6.8 (Papazachos and Papazachou, 1989, 1997, 2003; Papadopoulos et al., 2000). The historical sources available do not support that tsunamis occurred in Corinth Gulf, including Lechaion, during the 6th century CE.

The detailed study of the excavation reports of Pallas (1961, 1962, 1963, 1964, 1965a,b, 1966, 1967) do not provide any clue about the collapse of the Early Christian Basilica of Lechaion because of the 551/552 CE earthquake. The Basilica was not completed before the 524 CE earthquake, as attests a coin dated to 518–527 CE found below the floor in the central part of it. These findings indicate that the Basilica was unroofed and its floor was not paved until 530 CE (Pallas, 1967). A coin dated to 641–668 CE and found within the non-disturbed strata of the earlier fill of the Basilica just above the south part of the Holy Bema, i.e. dated to 641–668 CE (Pallas, 1964), provides strong evidence that the Basilica remained in use until at least the mid-7th century. This point is extensively discussed in the Discussion section.

Corinth was possibly destroyed by a late 6th century earthquake occurring around 580 CE (Evagelatou-Notara, 1987/88) with an estimated intensity of I = 7 + and magnitude M = 6.3 (Papazachos and Papazachou, 1997; Papadopoulos et al., 2000). However, Evagelatou-Notara (1987/88) noted that the destruction of Corinth seems to coincide with the devastation caused by the Arabs and Slavs over the same period.

In summary, the available historical and archaeological evidence do not support that tsunami flooding occurred in Lechaion during the 8th–6th century BCE, in the 1st–2nd century CE, and during the 6th century CE, which is the hypothesis put forward by Hadler et al. (2013). Such hypothetical tsunami events are absent from the published tsunami catalogues for either Greece or the Mediterranean (Heck, 1947; Galanopoulos, 1960; Ambraseys, 1962, 2009; Antonopoulos, 1980; Papadopoulos and Chalkis, 1984; Papazachos et al., 1986; Papazachos and Papazachou, 1989, 1997, 2003; Soloviev, 1990; Papadopoulos, 1993, 1998, 2000, 2001, 2003, 2009, 2015; Papadopoulos et al., 2000, 2014; Soloviev et al., 2000). Also in the Ionian Sea (Greece), the tsunami occurrence rate resulting from a series of published palaeotsunami investigations is highly overestimated as compared to the tsunami record from documentary sources and needs reexamination (Marriner et al., 2010; Marriner and Morhange, 2013; Papadopoulos, 2015).

5. Winds, swell, gravel transport and coastal erosion in the Gulf of Lechaion

The south coast of Lechaion Gulf is naturally dynamic. Wind, swell and currents, are natural forces that, in combination with human interventions over time, define the coastal morphology resulting in rapid changes in the coastal area.

We performed detailed statistical analysis of meteorological data for the site concerning the period January 2008–January 2014, as provided by the National Observatory of Athens (http://meteo.gr/meteoplus/Monthly_Bulletins.cfm) for Isthmus of Corinth (Posidonia) Weather Station located 6 km east of Lechaion. From this we can infer that the wind speed ranges from 8.2 km/h to 18.7 km/h (average 14 km/h),

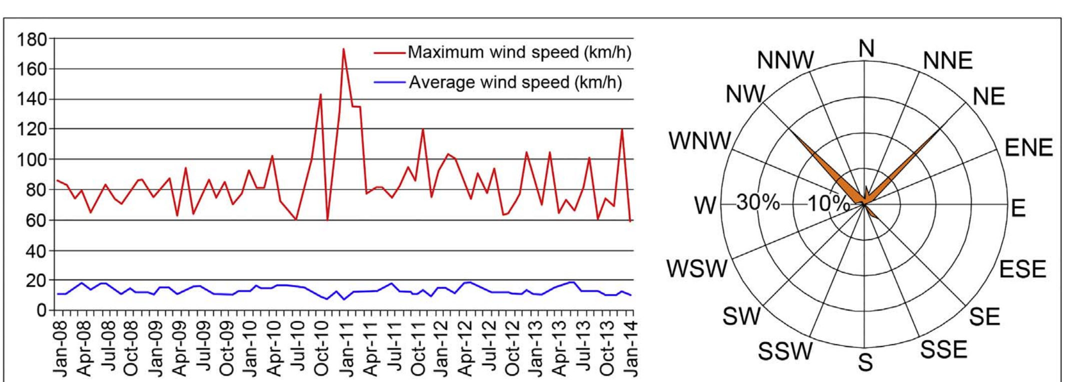

Fig. 3. Graph of average and maximum wind speed (km/h) and wind rose of maximum wind direction, both for the period Jan. 2008–Jan. 2014. (Data: National Observatory of Athens, Isthmus of Corinth Station.)

Fig. 4. Inclination of trees because of strong winds along the seaward side of Lechaion archaeological site (in front of the Basilica).

whereas the maximum wind speed ranges from 59.5 km/h to 173.8 km/h (average 85 km/h), in winter and summer as well (Fig. 3). The dominant wind direction is NE (37%) and NW (31.5%), followed by the N (5.5%), WNW and NNE (4.2%), and NNW, WSW and ENE (1.4%) directions (Fig. 3). In conclusion, the dominant local winds are the landward NW to NE ones, perpendicular to the orientation of the Lechaion Gulf. The inclination of the trees because of such strong winds makes it obvious even to an ignorant visitor of the site (Fig. 4). The sea wave height for the average speed (14 km/h) of NW wind is 0.30 m and for a wind speed 35–45 km/h the wave height is 0.80 m–1.30 m (data source: National Observatory of Athens, Isthmus of Corinth (Posidonia) Weather Station; http://meteo.gr/meteoplus/Monthly_Bulletins.cfm). These data do not support that in the entire Corinth the dominant wind systems are from the E and WSW with an average wind speed of 4 m/s during winter time and that, although the wind direction coincides with the orientation of the Lechaion Gulf, average wave heights do not exceed 0.20 m, as suggested by Hadler et al. (2013).

The coastal zone of Lechaion suffers major erosion due to storm action (Fig. 5). Given the large urban and touristic development in the last quarter of the 20th century, extensive waterfront protection and defense works have been constructed for a total length of 4 km shoreline that stretches 1.6 km west of the ancient harbor of Lechaion to Assos (Fig. 6).

A very difficult task for specialists is to distinguish tsunami deposits from storm deposits (e.g. Dawson et al., 1991; Sugawara et al., 2008 and references therein). Both tsunamis and storms are high-energy events that may leave marine deposits in coastal sediment sequences, as described by Kortekaas et al. (2011) in their attempt to geologically identify historical tsunami events in the central and western part of the Gulf of Corinth, particularly at the sites of Kirra and Aliki (Fig. 1). Although the sediments they examined exhibit many of the characteristic features found in tsunami deposits all over the world, these characteristics only indicate high-energy conditions and a marine source for the event; similar traits have also been reported for storm deposits (Kortekaas, 2002; Morton et al., 2007). However, some of the sediment layers identified by Kortekaas et al. (2011) are probably due to tsunami inundations that correlate with the historical tsunami documentation.

6. Beachrock analysis in the Gulf of Lechaion

Neumeier (1998) studied several beachrock formations in mainland Greece, in Peloponnese including Lechaion, Crete Isl. (Greece), the Red Sea, French Polynesia and Australia. The beachrocks that have been formed on the coast of the ancient Lechaion harbor, just in front of the Lechaion Basilica and west of the western mole at a length of 800 m (coordinates: 37°56′4″N, 22°53′30″E, coast moderately exposed), were sampled systematically (samples code: 401–407) by Neumeier (1998) at several elevations between 0 m and 2 m along a cross section perpendicular to the shore up to the existing dirt road. Intergranular cements were analyzed by several methods (petrographic microscope, electron microscope, microanalysis of X-ray energy dispersion – EDS, X-ray diffractometry - XRD, cathodoluminescence - CL, stables isotopes) aiming to determine the cementation patterns and characterize the environment of formation. Neumeier's (1998) results on the intertidal sediments, showed that the composition comprises 80% carbonate lithoclasts and 20% non-carbonates, while the grain size ranges from medium sand to pebbles (0.2 mm to > 15 mm). The residual porosity was found to range from 20% to 50%, while the nature of fluids is represented by marine water with rare fresh water influence. With regards to the cementation, two successive phases of Mg-calcite micritic, which differ from each other in colour, texture and distribution, followed by orange micrite that represents the last phase of diagenesis. The latter, however, is absent in some samples. This type is generally found on the landward part of the beachrock and at depth (Neumeier, 1998).

The High Magnesian calcite (HMC) micritic cement is one of the principal early marine cements and is the most common type in the Aegean Sea, as reported by several studies (e.g. Neumeier, 1998; Neumeier et al., 2000; Vousdoukas et al., 2007; Desruelles et al., 2009; Vacchi et al., 2012; Mauz et al., 2015; Karkani et al., 2017).

In order to improve our knowledge on the diagenetic environment of the beachrocks outcropping in Lechaion, new samples were collected and thin sections were cut to perform microstratigraphic analyses. These analyses allowed the characterization of the constituents, the identification of bioclasts as well as the description of the type of cements and the consequent identification of the environment of formation along the beach profile (e.g. Desruelles et al., 2009; Mauz et al., 2015; Vacchi et al., 2016). The specific aim was to define the cementation models of beachrock that has incorporated and covered the pavement of the entrance quay at an elevation of + 1.20 m. Beachrocks from this position (coordinates: 37°55′59.38″N, 22°53′37.51″E) were sampled at elevations of + 0.10 m (Lech1) and + 1.45 m (Lech2).

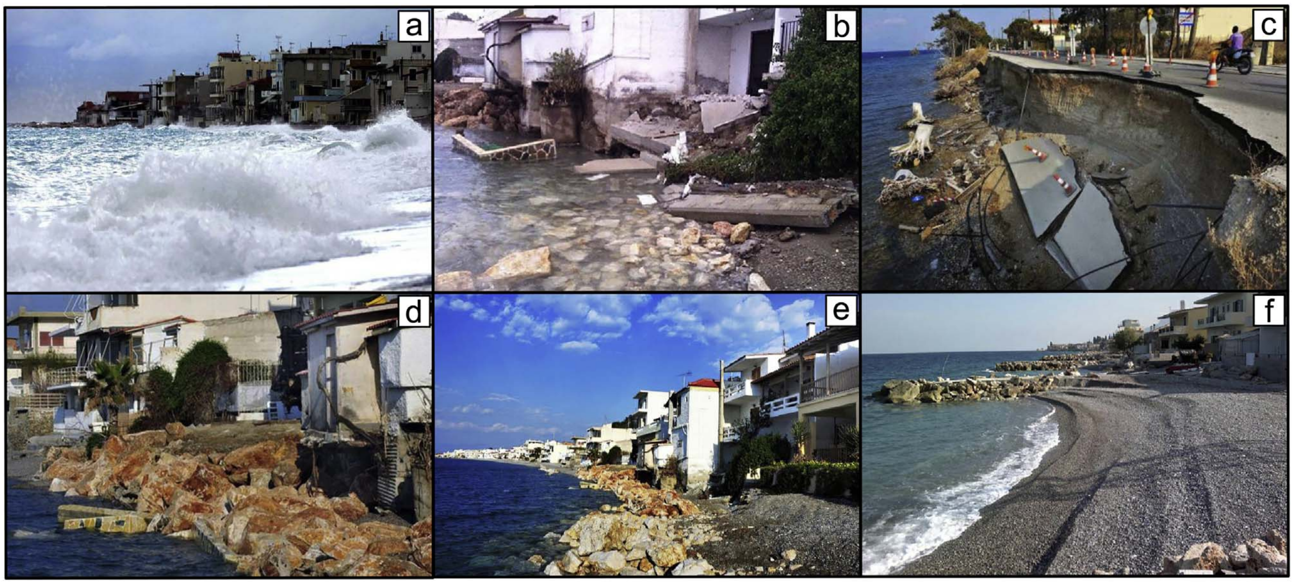

Fig. 5. Views of: (a, b, c) the recent storm damage and flooding (images from korinthiakoi-orizontes.blogspot.gr/2012_03_08_archive.html, uploaded March 8, 2012), (d, e, f) the protective works (images from http://www.newsbeast.gr/travel/sea/arthro/557812/oi-paralies-me-galazies-simaies-se-korinthia-argolida-ileia-ahaia, uploaded July 16, 2013) in the coastal zone of Eastern Corinth Gulf.

Both samples are mainly characterized by well-rounded grains and, in very minor terms, by smaller sub-angular clasts (Fig. 7). Fragments of marine shells are very rare or totally absent. Cementation pattern of sample Lech 2 is similar to the Neumeier's (1998) description. We observed a first undulated micritic phase followed by an orange micritic layer and by a final partial fill of internal sediments. Cementation pattern is more complex in sample Lech 1, where grains are cemented by microbial cement filling the intergranular pore space (Fig. 7). The occurrence of such microbialites in the intergranular pore spaces is similar to those that were found in the upper intertidal portion of beachrocks from the Great Barrier Reef (Webb et al., 1999) and the Caribbean Sea (Caron, 2011a,b). Microbial cement is only indicative of the cementation conditions and not of the type of transport that generated the cemented deposit. In fact, beachrocks are capable of rapidly cementing material from the upper subtidal to the lower supratidal zones, thereby increasing their preservation potential, including swash-built ridge sediments, and also deposits resulting from coastal inundations by high-energy waves (e.g., Morton et al., 2007; Caron, 2011b).

These cementation patterns suggest a beachrock formation ranging from the upper intertidal to slightly supratidal zone. However, our observations coupled with those performed by Neumeier (1998) did not show evidence of beachrock-type tsunamite as suggested by Vött et al. (2010). In fact, the structure is generally non-chaotic, there is a significant majority of well-rounded clasts and almost complete absence of mollusc fragments (Fig. 7). Thus, microstratigraphy did not provide enough robust evidence for tsunami events as the mechanism forming the beachrocks at Lechaion.

Hadler et al. (2013) characterized the beachrocks developed along the south and east coast of Lechaion as “tsunamites”, a term that refers to the cemented part of the corresponding high-energy deposit. These

Fig. 6. Aerial view of the extensive coastal protection works along 4 km of coastline, 1.3 km east of Lechaion up to Assos.
(Image from https://www.tripinview.com/en/presentation?layer=detailed&datasetId=58007&id=39026, 2014 Geotag Aeroview.)

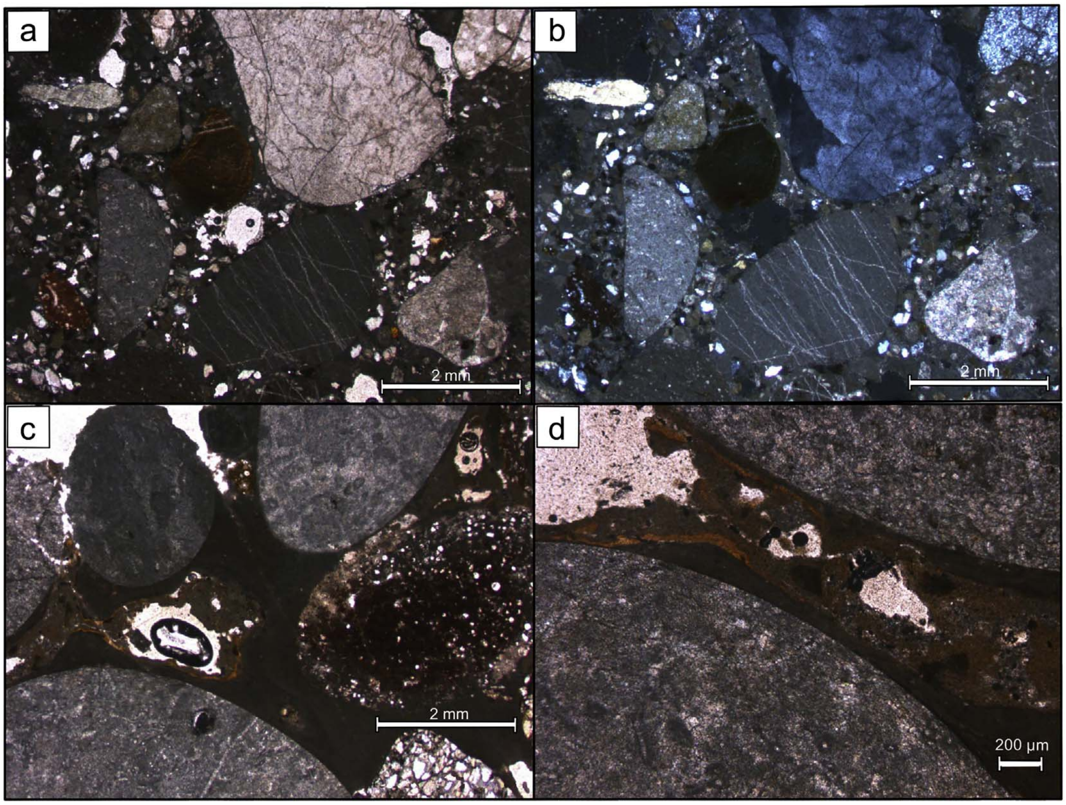

Fig. 7. Thin sections of the beachrock samples analyzed in this study: (a, b) sample collected at 0.10 asl (Lech1), (c, d) sample collected at 1.45 asl (Lech2). Thin sections are seen with plane-polarized light (a, c, d) or with crossed Nichols (b).

tsunamites were attributed to the late 5th to early 6th century CE tsunami event, which was supposedly triggered by a strong earthquake. To substantiate their conclusion, Hadler et al. (2013) provided stratigraphic evidence only from the lower consolidated unit, which, however, is not representative of the beachrock stratigraphy. This is characterized by alternations of cemented coarse, well-rounded beach deposits (boulders, cobbles), gravels, and sands, and is similar to the stratigraphy of the unconsolidated present beach deposits that comprise well-rounded boulders, cobbles, gravels and sands, linked to the nature of the sediment sources from the surrounding basement and also to the dynamics of the coastal system (Fig. 8). The inland continuation of beachrocks does not exceed 21 m. Interpretations for liquefied or fluidized flow dynamics focusing on point/spot structures of a thickness not exceeding 10 cm, located at a maximum distance only 5 m from the shoreline of a dynamic beach (Hadler et al., 2013) are not indicative of tsunami impact since similar microstructures are very common on exposed high-energy beaches throughout Greece. Fig. 9 shows the undisturbed structure of the pavement of the harbor entrance quay, which is incorporated into the beachrock.

In the adjacent area of the ancient diolkos, at the Posidonia entrance of Corinth Canal, two beachrock generations can be observed. The earlier beachrock extends landwards and on it the pavement of the ancient diolkos was constructed, likely in 7th–6th centuries BCE. The pavement is incorporated into, and covered by, a younger beachrock generation (Figs. 10, 11). Hadler et al. (2013) were probably misled by the mistaken interpretations of Mourtzas and Marinos (1994) and Pirazzoli (2010), and considered that there was only a single beachrock generation. However, Maroukian et al. (1994) had already correctly observed and described the two distinct beachrock generations. The earlier generation is formed only in the Posidonia entrance of the Corinth Canal and is absent on the coast to the north (Loutraki coast) and south (Corinth coast). The formation of beachrocks in Posidonia may be favored by local conditions, related to the volume of the sediment supply and the prevailing hydrodynamic conditions (Figs. 10, 11).

7. Discussion

Before the formation of the inner Lechaion harbor, the area was a coastal marsh fed by materials and water from an imperfect hydrographic network upstream that consists of at least nine first order streams draining into the marsh. It was separated from the sea by a narrow sand barrier, through which water percolated, thus providing communication with the sea.

In the time of the Kypselids (7th–6th c. BCE), Corinth enjoyed great prosperity mainly based on trade, and colonies were established in NW Greece, Italy and Sicily, necessitating the formation of a harbor on the south coast of the Corinth Gulf, exposed to the NE - NW winds. It was around this time, when the inner basin was dredged, that parts of the meander were deepened in order to form at least three inner basins. The narrow and low sand barrier was reinforced with boulders covered by the sandy-silt gravel material of the excavation works. During the same period, the eastern entrance channel, and probably a second entrance at the limit of the western mole, were opened (Paris, 1915; Roux, 1958; Sakellariou and Faraklas, 1971; Theodoulou, 2002) allowing seawater to enter the inner basin.

There are several excavation reports (Pallas, 1961, 1962, 1963, 1964, 1965a,b, 1966, 1967) for the Basilica and the surrounding buildings. After cleaning the wells of many of them down to a depth of 3.20 m from the surface, an accumulation of boulders was revealed, probably intentionally transported and placed there to make a reinforcing barrier on the coastal side. Southeast of the Basilica, in an excavation pit of the so-called “agrepavlis”, an accumulation of boulders with Corinthian pottery sherds covered by a thick sand layer was also found (Pallas, 1965b). Accumulations of boulders were also observed at the excavation pits south of the Basilica courtyard at depths

Fig. 8. Views of: (a) the beachrock along the coast of the industrial area of Lechaion (some 250 m to the west of the archaeological site), with maximum landward width 21 m, thickness not exceeding 1.0 m and at maximum elevation + 1.45 m; (b, c, d) the typical beachrock stratigraphy is similar to the stratigraphy of the recent unconsolidated beach deposits.

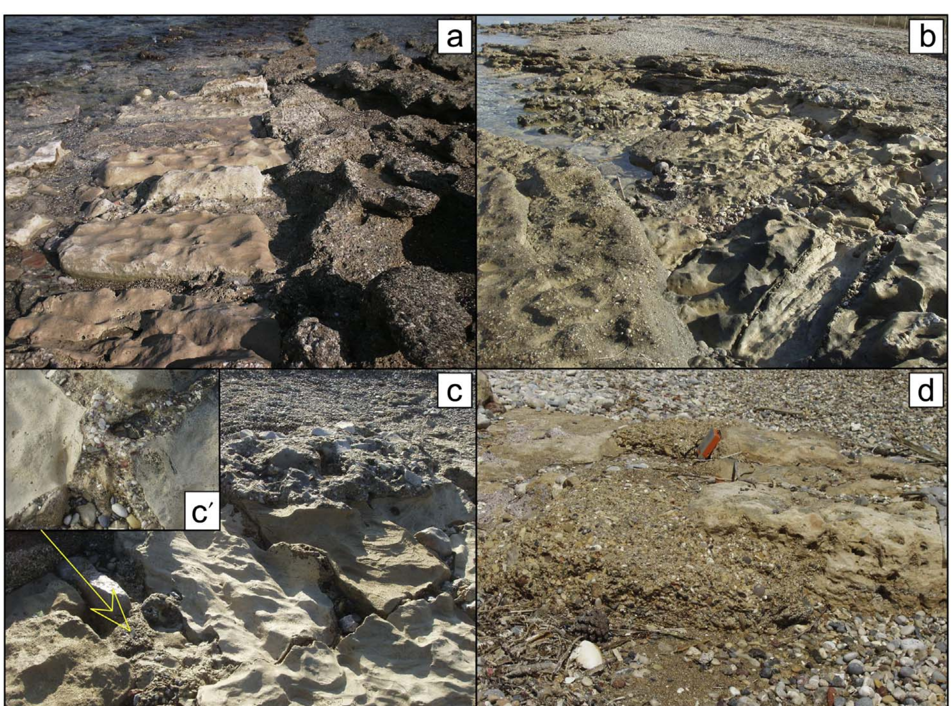

Fig. 9. Views of: (a) the entrance quay covered by beachrock, (b, c) the undisturbed structure of the entrance quay that has been naturally incorporated into the beachrock (detail c′), (d) the beachrock at elevation 1.30 m into which has incorporated the landward visible part of the entrance quay within 20 m from the shoreline.

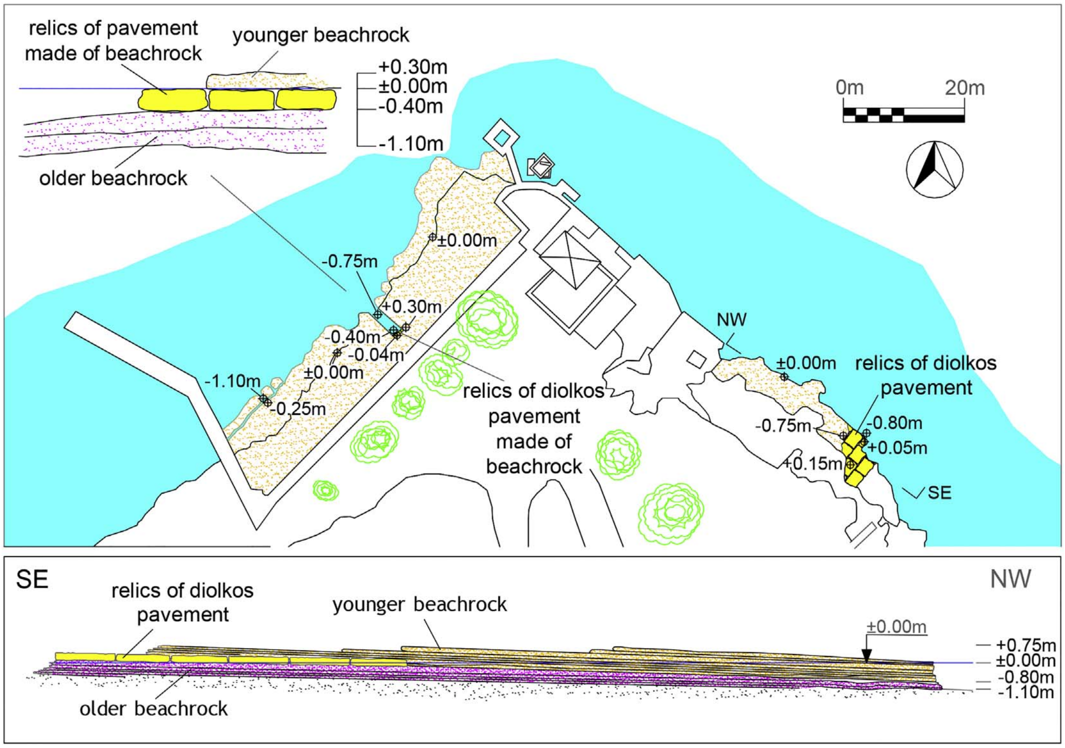

Fig. 10. Plan of the south coast of the Posidonia entrance (Gulf of Lechaion) of the Corinth Canal. In detail: characteristic cross section where the diolkos pavement is found between the two beachrock generations.

from 1.45 m to > 2.35 m, covered by sand and some silt. Fragments of Corinthian pottery with remains of seashells on some fragments were found in the interstices of the boulders, dating the filling to the period of the Kypselids (7th–6th c. BCE) (Pallas, 1965b).

The Kypselids works of forming the inner harbor are confirmed by the three vibracore profiles, drilled in the central inner basin of Lechaion by Hadler et al. (2013). From the end of the drillings (8.0 m LEC1, 9.0 m LEC2 and 6.0 m LEC3) up to the depth of ~4.25 m (LEC1), 4.74 m (LEC2) and 3.50 m (LEC3) shallow marine, littoral and grey clayey to sandy silts were drilled indicating a mean depth of 4 m for the harbor foundation. After opening the entrance channel (or channels) seawater flooded the inner basins and marine sandy sediments entered, aided by the landward NW to NE dominant winds and waves, and together with sandy clayey silt material from the dredge mounds and the upstream slopes transported by flash flood events caused the gradual siltation of the inner basin. This material was also drilled by Hadler et al. (2013), and described as a mean to fine grained sand, lying with a sharp contact, on the deeper unit with a thickness ranging between ~2.2 m (LEC2), ~1.9 m (LEC1), and probably ~0.4 m in LEC3 and was characterized as "tsunami generation I". What we considered as the bottom of the Kypselids foundation, Hadler et al. (2013) described as a "sharp erosional contact", whereas the sediment that resulted from siltation processes after opening the channel/s they described as a "high-energy deposit". The harbor foundation floor has also been revealed by the geophysical investigations carried out by Hadler et al. (2013), who referred to one upper unit reaching a seaward maximum thickness of 4 m thinning inland and that is characterized by the highest resistivity values running N-S for nearly 90 m inland perpendicular to the coast. Hadler et al. (2013) dated this high-energy impact using radiocarbon sandwich dating and provided distant ages for the deposits right above (e.g. from 792 to 774 cal BCE (LEC2) to 44 cal BCE–1 cal CE (LEC1), a time interval of about 800 years) and below the event layer (e.g. 763–562 cal BCE downwards to 830–784 cal BCE upwards). Accordingly, they suggested a *terminus ante quem* age for this layer of 792–774 cal BCE that, in case that it is correct, assigns to the Kypselids project as well. It should be noted that Morhange et al. (2012) suggested a radiocarbon age of 752–407 cal BCE for their drilled unit 1 (depth 2.35–2.85 m), as obtained from a charcoal fragment, which is consistent with the progressive filling of the inner basin during that period.

The archaeological excavation reports give clues about the gradual siltation and repeated dredging/maintenance works in the inner basins over time and, therefore, confirm the continuous activity there (Pallas, 1961, 1963, 1965a,b, 1967). At several depths in the area of the Basilica and in the surrounding buildings, potsherds of the Hellenistic period and remnants of lead sheets used for the lining of the hulls of ancient ships were identified at several depths, while Corinthian coins from the 3rd century BCE were found at a depth of 3.05 m (Pallas, 1963).

As regards the Pb content, Hadler et al. (2013) based on XRF measurements state that pre-harbor marine sediments at Lechaion are void of lead whereas sediments associated with the Greek harbor foundation (8th to 6th c. BCE) show a sudden increase in lead content. However, their graph 5 Pb (ppm) vs depth (m), nil Pb content is shown from the core bottom up to the depths of 2.9 m (LEC 1), 2.6 m (LEC 2) and 1 m (LEC 3) approximately. The highest Pb accumulations (150 ppm), but not following a linear distribution with depth, are found in the upper lagoon – limnic sediments, the 'tsunamigenic' sediments of generation II (LEC 1, 2 and 3), and the terrestrial sediments encountered above the mentioned depths of the three cores. An extremely high Pb content (1300 ppm) was measured locally in LEC 2 at a depth of ~1.2 m to ~1.3 m. Hadler et al. (2013) claimed that allochthonous materials are characterized by decreased lead concentrations, without explaining the high Pb content (100 ppm) in allochthonous event generation II assessed in all cores or the nil Pb content in near-surface contaminated sediments of LEC 1 (~0.20 m–0.30 m) and LEC 2 (~1 m–1.4 m).

On the other hand, as regards lead mining it has been suggested that the mining exploitation of lead in ancient Greece "*reached a maximum around the 1st century AD, as did the environmental contamination*"

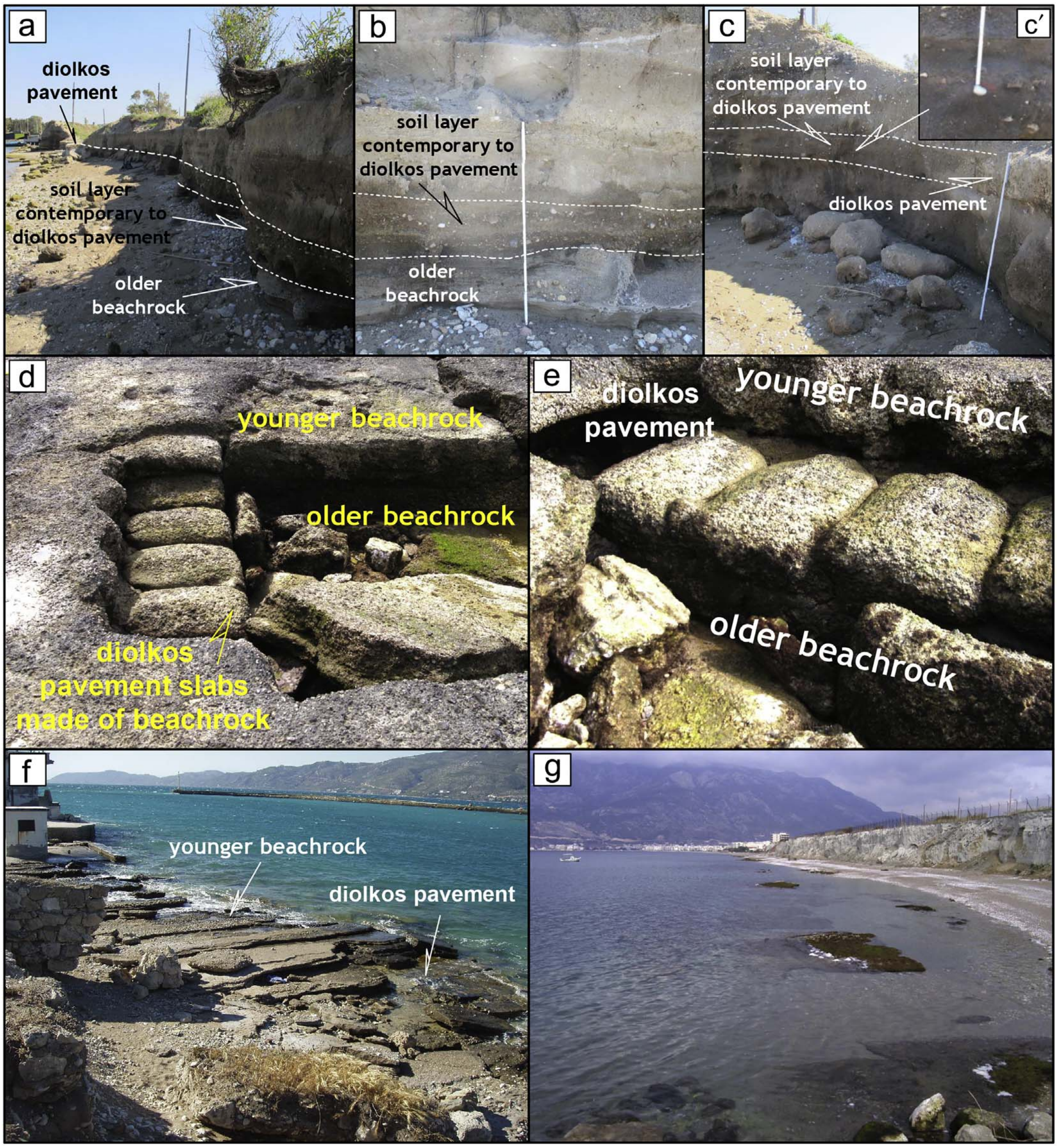

Fig. 11. Views of the south coast of the Posidonia entrance of the Corinth Canal: (a, b, c) details of the stratigraphy observed on the coastal cliff of the south coast of the canal entrance, (d, e) the seaward end of diolkos pavement made of the older beachrock, in between the older and younger beachrock generations, (f) the younger beachrock generation that covers the relics of diolkos pavement uplifted at + 0.75 m, (g) the younger beachrock generation along the Loutraki coast with its seaward end submerged at − 1 m, 100 m north of the Posidonia entrance. The extensive older beachrock observed at the Posidonia entrance does not appear along the extensive Loutraki coast.

(Hadler et al., 2013). According to Konofagos (1980) and Papadimitriou (2008) the peak of mining and smelting activities in Lavrion (the main mining and metallurgical area in mainland Greece) was between the 6th and 4th centuries BCE, and especially during the 5th century BCE, the Golden Age of Athens, whereas after the 4th century BCE it appears that exploitation declined. Mining and smelting activities continued intermittently until the 1st century CE, while during the Roman and Early Byzantine period (2nd c. BCE–6th c. CE) it was sporadic and of small scale. It is estimated that, between the 7th and 1st centuries BCE, approximately 3.5×10^3 t silver and 1.4×10^6 t lead were exploited from Lavrion mines (Konofagos, 1980). The suggested correlation between distance from Lavrion to Corinth and the environmental pollution caused by lead is unclear (Hadler et al., 2013), even more so if we consider that maritime communication between the Saronic and Corinth Gulf was not possible at that time because the Corinth Canal had not yet been excavated. The relatively high lead content encountered at various depths above the dredging floor of the inner basin can simply be attributed to the lining of the hulls of ancient ships with lead sheets, as early as 1956 explained the main excavator of Lechaion Basilica, who found remains of lead sheets during the excavations (Pallas, 1961, 1962, 1963, 1964, 1965a,b, 1966, 1967) and then supported by other scholars (e.g. Theodoulou, 2002).

This first period of the harbor operation lasted for about 600 years up to the Roman invasion of 146 BCE. Assuming a rough thickness of the filling material of 2 m, the minimum siltation rate was estimated at 3.5 mm/year approximately, but in fact it should be greater if we compare it with the usual rates found in other ancient harbors (Morhange et al., 2003; Marriner and Morhange, 2006, 2007; Carsana et al., 2009).

The harbor seems to have been destroyed and abandoned after the invasion of Roman legions and the razing of Corinth by General Lucius Mommius in 146 BCE (Pallas, 1963). This is commonly referred to in ancient literature (e.g. Strabo 8.6.23), and is also evidenced by traces of conflagration from a major destruction at a depth of 2 m in the area of the Basilica (Pallas, 1963). It is also argued by Wiseman (1979), who based on testimonies of Cicero on the existence of Corinthians in 77 BCE, the period of the supposed abandonment of the city of Corinth, he stated that although there are clear traces of violent destruction in excavated buildings, it was probably less extensive.

The destruction and abandonment of the harbor caused the entrance/s closure. The greyish-brown, clayey to silty sediments that were drilled by Hadler et al. (2013) at depths of 2.56–1.83 m (LEC 2) and ~2.4–2 m (LEC 1), as well as between 2.35 m and 0.85 m with thin sandy layers by Morhange et al. (2012), indicate a "change back towards more quiescent sedimentation conditions" in the inner basin and reflect a lagoonal environment.

This intermediate phase lasted for about 100 years, until the Roman reconstruction after 44 BCE. Assuming a rough thickness of sediments of 0.5 m, the siltation rate is estimated to be at least 5 mm/yr. Lechaion, like other harbor basins, is characterized by apparent accelerated accretion rates, at least ~10 times greater than nearby naturally prograding coasts. On natural coasts, sediments are re-suspended from the seabed due to energetic wave processes and transported by currents in the water column. In ancient harbor basins, harbor infrastructure attenuated the swell, marine currents and energy, accounting for a sharp fall in water competence (Marriner and Morhange, 2007; Morhange et al., 2016; Marriner et al., 2017).

The Roman colonization of Corinth in 44 BCE (Strabo 8.4.8) followed by large-scale works to reconstruct, reorganize and expand the ancient harbor, highlights the second major phase of operation and seems to have been implemented in the new period of zenith for Corinth during Roman imperial times (Pallas, 1963). The fore-harbor, the remains of which are visible today, and the construction of retaining walls to protect the banks of the inner basins and the banks of the entrance channel are assigned to this period (Paris, 1915; Rothaus, 1995; Theodoulou, 2002; Mourtzas et al., 2014). More specifically, the harbor reconstruction is associated with the growth of Corinth in the Julio-Claudian period (second half of the 1st c. BCE–68 CE), as evidenced by the existence of swallow-tail clamp cuttings on some blocks of the west mole and the base of a monument on the islet in the inner harbor (Shaw, 1969; Mourtzas et al., 2014). Furthermore, the inner basin was dredged to a mean navigable depth of 2 m (Boetto, 2010), in order to remove the later material from the abandonment phase of the harbor. The dredged material was deposited on top of the archaic dredging mounds. The entrance channel was reopened and the banks of the channel and the inner basins were supported by the retaining walls.

Our interpretation of the 3-phase evolution of the Lechaion harbor is strongly supported by numerical hydrodynamic simulations performed by Repousis et al. (2015) in order to study the efficiency of the Lechaion harbor layout and investigate the impact of the coastal structures on sediment transport along the ancient harbor. The numerical models were tested on one incident wave scenario based on the prevailing NW winds blowing towards the Lechaion Gulf and confirming it by assessing on-site observations during a windy storm event. Repousis et al. (2015) concluded that the adopted layout in the Roman foreharbor design was able to control the retained sediments at both sides of the harbor entrance while, at the same time, siltation in the entrance channel was minimized increasing its navigational efficiency. The sediment transportation model by Repousis et al. (2015) showed that the NW wind creates long-shore currents from west to east. The direction of sediment transportation is mainly perpendicular to the shore-front. The breakwater-system functions as a sediment flow bypass, trapping granular material behind the jetties. The sediment follows a path close to the coast and is then received by cross-shore currents finally disposing it to the beach east of the entrance channel. Significant sediment transportation occurs in front of the harbor entrance, drifting material to the downstream beach and deflecting it to the open sea. Those authors also estimated an average sediment transport rate in volume of sediment per unit time and unit width of 50,000 m^3/yr/m. It becomes obvious that, from the initial formation of the harbor in the 6th century BCE (1st harbor phase) until the Roman reconstruction (second harbor phase), in a period during which there is no evidence for fore-harbor infrastructure, the hydrodynamic conditions due to wave-induced currents favored high sediment transport to the inner basin via the harbor entrance/s. This caused the final closure of the channel entrance/s, after the Roman destruction of the harbor in 146 BCE and before the Roman reconstruction of the inner harbor and the construction of the fore-harbor, probably in the 1st century BCE.

According to excavation reports (Pallas, 1963), the stratigraphy of Lechaion includes a manmade layer of sand and sediment, which appears to have been created after the destruction in 146 BCE and refers to dredging works and fill. The mounds of a maximum height of 17 m and an overall estimated volume of 85.000 m^3 on both sides of the entrance channel and the two central inner basins, are the result of the extensive dredging that started in the Kypselids period and continued in Roman times. It is estimated that roughly 4 m thick deposits were dug out of the basins. Repairs and reconstructions were most likely made throughout the operation of the ancient harbor, depending on needs at the time. Wide-scale works, such as dredging, conservation and interventions in the foreharbor and the inner basins, seems to have been repeated in the mid-4th c. CE, as evidenced by the finding of a plaque with a dedication to 'Flavius Hermogenes', Proconsul of Achaea (353–358 CE), who financed the construction project (Kent, 1966). South of the courtyard of the Basilica, the area of the bath-house (balneum) appears to have been filled with sandstone slabs at a depth of 1.95 m, covered by a layer of sand that is dated back to the second quarter of the 3rd c. CE, based on an 224 CE coin of Severus Alexander found there, bearing cemented sand grains probably deriving from the underlying sandstone slabs (Pallas, 1967). Building foundations and fortification ruins, probably dating to Roman or Byzantine times, are scattered throughout the narrow part of the harbor, whereas on the top of the northeast mound there are two constructions, probably beacons or smoke-signaling stations, with the masonry of small stones and tiles that may belong to the Roman or Byzantine phase (Rothaus, 1995). All over the area there is Roman pottery, mainly from the 2nd century CE, and limited Late Roman moveable finds (Rothaus, 1995).

The Roman reconstruction phase of the harbor is confirmed by the vibracore profiles of Hadler et al. (2013). In all drillings between the depths 1.83 m and 1.5 m (LEC2), ~2 m and ~1.65 m (LEC 1), and ~1.9 m and ~1.55 m (LEC3) marine shell debris and gravels with large limestone fragments and marine macrofossils were drilled. This material was interpreted by as a high-energy input that affected the lagoonal system and is characterized as "tsunami generation II" (Hadler et al., 2013). However, the material was deposited after the reopening of the entrance channel, the sea inflow with marine debris transportation to the inner basins, and the intensive human activity during this period. The high-energy input was not identified by Morhange et al. (2012) although their core was drilled closer to the sea. By contrast, they described a low-energy sub-littoral environment between 2.35 m and 0.85 m, where silty sands were deposited. They also reported a radiocarbon date between 66 and 242 cal CE at the depth of 1.7 m to 1.85 m.

After the final repair of the harbor facilities about 350 CE, the harbor was finally abandoned, when during two successive tectonic subsidence co-seismic events, the relative sea level rose by 2.0 m in total, 1.60 m during the first event and 0.40 m during the second one. A strong uplift event followed and the sea level dropped by 1.10 m (Mourtzas et al., 2014).

Another point that needs further attention is the inner harbor silting and dredging. Morhange et al. (2012) refer to two sources for sediments in the inner harbor, either from the erosion of the artificial mounds or from the lower slopes of Akrocorinthos because of flash flood events. They claimed that the easterly long-shore currents contribute only to the silting of the entrance channel. Additionally, Morhange et al. (2012) estimated low relative sedimentation rates (< 1 mm/yr), without evidence of sediments dating back to the archaic period. Furthermore, they characterized the inner harbor as an "efficient sediment trap" and assume that harbor dredging was required to create and maintain the basin. As indicated in Fig. 14, throughout the area of the inner basins, abundant cobbles, boulders, gravels and sand are scattered, originating either upstream from the surrounding slopes or from the artificial mounds. An alternative has been that the mounds correspond to the post-tsunami re-excavation of the harbor basin between the 6th and the 10th CE (Hadler et al., 2013). However, one may take into account that the gravel facies of the mounds are very similar to those from the Lechaion floodplain, and might correspond to palaeo-wadi fans. In the absence of excavations of the mounds, caution is required in the interpretation of these artificial deposits.

Of crucial importance is to identify when and under which conditions the Christian Basilica was destroyed. The ground on which the Basilica rests was levelled by filling to a thickness of up to 1.3 m, with the exception of the north side that was excavated to the desired level (Pallas, 1961, 1963, 1965a,b, 1967). Specifically, the archaeological excavation below the central aisle and the outer atrium of the Basilica revealed filling with rubble of an earlier building and hauled soil. Based on coins found there, it is dated to the period from Theodosius II (reign 408–450 CE) to Justin I (reign 518–527) (Pallas, 1965b, 1967). The foundations of the Basilica towards the south wing are 1.8 m below the wing's floor, on a layer of coarse sand that contains Corinthian potsherds and Hellenistic utensils (Pallas, 1961). During excavations, the original ground extending from the north wall of the Basilica was found to be at a higher level than the internal floors and consisted of coarse sand and marine gravels (Pallas, 1965a). According to Hadler et al. (2013) this material is the high-energy sediment in which the Basilica was embedded and was transported in the 6th century event. The same material, however, appears below the foundation of the south building VI, which is earlier than the Basilica, thus proving that this is the original material of the past earthworks to form the barrier (Figs. 12, 13g). Therefore, little doubt remains, that the ground surface in the outer NE side of the Basilica was at a higher level than the internal floor (Figs. 12, 13a, a′, b).

On the northwest-seaward side of the Basilica the baptistery and photistery (Figs. 12, 13c) were built on a 2.25 m thick foundation layer and their euthynteria is located at a higher level than the euthynteria of the Basilica (Pallas, 1963). This clue indicates that the ground surface along the north side of the Basilica was higher, progressively decreasing to the west (Figs. 12, 13a, a′, b). The ground surface during the Basilica construction should be 1.5 m lower than the present ground, as can be determined by the thickness of human deposits and excavation debris. According to testimonies given by the workers of the excavations these were deposited right at the north seaward side of the Basilica. Excavation debris encountered throughout the north side of the Basilica up to the dirt coastal road (Figs. 12, 13k, l). This was also deduced by macroscopic observations on a small slope in the zone on the NW side that was left intact during the excavations to provide access to the excavation pit (Figs. 12, 13).

Pallas (1966, 1967) established that the erection of the Basilica started no earlier than the sixth decade of the 5th century CE, from a coin of Marcian (450–475 CE) discovered in the foundations of the Basilica. A coin of Anastasius I (491–518 CE), found under a section of the interior pavement, shows that it was more-or-less complete after the turn of the 5th century CE (Sanders, 2005). The pavement completed around 530 and until that period the Basilica was incomplete and potentially roofless (Pallas, 1967). A coin of Justin I (518–527 CE), discovered in the foundations of the outer atrium, which does not bond with the basilica, shows that additions were still possible during or after the first quarter of the 6th century (Rothaus, 1995; Sanders, 2005). A coin found within the non-disturbed strata of the earlier fill of the Basilica, just above the southern part of the Holy Bema dated to 641–668 CE (Pallas, 1961), documents that the Basilica remained in use until at least the middle of the 7th century.

From the above we can infer that the Basilica was completed after 530 CE and was neither destroyed by the 521 CE earthquake nor buried by high-energy impact from the sea side as Hadler et al. (2013) suggested. Furthermore, no reference is made for an earthquake that struck Corinth in 521 CE. According to historians (e.g. Evagelatou-Notara, 1987/88), Corinth suffered damage from an earthquake occurring very likely in 524 or 525 CE. There is no evidence at all that the 524/525 CE earthquake was followed by a tsunami wave (Papazachos and Papazachou, 1997; Papadopoulos et al., 2000) and definitely not one that destroyed the Basilica, since it has been archaeologically established that the construction project was still in progress. In addition, the suggestion that the destruction and burial of the Basilica was caused by the 551/552 CE earthquakes is groundless, since according to Pallas's excavation reports there is no archaeological evidence that the earthquake struck Corinth (see also Sanders, 2005). Besides, the Byzantine historian Procopius did not name Corinth among the cities that were hit by the 551/552 earthquakes. Moreover, the coin found within the non-disturbed strata of the earlier fill of the Basilica, just above the south part of the Holy Bema dated to 641–668 (Pallas, 1961), documented that the Basilica remained in use until at least the middle of the 7th century CE. On the other hand, serious damage of the Basilica could be linked with the invasion and devastation caused by the Arabs and Slavs around 580 CE (Evagelatou-Notara, 1987/88).

The floor of the wing of the Basilica was found in the major part well-preserved, paved with marble slabs (Pallas, 1961, 1965b), as well as the floors of the lateral aisles (Pallas, 1965a,b). The floors of the Holy Bema and the central aisle are not well-preserved because the majority of the slabs are missing (Pallas, 1965a). A similar view presents the floor of the apse (Pallas, 1962). The floor of the baptistery, especially the photistery, was found very well-preserved in the excavations of 1961/2 (Pallas, 1963). Pallas makes no reference to the deformation structures (e.g. depressions) that have formed in several places on the floor nor do these appear in the pictures of his excavations. Minos-Minopoulos et al. (2015) suggested that the deformation structures observed on the temple floor are indicative of an earthquake induced ground liquefaction in at least three seismic events: the first pre-dates the construction of the Basilica, when Lechaion harbor was in operation; the second event post-dates the construction of the Basilica potentially corresponding to the 524 CE earthquake; and the third event is commensurate with the 551/552 CE earthquakes and the destruction of the temple. It is most likely that these ground deformation features (Fig. 13h) formed after the total exposure of the monument to weather, the accumulation of surface water in places and penetration, and the precipitation and leaching of the underlying soil.

Backfilling of the Basilica after its destruction seems to have occurred during several periods from the end of the 6th century until the 12th century, as supported by various archaeological findings. At the chord of the apse of the Basilica a coin of Justin II (reign 565–574) was found within the thin fill. On the south wall of the wing, within an undisturbed layer, was discovered a coin of Constance II (reign 641–668), whereas in the area of the Holy Bema the filling was dated by a coin of Ioannis Tzimiskes to the 11th to 12th century (Pallas, 1961). In general, the filling of the Basilica seemingly did not occur immediately after its destruction, but human activity intervened upon its ruins. This is also inferred from the traces of fire found throughout the wing, on the floor and the walls, and the base of the columns after the removal of members of the marble colonnade. Later traces of fire were also found in the Holy Bema of the Basilica (Pallas, 1961).

In a series of excavation reports (Pallas, 1961, 1962, 1963, 1964, 1965a,b, 1967) it has been shown that above the Basilica and in its vicinity various buildings were excavated, either pre-dating it or contemporary with it (houses, the baptistery), whose use continued even after the destruction of the Basilica, but also new buildings subsequent to it (Christian sanctuaries, the south houses, the “agrepavlis”) (Figs. 12, 13d, e). Their existence clearly demonstrates that (1) no disaster occurred in the area of the Basilica and; (2) that human activity (religious rituals or everyday life) continued there less extensively even after the destruction of the Basilica. A more detailed documentation of the archaeological excavation results and interpretation is provided as Supplementary material.

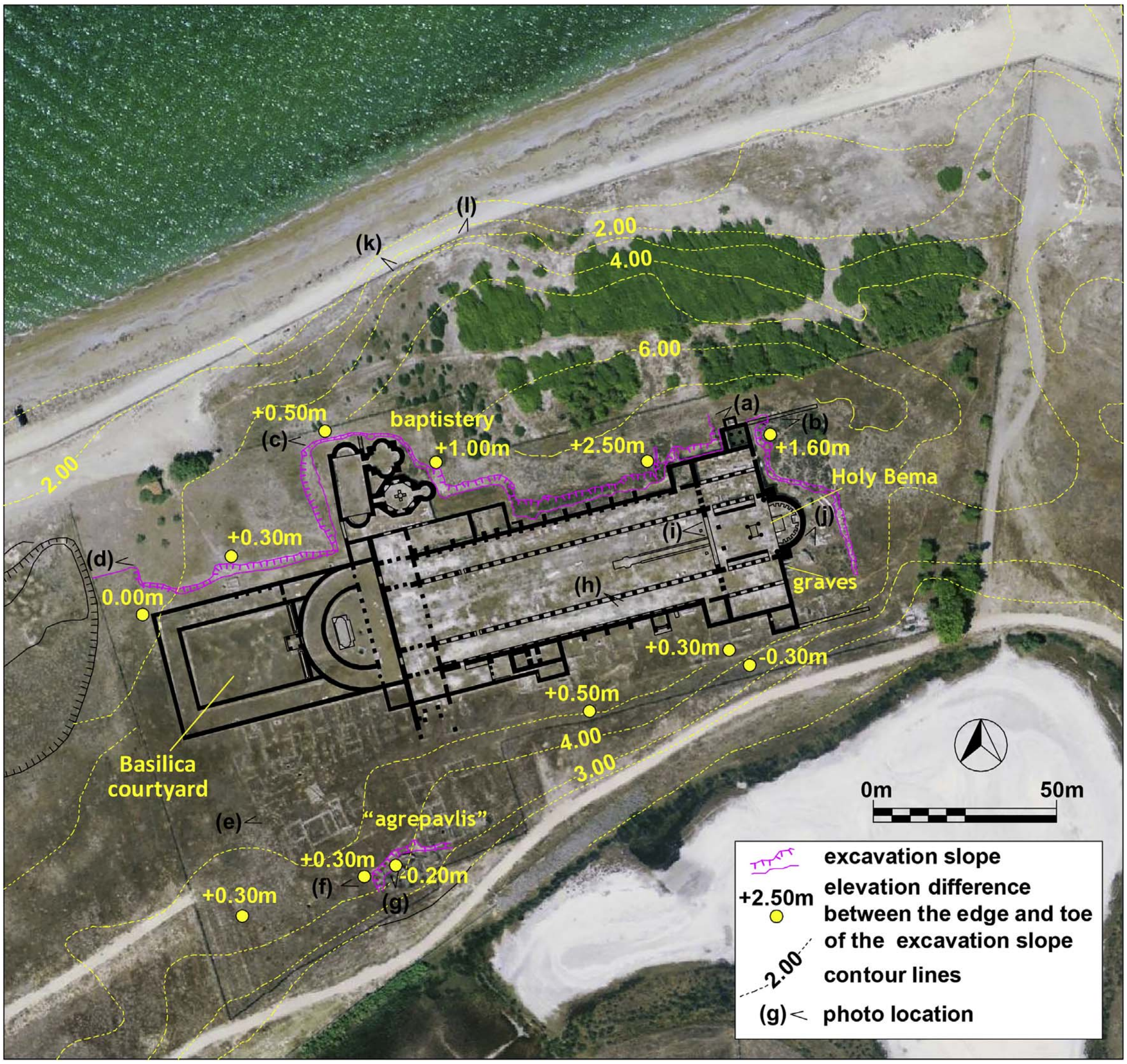

Fig. 12. Plan of the Lechaion Basilica and its surroundings.

8. Conclusions

Shedding light on the question "storm versus tsunami" in Lechaion is paramount in providing robust, cost-effective and better-adapted assessments of present and future hazards in coastal areas, both in the Corinth Gulf and in the Mediterranean (Anthony et al., 2014; Morhange et al., 2014a,b).

Our microstratigraphic analysis and field observations on the beachrocks of Lechaion and comparison with beachrock occurrences at Posidonia did not provide unambiguous evidence of tsunami inundation as the mechanism forming the beachrocks in Lechaion.

The historical evolution of the Lechaion inner harbor, as revealed by the reassessment of the seismotectonics and the tsunami history of the area, as well as from sedimentological, archaeological and historical evidence, supplemented with new field observations, can be divided into two main phases and one intermediate: (a) the first harbor phase that is the harbor initial formation in the Kypselids period (7th–6th centuries BCE). It was then that the entrance channel (or channels) were opened, seawater flooded the inner basins and sandy marine sediments entered, aided by the landward NW to NE dominant winds and waves, and together with sandy clayey silt material from the dredge mounds and the upstream slopes transported by flash flood events caused the gradual siltation of the inner basin requiring repeated dredging/maintenance works. The harbor operated continuously for about 600 years until the Roman invasion of 146 BCE. The intermediate phase of destruction by the Romans and desertion that caused the entrance closure and interruption of direct communication with the sea lasted for about 100 years, up to the Roman reconstruction after 44 BCE. (b) The second harbor phase refers to the harbor reconstruction in the 1st century CE after the Roman colonization of Corinth in 44 BCE. The fore-harbor, the construction of retaining walls to protect the banks of the inner basins and the entrance channel, the dredging of the inner basins to a mean navigable depth of 2 m are assigned to this period.

The Lechaion Basilica was completed after 530 CE and was neither destroyed by the 521 CE and 551/552 CE earthquakes nor buried by a high-energy impact from the sea side. No reference was found for an earthquake that struck Corinth in 521 CE. Corinth suffered damage from an earthquake occurring very likely in 524 or 525 CE. There is no evidence at all that the 524/525 earthquake was followed by tsunami wave and definitely did not destroy the Basilica, since it is archaeologically evidenced that the construction project was still in progress. There is no archaeological or historical evidence that the 551/552 CE earthquakes struck Corinth. Moreover, archaeological findings document that the Basilica remained in use until the middle of the 7th century CE at least. Serious damage of the Basilica could be linked with the invasion and devastation caused by the Arabs and Slavs around 580 CE. Backfilling of the Basilica after its destruction seems to have

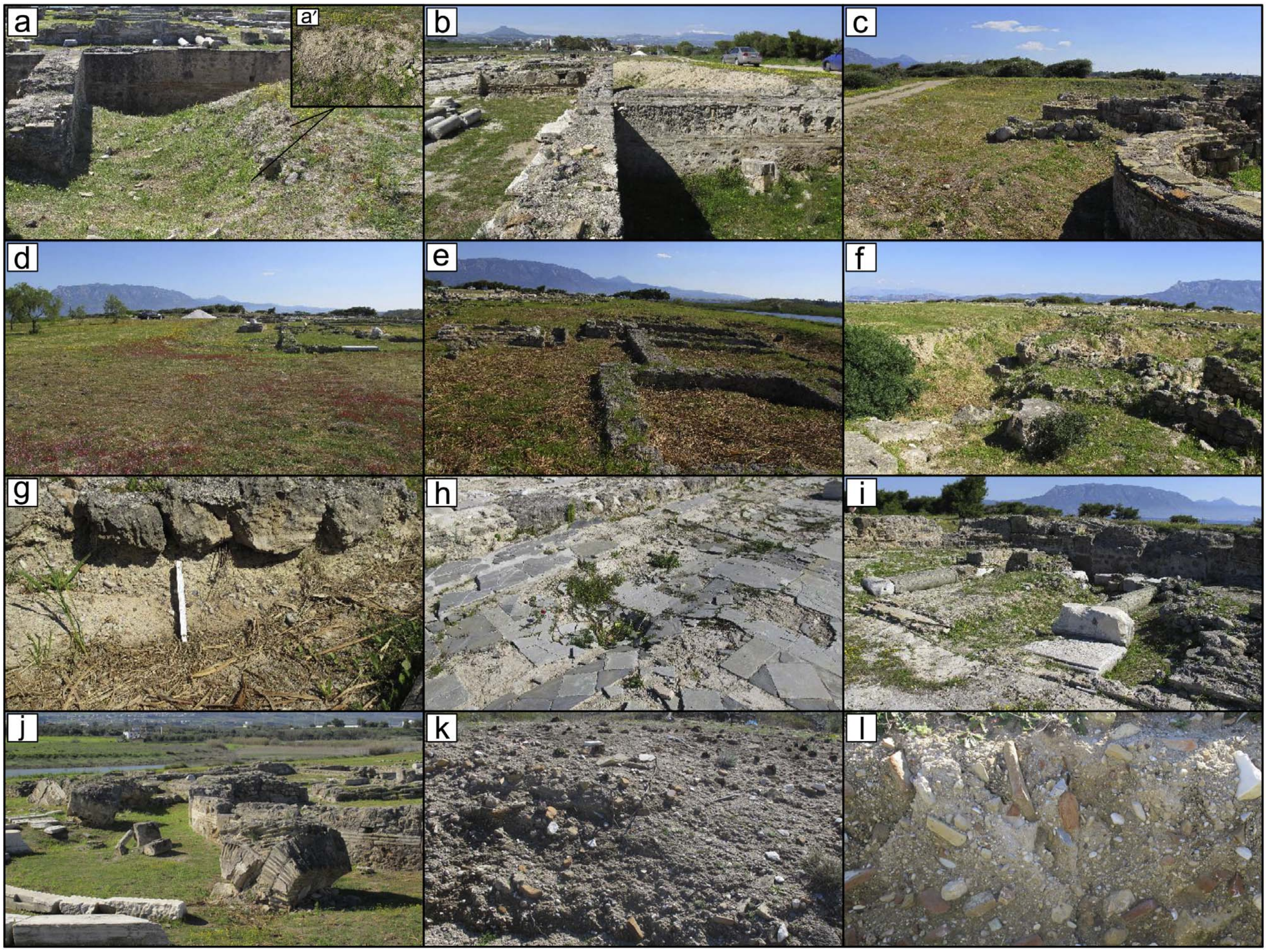

Fig. 13. Views of the Basilica area: (a) NE side, intact zone between the north wall and the ground surface that shows the original ground surface and the thickness of the excavation debris; in detail (a′) the boundary between old and recent deposits, (b) NE side, view of the Basilica north wall, very well-preserved, in perfect alignment, intact, without any visible deformation, (c) north side of the baptistery and photistery, (d) the Basilica courtyard, (e) south side, house complex and agrepavlis, (g) detail of the material below the foundation of the south building VI, (h) the deformation structures on the Basilica floor, (i) the Holy Bema, (j) the apse, (k, l) the excavation debris on the slope of the coastal dirt road.

occurred in several periods from the end of the 6th century until the 12th century, as proven by the archaeological excavation. Human activity (religious rituals or normal life) continued there less extensively even after the destruction of the Basilica.

There is no historical or archaeological evidence that tsunami waves inundated the area of Lechaion (including fore-harbor, inner harbor basins and the Basilica) in the 8th–6th century BCE, in the 1st–2nd century CE, and during the 6th century. Such a tsunami event is included in none of the published tsunami catalogues for either Greece or the Mediterranean. Seventeen tsunami events are known in the Corinth

Fig. 14. Coarse material scattered throughout the area of the inner basins, originating either upstream from the surrounding slopes or from the artificial mounds (picture taken on March 15, 2013).

Gulf from the antiquity up to the present. Tsunamigenesis is decreasing from west to east given that 12 out of 17 tsunamis and the most powerful ones were observed in the western part of the Corinth Gulf, three waves in the central part, whereas the eastern part is the less tsunamigenic with only two minor events being historically reported in 1898 and 1981 CE. The neocatastrophic hypothesis that Lechaion was hit by strong tsunami impacts which caused the destruction of the early Christian Basilica and the harbor facilities should be reappraised, by reviewing all the available data and evidence in order to restore the history of this significant ancient coastal site. Our results indicate that the tsunami potential in the east Corinth Gulf is at all evidence low as compared to that on the west part of the Gulf.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.margeo.2017.08.004.

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