Short Communication

Late Holocene Tectonic Uplift and the Silting Up of Lechaion, the Western Harbor of Ancient Corinth, Greece

C. Morhange,[1] P. A. Pirazzoli,[2] N. Evelpidou,[3] and N. Marriner[1]

[1]Aix-Marseille Université, CNRS CEREGE (UMR 7330), Aix-en-Provence, France
[2]CNRS-Laboratoire de Géographie Physique, Meudon, France
[3]Faculty of Geology and Geoenvironment, University of Athens, Greece

Correspondence
*Corresponding author;
E-mail: marriner@cerege.fr.

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Lechaion's ancient harbor is now a coastal swamp filled with sediments. Two natural factors explain the harbor's abandonment: (1) tectonic uplift during historical times and (2) the location of the harbor basin in a serpentine depression protected from the sea. Although it undoubtedly functioned as a very efficient sediment trap, only modest sedimentation rates (<1 mm/yr) have been measured in the basin. This paradox suggests that the basin was dredged and that the extracted sediments were dumped, forming a number of mounds around the harbor edges. The transition from marine organics to silt is dated to 750–400 cal. B.C. and precedes the 1.2 m uplift of the harbor at around 340 B.C., which underscores the minimal impact of tectonic forcing factors. The presence of fine-grained sediments is consistent with an increasingly protected environment. The macrofauna indicate a low-energy environment enriched with organic matter and brackish conditions. All data suggest that this environment became isolated from the sea. Although a seismic uplift around 340 B.C. played a partial role in the evolution of the harbor, it is not the sole natural forcing agent involved in the silting up of the basin. © 2012 Wiley Periodicals, Inc.

INTRODUCTION

The Gulf of Corinth separates the Peloponnese from continental Greece and is an important graben located in one of the most seismically active regions of Mediterranean Europe. One main characteristic of this gulf is the contrast between vertical seismic movements, with predominant subsidence on the north coast, and uplift to the south (Mariolakos & Stiros, 1987; Stiros, 1988a; Maroukian, Gaki-Papanastassiou, & Papanastassiou, 1994). Uplift of the southern coast is not uniform, reaching a maximum in the middle of the gulf and diminishing toward its extremities (Dufaure, 1975; Sébrier, 1977; Pirazzoli et al., 2004). The investigation of sea level variations and sedimentation inside Lechaion's ancient harbor basin, and the effects of a coseismic uplift that occurred around 340 B.C., provides a timely opportunity to investigate crustal mobility in west Corinth during antiquity, a region of Greece that is still poorly documented. Recently, Soter and Katsonopoulou (2011) in the Gulf of Corinth and Bernasconi and Stanley (2011) investigating the ancient shipyard area at Locri-Epizephiri in Italy have used sedimentary records and archaeological data to reconstruct Late Holocene coastal changes.

CONTEXT OF LECHAION'S ANCIENT HARBOR

The modern city of Corinth is built near the uplift zone, on a marine terrace formed during the Last Interglacial period (Figure 1). Ancient Corinth flourished in Archaic (700–600 B.C.) and Roman (44 B.C. to 400 A.D.) times. Lechaion was the western harbor of ancient Corinth, the eastern harbor being located in Kenchreai, on the opposite side of the isthmus. Lechaion was probably one of the first harbors to be excavated in Greece in such soft rocks (Georgiadès, 1907; Pâris, 1915). Traditionally, the harbor's construction was assigned to the Roman period, but biological and radiometric evidence suggests that it can be dated to the beginning of the 6th century B.C. (Rothaus, 1995; Stiros et al., 1996). It is generally assigned to the period of prosperity of ancient Corinth.

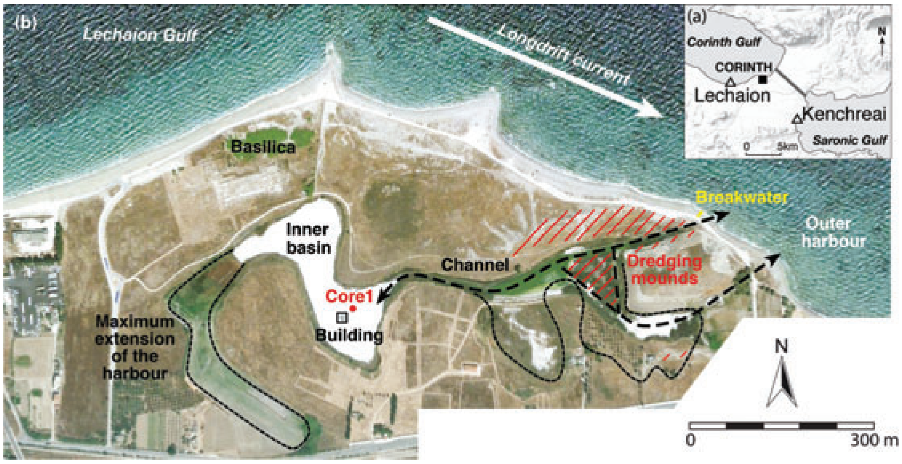

Figure 1 (a) Map of the Gulf of Corinth showing the location of Ancient Corinth and the ancient harbor areas. (b) Map of Lechaion's ancient harbor area based on Google Earth Imagery. The white area corresponds to the main silted harbor basin. On the western side the ancient harbor's access channels are delineated. Dredging mounds and other inner basins are also visible.

The port comprised inner and outer basins. Remnants of two jetties of the outer basin are still visible today. It was an artificial harbor, like a cothon, dug in a swamp zone (Carayon, 2005) (Figure 1). Lechaion was in use as a harbor at least until 400 A.D. (Stiros et al., 1996). It was probably one of the most important seaport complexes of this type during ancient times and remained a major Greek harbor for more than a millennium. Around the harbor, one may find mounds of silt, sands and gravels—rich in lagoonal macrofauna—that were left after dredging operations (Figure 2). Today, only the waterfront constructions remain around an almost entirely silted up inner basin, with a rectangular construction whose function is unknown due to the absence of archaeological excavations. The harbor has a peculiar serpentine geometry, which evokes the dredging of a natural watercourse rather than a palaeolagoon (Figure 1).

The edges of the access channel, connecting the eastern side of the inner basin to the sea, were constructed of ashlar blocks. Stiros et al. (1996) have used elevated marine bivalves in growth position to date a coseismic uplift event. Four samples of emerged marine fossils from the access channel wall were collected. They have shown that an uplift of at least 70 cm occurred between 500 and 200 B.C., most probably around 340 B.C. (Stiros et al., 1996) (Table I). Emerged *Balanus perforatus* fossils, indicating a former biological sea level 1.2 m above the basin surface (upper limit of the marine incrustation) allowed the magnitude of uplift to be estimated. They were collected in growth position from a rectangular structure in the middle of the main basin (Figures 1 and 3). Radiocarbon analyses have constrained the date of the uplift to 2470 ± 45 B.P. (375 ± 120 cal. B.C.). No evidence has been found

Figure 2 (a) The entrance channel seen from one of the mounds of sediment left after dredging operations. (b) Dredged mounds around the harbor perimeter.

Table I Radiocarbon dates of samples collected from the Lechaion area. (a) Stiros et al. (1996); (b) the present study. Calibration according to Reimer et al. (2009).

Elevation (m Above Present Sea Level)	Sample Code	Material	Conventional ^{14}C age BP $\pm \sigma$	Calibrated Age $\pm 2\sigma^d$	Source
+0.7	Gif-A-90SS4-A	Lamellibranch	2530 ± 90	466–5 B.C.	a
+0.7	Gif-A-90SS4-B	Lamellibranch	2400 ± 45	202 B.C.–54 A.D.	a
+0.7	Gif-A-91LE1-A	Lithophaga	2620 ± 50	493–197 B.C.	a
+0.7	Gif-A-91LE1-B	Lithophaga	2430 ± 50	296 B.C.–21 A.D.	a
+1.2	Gif-A-92LE1	Barnacles	2470 ± 45	330–46 B.C.	Unpublished
−0.8	Lyon 2378 OxA	Charcoal	1070 ± 35	895–1022 A.D.	b
−1.8	Lyon-2379 OxA	Wood	1860 ± 40	66–242 A.D.	b
−2.4	Lyon-2312 OxA	Charcoal	2440 ± 30	752–407 B.C.	b

of later higher Holocene uplift. Nonetheless, recent literature on the late Quaternary and Holocene tectonic uplift history around the Gulf of Lechaion, suggests a model of gradual coastal uplift in the geologically recent past (e.g., Turner et al., 2010 and therein). In light of this, an individual uplift event of 1.2 m is probably not the unique solution for the data available.

INNER HARBOR SEDIMENTATION

The history of Lechaion's harbor is open to conjecture due to the paucity of archaeological excavations. In light of this, we drilled two sediment cores in the now dry basin to understand the harbor's sedimentary evolution. These were drilled using a Dachnowsky 40 mm hand-drilling device. Core 1 (285 cm in length) was taken in the ENE direction 5 m away from the north extremity of the rectangular construction (Figure 1—37°55′N; 22°53′E). Core 2 is 235 cm long and was taken 25 m from the southern extremity in the SSE direction. The second core is shorter and seems to have undergone considerable reworking. Indeed, the layer between 210 and 220 cm depth was dated to the modern period. In light of this, we have decided to only present the results from core 1 and its location is shown on Figure 1. The latter is constrained by three radiocarbon dates that are consistent with the stratigraphy.

Core 1: Biosedimentary Description

Core 1 shows three distinct facies (Figure 4). The basal unit 1, between 235 and 285 cm depth, has a yellow-brown color. Radiocarbon analysis of a charcoal fragment from the upper part of the unit (235–250 cm) was dated to 2440 ± 30 B.P. (752–407 cal. B.C., Lyon 2312 OxA). Due to the presence of a large amount of organic fibers (*Posidonia oceanica*) in the samples, sieving was ineffective. The malacological content was very sparse with only a few small fragments of broken marine shells.

Unit 2, between 85 and 235 cm below the soil surface, is characterized by a predominantly silty texture, constituting 40–88% of the total amount of material deposited. We observed a number of thin sandy layers. For instance, a sample taken at 110–120 cm depth contains 60% sand. A wood fragment from the sample at 170–185 cm was dated to 1860 ± 40 B.P. (66–242 cal. A.D., Lyon 2379 OxA). The biological content of this unit is characterized by many fragments of deteriorated shells including *Bittium* sp. and *Gibbula racketti* that are gastropods characteristic of sublittoral rocks. Among the pelecypods, *Cerastoderma edule*, *C. glaucum*, *Paphia aurea*, and *Parvicardium exiguum* were identified. They attest to a low-energy sublittoral environment where silty sands were deposited. *Parvicardium exiguum* is also a bioindicator of natural pollution by enrichment in organic matter. It is typical of a harbor environment in a leaky lagoon context (Marriner & Morhange, 2007).

Unit 3, between 85 cm depth and the soil surface, shows a particularly fine-grained texture attesting to an increasing protection from offshore dynamics and confinement of the basin. The silt content never represents less than 84%. A charcoal fragment from 75 to 85 cm was dated to 1070 ± 35 B.P. (895–1022 cal. A.D., Lyon 2378 OxA). This unit contains many fragments of broken and deteriorated shells, including *C. glaucum*, typical of a lagoonal environment, and *P. exiguum*, indicative of an environment enriched in organic matter. Between 1860 ± 40 B.P. and 1070 ± 35 B.P., the sedimentation rates decrease further with values between 0.68 and 0.82 mm/yr.

Discussion of the Harbor's Evolution

Harbor silting and dredging

It should be noted that sedimentation in Lechaion's harbor can occur in three ways. (1) Due to the geometry of the harbor, easterly long-shore currents do not input

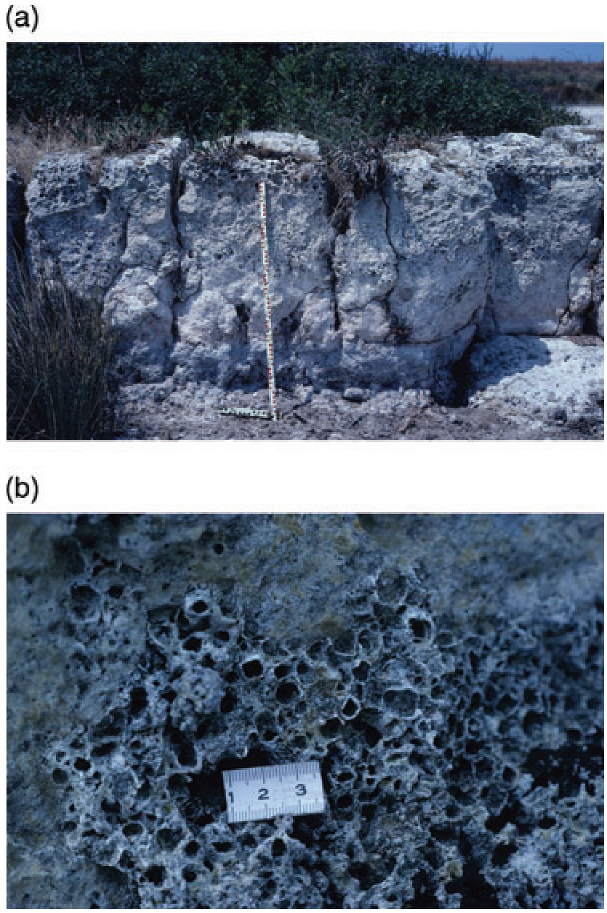

Figure 3 (a) Marine/brackish bioincrustations on a limestone structure in the middle of the former Lechaion basin (arrow corresponds to a raised shoreline about 1.2 m above sea level). (b) Detail of the raised shoreline at about +1.2 m. A sample of barnacle shells was dated to 2470 ± 45 yr B.P. (Table I).

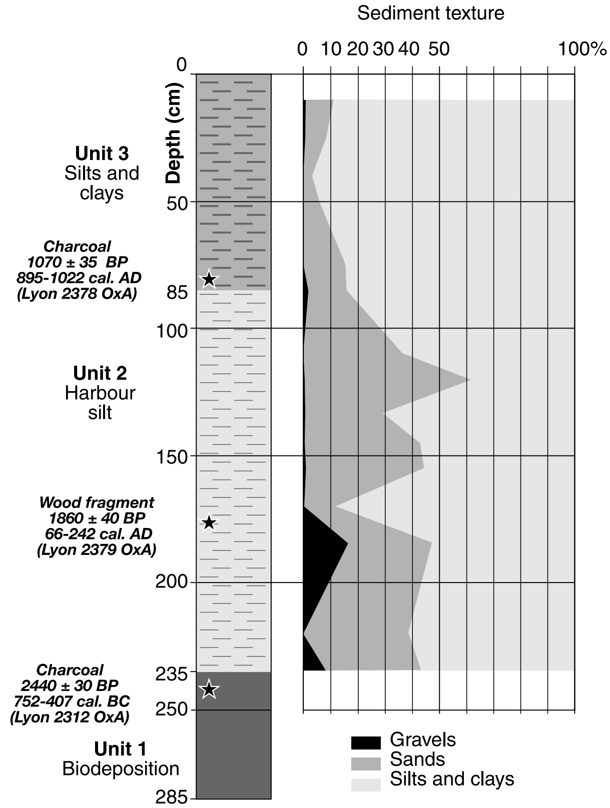

Figure 4 Stratigraphy of core 1 showing the radiocarbon dates and grain size characteristics of the sediments.

significant sediment into the inner harbor, and cannot significantly contribute to the silting of the harbor basin, with the exception of the entrance channel. (2) Material can also derive from the erosion of artificial mounds around the harbor, which might have been alleviated by ancient protective walls, still visible today (Stiros, personal communication). (3) A third potential source could be sediments from the lower slopes of the Akrokorinthos Mountain transported by flash flood events (Figure 1).

A number of different reasons lead us to suggest that Lechaion's harbor was dredged: (1) we measure very modest sedimentation rates compared to other ancient harbors such as Graeco-Roman Tyre (10 mm/yr; Marriner & Morhange, 2006), Byzantine Theodosius harbor (15 mm/yr; Bony et al., 2011), or Archaic Marseille (22 mm/yr; Morhange et al., 2003). In Lechaion, we observe remarkably modest rates of <1 mm/yr. These rates are comparable to those measured in Frejus' Roman harbor (0.4 mm/yr) (Gébara & Morhange, 2010) and in the harbor basin of Naples (Marriner & Morhange, 2007; Carsana et al., 2009) that are very variable. (2) Although core 1 is only 285 cm in length, we note the absence of sediments dating from the Archaic period that can be explained by periodic dredging, responsible for the removal of most of the ancient sediments. This is the case for the majority of ancient harbor basins in the Mediterranean (Marriner & Morhange, 2007). Nonetheless, further radiocarbon dates are required to confirm whether sediments were removed by dredging.

Excavated in antiquity in an existing "natural" depression, Lechaion's inner harbor was a cothon whose serpentine configuration was an efficient sediment trap that was particularly problematic for ancient engineers. This sedimentary setting leads us to favor the hypothesis that harbor dredging was needed to create and to maintain the basin. There is mounting evidence for this process throughout the Mediterranean (Pomey, 1995; Morhange & Marriner, 2010).

Relative sea level forcing

Recent literature on the late Quaternary and Holocene tectonic uplift history around Lechaion suggests a complex model of coastal uplift in the recent past (see Turner et al., 2010) and this has been confirmed by research into the tectonic uplift of the harbor (Stiros et al., 1996). Even though we find some local indications of submersion that are still poorly studied, the harbor of Lechaion appears to have been uplifted by 1.2 m above mean sea level since the 4th century B.C. An important shift in the sedimentary facies is recorded, passing from marine organic matter (unit 1) to silt (unit 2). This change is dated to 2240 ± 30 B.P. (752–407 cal. B.C.) and precedes the harbor uplift date. A fining upward sequence is characteristic of an increasingly protected environment as indicated by the low-energy silty sand macrofauna assemblages. All these data point to a progressive land locking of the inner harbor and a reduction in water depth, with a basin confinement that becomes increasingly pronounced as indicated by the dominant clay-silt texture of the uppermost facies (unit 3). This evolution was accelerated by the later tectonic uplift.

Comparison with other uplifted harbors

At Mavra Litharia, around 50 km away, Papageorgiou et al. (1993) and Stiros (1998b) studied the elevated harbor of ancient Aigeira. Archaeological and biological evidence indicates that the approximate sea level position around A.D. 150–250, the period of construction of the ancient harbor of Aigeira, is 4 m above present sea level. The harbor uplift is related to a series of earthquakes, one of which was possibly responsible for the demise of Aigeira in the 3rd century A.D. and the abandonment of that harbor. Unfortunately, no sedimentary research has been undertaken at this site.

In Crete, the Roman harbor of Phalasarna was uplifted by ca. 6.5 m above present mean sea level, probably in 365 A.D. (Pirazzoli et al., 1992; Dominey-Howes, Dawson, & Smith, 1998; Stefanakis, 2010). Unfortunately, sedimentary and palaeoenvironmental research have focused on the tsunami deposits of 66 A.D. and 365 A.D. rather than harbor silting and basin confinement. It is assumed that the two basins were removed permanently from marine influence after the 365 A.D. seismic uplift of western Crete.

In Cyprus, the minor uplift of the harbor of Kition-Bamboula shows a similar evolution (Morhange et al., 2000). The sediment facies reveals a similar sequence of change toward terrestrial environments and the formation of coastal swamps. At Lechaion, the ca. 340 B.C. episode reinforced the land locking of the harbor, expressed by the presence of lagoonal silt (unit 2). However, it was not the sole natural forcing agent in this case. The harbor access channels are rather narrow and the silting-up process must have begun immediately after its foundation.

CONCLUSIONS

Today Lechaion's ancient harbor is a polyhaline swamp filled with sediments. Tectonic uplift after its foundation, and a basin located in a distinctive s-shaped depression that is well protected from the open sea, explain why the harbor was abandoned. It now seems clear that this location, which is very confined, was not particularly favorable for the long-term viability of a coastal harbor. Although these preliminary results have provided some valuable insights into the history of this site, a far more extensive coring program is needed to fully characterize harbor evolution in such a complex area.

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